



Conference Article

# Assessment of the Strength Reduction on the Forged Fuel Rails due to Corrosion Impact of the Ethanol Content in Gasoline Fuels

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## Abstract

*In this study, strength reduction of the bare rails under corrosive loads which is produced by the forging method is investigated and visualized. Aggressive media of Ethanol has a high corrosion impact on the steel components that reduces the fatigue strength of those parts. Reliability of the forged bare rails are checked after the strength reduction to prove the forged bare rail must be still reliable in the field usage during its service time which is equal to 240.000 km or 15 years. It is proven that failure probability of those parts which are affected by the 100% ethanol content of the fuel in the gasoline internal combustion engine is less than 1 ppm (parts per million).*

**Keywords:** Corrosion, E100 Gasoline, strength reduction, Forging, Fuel Rails, fatigue

## 1. Introduction

### a. Schematic of the Gasoline Injection System

Internal combustion engines (ICE) convert chemical energy to the movement by burning gasoline fuel in the combustion chamber. In this engine layout, it is an example to the

internal combustion engine with high pressure fuel injection system. Gasoline fuel from tank is transferred to the pump with an electric driven low-pressure pump. Low pressure fuel that arrives to the pump will be pressured up to 350bar based on requirements. High pressured fuel at 350bar will be transferred to the forged bare rail in this example (Figure 1).

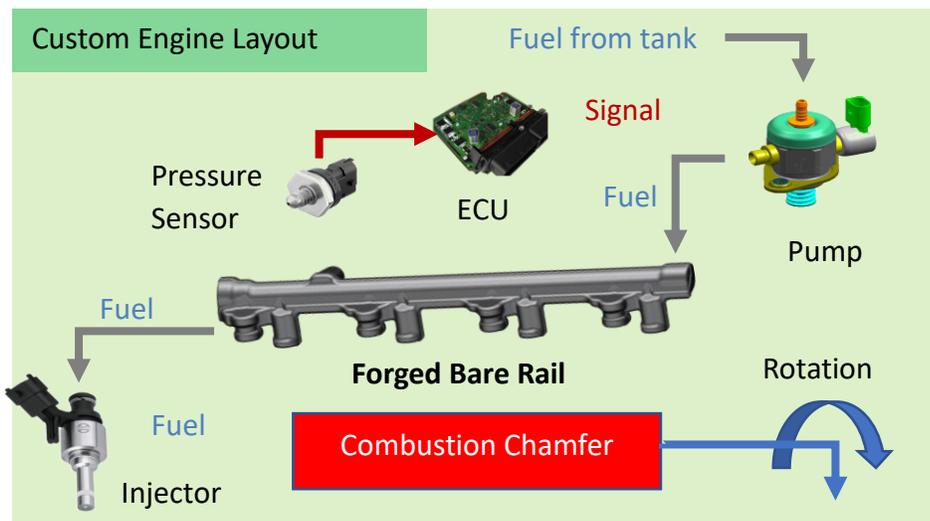


Figure 1. Internal Combustion Engine (ICE) Schematic View

### b. Function of FRA and Motivation of The Strength Detection

The main function of the forged bare rail (Figure 2) is to store high pressured fuel inside of the rail and to be tight during the service life of the product. Another function of the forged bare rail together with injectors that is called as fuel rail assembly (FRA) is to transfer required amount of fuel in desired time and in desired volumes to the combustion chamber.

Gasoline fuel is a highly flammable liquid and can cause to the fire in the engine compartment in case of any leakage. In this study, strength reduction on the internal surfaces of the forged bare rail is checked in case of any crack occurrence under pressure, temperature, and vibration loads after strength reduction of corrosion impact of Ethanol. The main change of the new application is the content of the fuel. EXX content of the gasoline fuel can be found in the various markets such as EMEA, China, America except



Brazil market. Ethanol contents such as E5, E10, E85 can be found in these markets, and this means for E5 for 5% Ethanol in the gasoline fuel or E85 meant 85% ethanol content in the gasoline fuels. E100 is a special fuel type used in the Brazil market meant to be 100% Ethanol in the fuel and 0% gasoline inside which will be burned in the gasoline internal combustion engines. This makes this E100 fuel is more aggressive fuel in the gasoline internal combustion engines.

Currently forging method is preferred in the production method and there will be some potential critical design elements must be checked in the design. Based on the reliability requirements, internal side of the forged bare rail, cross holes are also checked to ensure the tightness of the rail with validation activities against environmental loads of pressure, temperature, and vibrations. The strength (loadability or load capability) of the internal surface of the forged bare rail must be known due to ethanol attacks during field usage. It must be checked not to have an early crack initiation point from these locations.



*Figure 2. Example Forged Fuel Rail*

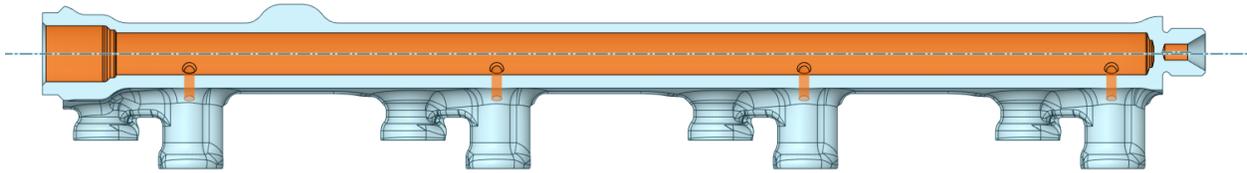
Validation activities to get the strength reduction impact of the Ethanol content of E100 fuels must be performed with accelerated tests and impact of this strength reduction must be done in a shorter and reasonable duration in to release of the new parts for the customer usage (Figure 3).

In reliability perspective, strength of the design elements must be known by the validation methods and more common way to create the Wohler curves of the design element by using hydro pulse or mechanical pulse devices under variable loading. Pressure-cycles curves will be created after running hydro pulse tests in this study for the internal surface of the forged bare rail.

FEA methods are also important activity for this study. Because as an output of hydro pulse test, Wohler curve will be created as Pressure-cycle curve and it must be converted to Stress-cycle (SN) curve to get a universal representation of this test and SN curve is a load independent curve and can be used to perform assessments with different loads such as pressure, temperature, and vibration or in their combinations.



After getting SN curves and load spectrum from vehicle measurements, fatigue assessments must be performed to ensure the failure probability of the design element must be less than 1 ppm during the service life of the product.



*Figure 3. Section View in Forged Fuel Rail & Effected Areas due to Ethanol.*

## **2. Reliability Requirements for The Internal Surfaces**

Rail design must fulfil reliability requirements during project phase. Since rail is a part which stores fuel and supplies to the injectors required amount of fuel, therefore leakage is not allowed as a safety relevant requirement. Rail should withstand loads during lifetime. Rail is evaluated by finite life fatigue approach which is considering load collective from the field therefore failure probability must be less than 1 ppm.

Strength data is required for focused area to complete fatigue assessment. When a new project is started, strength data (Wohler curves) is not known as shown in Figure 4, and it should be conducted by corrosion and hydropulse tests.

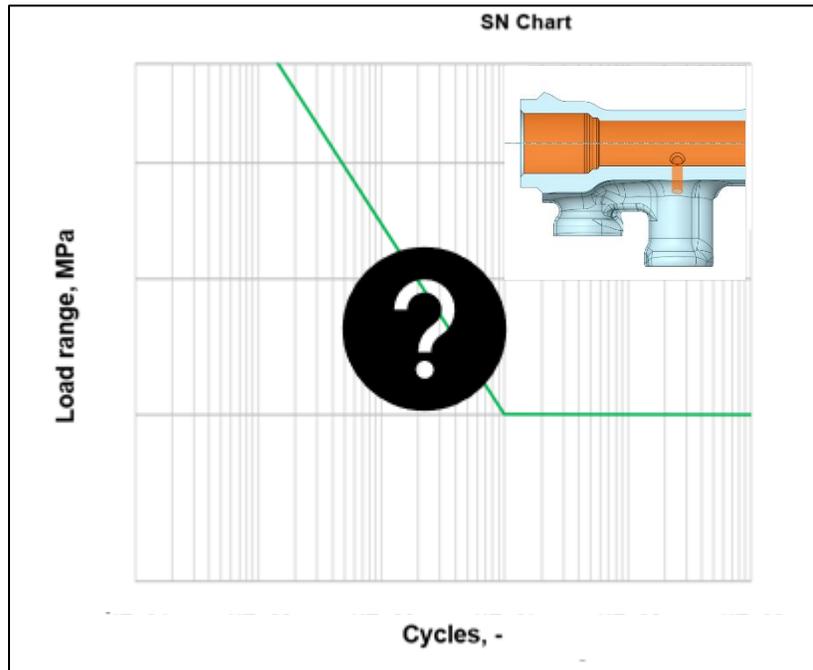


Figure 4. Unknown Strength Data of Internal surfaces (Illustrative Data)

### 3. Simulation Studies

Simulations are performed to evaluate and to improve the design against environmental loads. Initial simulation considers operational loads which are mounting, pressure and temperature loads. Boundary conditions represent engine working condition. If stress results are higher, design optimization studies are done.

Simulations are performed to see mode shapes, resonance points and stresses based on vibration load. ISO 16750-3 is used as vibrational load. Loads are applied to each 3 directions individually. In figure 5, boundary conditions are shown for different simulation types. Stress calculation includes mounting load, system pressure to fuel area and temperature load for all components. It's also called as operational loads. Vibration simulation includes modal analysis and PSD stress calculation with ISO load profile at each 3 different directions.



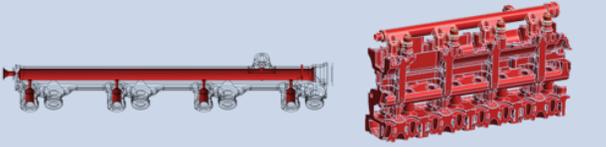
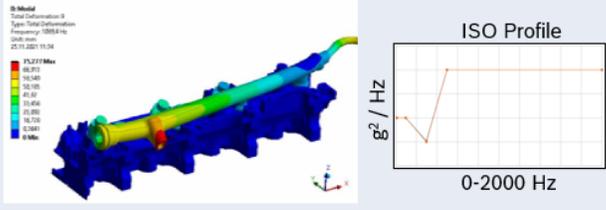
Activity	Definition
<b>Stress Calculation Under Pressure Temperature Loads</b>	 <p style="text-align: center;"><b>350bar</b>                      <b>20 °C → 130 °C</b></p>
<b>Stress Calculation Under Vibration Load</b>	 <p style="text-align: center;">ISO Profile</p> <p style="text-align: center;">g<sup>2</sup> / Hz</p> <p style="text-align: center;">0-2000 Hz</p>

Figure 5. Simulation Studies

#### 4. Mesh

Fine mesh is created on focused area to have accurate stress result. Mesh distribution and elements are seen in Figure 6. Areas in which have fine mesh distribution and smaller element size are used. Tetrahedral element type is preferred to have better transition between locations. FE model has nodes number around 7.000.000.

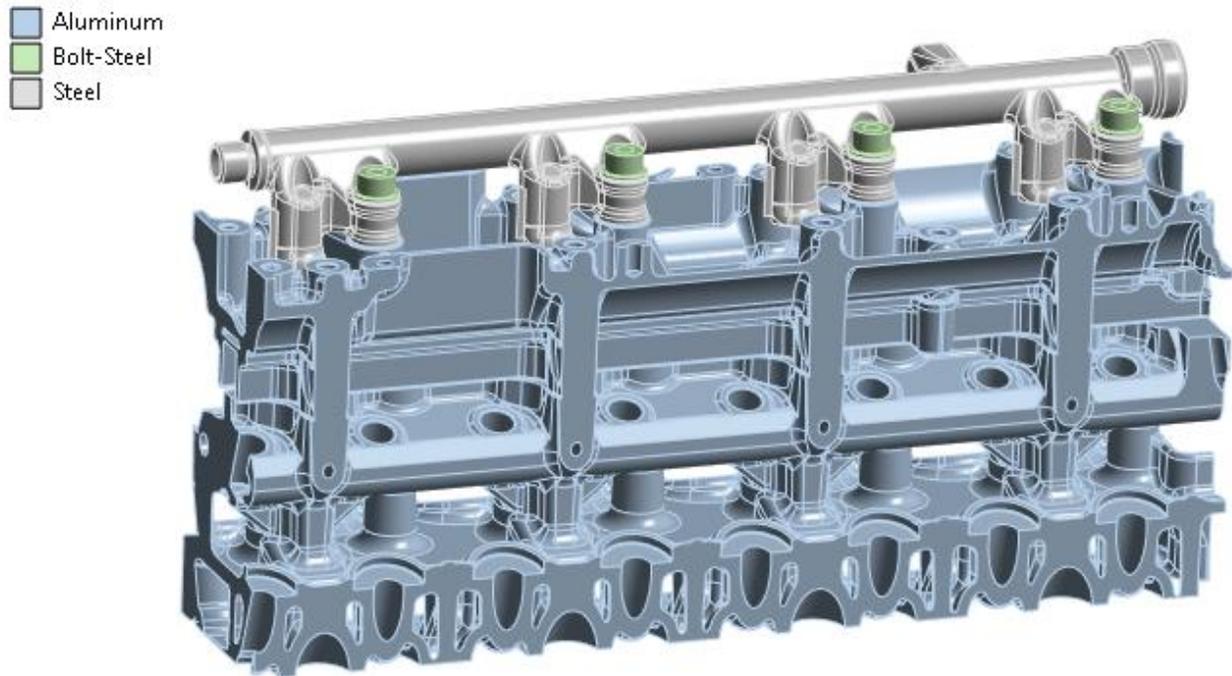


Figure 6. Mesh Distribution

#### 5. Material Model



In Figure 7, material models are seen. Steel is used for Rail and Bolts. Aluminum is used for engine.



*Figure 7. Materials*

## 6. Simulation Result: Under Operational Load

Stress calculation result is seen under operational load in Figure 7. Colors area shows stress level. Red color shows maximum stress levels, blue areas show minimum stress level. Maximum stress located at bridge between injector cup and mounting bracket. Since it is free end, cup is bended to upward due to inner pressure. Therefore, stress occurs due to bending.

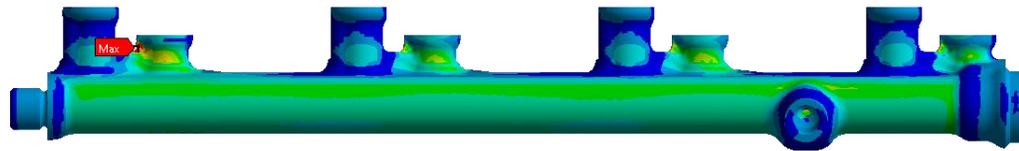


Figure 8. Stress Distribution under Pressure Load

Stress distribution is shown closer in Figure 9. This location is the internal surfaces of the forged rail that interacted with Ethanol fuel under pressure load. Fatigue assessment is done for this location.

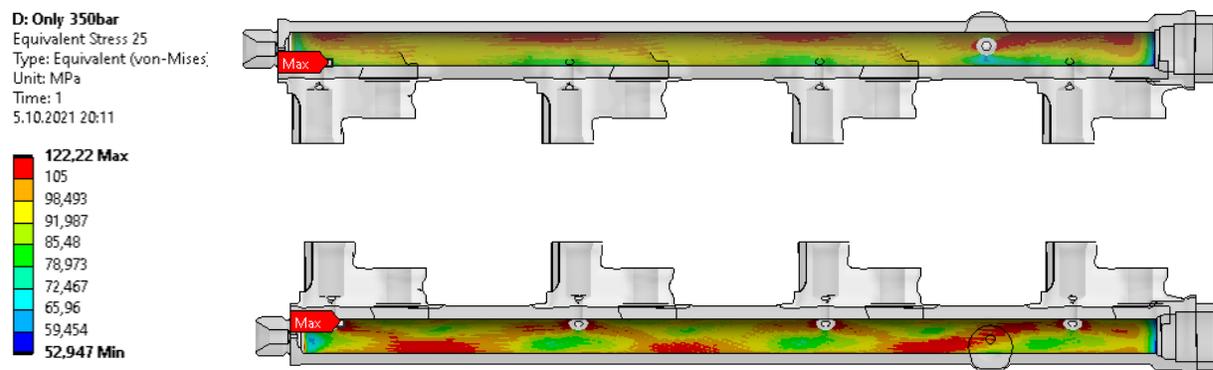


Figure 9. Stress Distribution at Internal surfaces under Pressure Load

## 7. Validation Activities

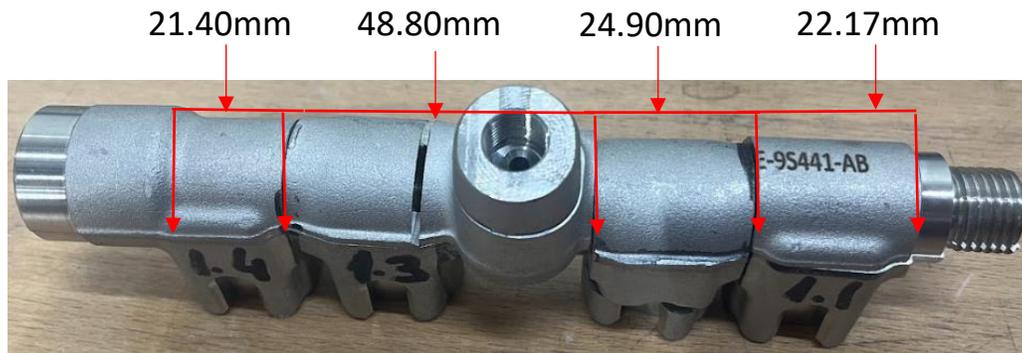
### a. Pre-Aging of the Bare Rails

Strength decrease is accepted after usage of the E100 fuel in the Brazil market and accelerated testing must be done to observe the influence of the E100 in the forged fuel rails.

A special fuel E60\_6\_3 pre-aging fluid for 336 hours is used to apply the same effect of the E100 fuel in the field during the service life of the product (240.000 km or 15 years). For our purpose, 10 bare rail parts have been used to examine the strength reduction effect.



After application of the pre-aging fuel, impact of the E100 fuel after 15 years can be observed from the internal surfaces of the forged bare rails.



*Figure 10. Rail Cutting for observation.*

### **b. Hydro Pulse Test**

After observation, 10 parts of forged fuel rail are also preaged with E60\_6\_3 fluid to observe the strength change after preaging. The aim to break the parts intentionally after a higher pressure than the system pressure is applied to the fuel rail of 350 bar. Due to limited time and the part costs, only 2 load levels have been done in the hydro pulse test. For each load level 5 parts have been used again due to time saving in the tests. It is suggested to have 5 load levels with 25 pieces of parts in each load level for this kind of fatigue tests to capture the scattering of the strength better and to draw the lines of the Wohler curve with more precise.

800 bar and 640 bar load levels are selected for the hydro pulse test with 5 parts for each load level (Figure 11).



# of parts	Load level ( $\Delta P$ ) [bar]
1	800
2	
3	
4	
5	
6	640
7	
8	
9	
10	

*Figure 11. Load Levels*

## 8. Result

### a. Observation of the Pre-Aging Effect

As mentioned before, pre-aging represents the impact of the E100 fuel in the field. Therefore, results show the status of the internal portion of the forged bare rail after 15 years passed.

In the below pictures, visible corrosion occurrence of the internal surfaces is detected under microscope with roughly 2 times exaggeration.

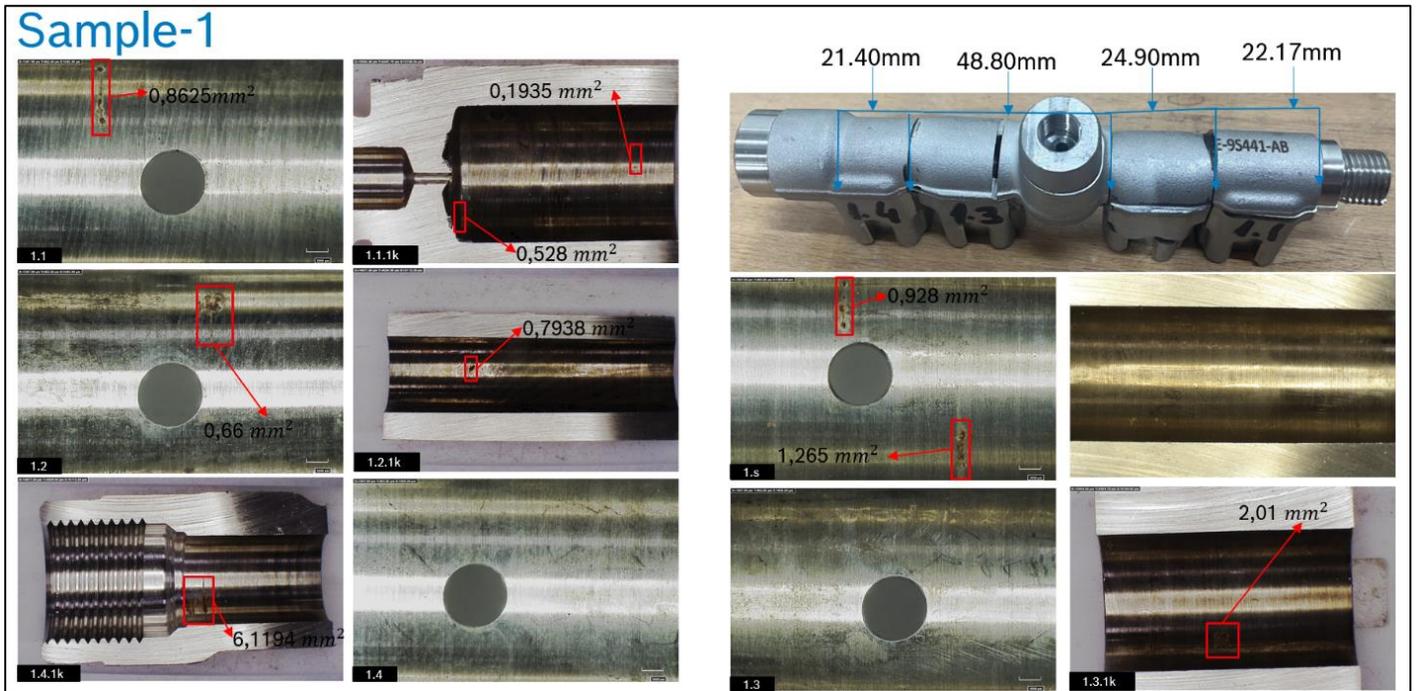


Figure 12. Corrosion Occurrence

All corrosion occurrences are measured with callipers and checked with the all-surface area (Figure 13). This gives the chance to create a statistical approach to check in mass production status.

E100 Corrosion Surface Area Calculations			
Sample Number	Total Corrosion Area (mm <sup>2</sup> )	Total Surface Area of Raw Tube (mm <sup>2</sup> )	Percentage Of Corrosion Occurrence (%)
Sample 1	13,36	4789,39	0,028%
Sample 2	30,09	4984,61	0,061%
Sample 3	30,13	4904,15	0,062%
Sample 4	3,13	4817,98	0,007%
Sample 5	58,83	4986,24	0,119%

Figure 13. Corrosion Occurrence Ratio

Once all samples are investigated, statistical evaluation of the occurrence probability is calculated with the Normal distribution. Based on the statistical assessment 1300 ppm parts will have corrosive surface after service life of the product.

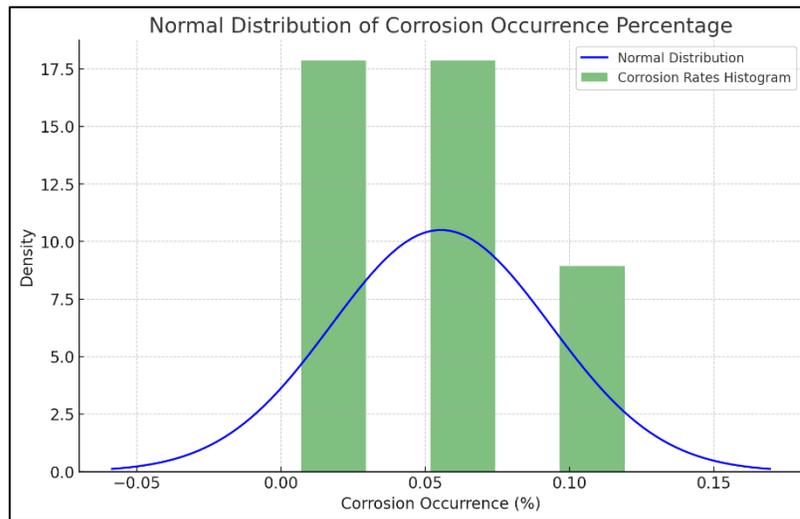


Figure 14. Normal Distribution of Corrosion Occurrence Percentage

Based on the normal distribution analysis of corrosion rates:

Average corrosion rate (%): 0.0554

Standard deviation (%): 0.0380

In the Figure 14, the green bars represent the histogram of the sample corrosion rates, while the blue curve represents the normal distribution. The normal distribution curve shows that most of the data points are concentrated around the mean, with extreme corrosion cases being less frequent.

This analysis indicates that the majority of corrosion rates cluster around 0.055%, with higher corrosion rates being relatively rare. Statistically, the probability of a new sample exhibiting a corrosion rate above 0.1% is low. This trend shows that 1000 ppm parts have %0.1 corrosion ratio in the field. Based on the sample size, Sample 5 represents one of those parts out of 1000 pieces in the field.



### b. Observation of the Strength Change

Hydro pulse test is performed in 2 load levels as seen the Figure 15.

It is observed that there will be roughly %33 strength reduction observable after applying preaging to the same parts.

# of parts	Load level ( $\Delta P$ ) [bar]	Failure Section	Failure cycle
1	800	Bare Rail	84.665
2		Bare Rail	409.682
3		Bare Rail	439.274
4		Bare Rail	518.651
5		Bare Rail	4.234.485
6	640	Bare Rail	807.849
7		Bare Rail	1.210.707
8		Runout	10.000.000
9		Runout	10.000.000
10		Runout	8.100.000

Figure 15. Hydro Pulse Test Results

### 9. Conclusion

Even with %33 strength reduction of the parts, fatigue assessments are performed, and failure probabilities of the parts are calculated less than 1 ppm during the service life of the parts in 15 years or 240.000 km usage.

Bare rails that produced with forging method had high strength without pre-aging. This benefit is also valid after E100 fuel even with strength reduction.



## References

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