CORCON
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Modeling the spatial distribution of internal corrosion in API 5L pipes carrying gasohol

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Engineering & Projects

Bharat Petroleum Corporation Limited

Introduction

- Present engineering practice for the design of the product piping for petroleum handling terminals involves size optimization based on hydraulic losses and the cost of the pipeline.
- Pipelines are usually replaced in 7-10 years to augment the terminal for the increased market demand.
- Stage-wise implementation of biofuel blending mandate requires frequent (3-5 years) rerouting and replacement of the pipelines.

Company	Current Tankage (Cr Lit)	Work-in-progress /Additional Planned (Cr Lit)	Total capacity (Cr Lit)
IOC	6.50	12.50	18.60
BPC	4.50	7.40	11.90
HPC	6.80	6.94	13.74
OMC Total	17.80*	26.84	44.64**

* With the current capacity, about **430 crore litres** of ethanol can be handled annually considering 15 days of coverage period.

** Similarly, with a total tankage capacity of 44.64 crore litres by 2025, about **1060 crore litres** of ethanol can be handled annually considering 15 days of coverage period.

Current and planned storage capacities of OMCs

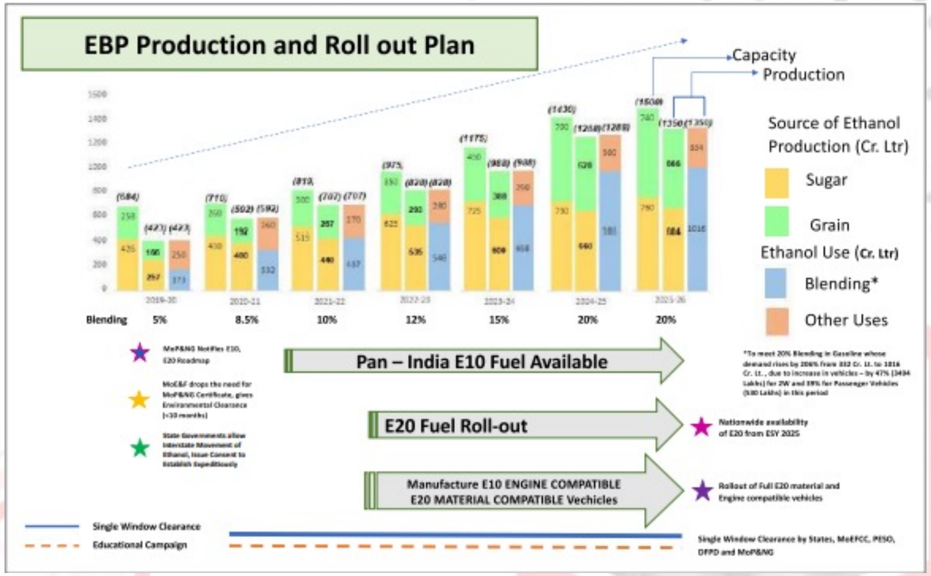
Ethanol Supply Year	Qty Supplied (crore Lit)	Blending %age PSU OMCs
2013-14	38.0	1.53%
2014-15	67.4	2.33%
2015-16	111.4	3.51%
2016-17	66.5	2.07%
2017-18	150.5	4.22%
2018-19	188.6	5.00%
2019-20	173.0	5.00%
2020-21	332	8.50%

Quantity Supplied (Ethanol) and % Blending Trends

Introduction

ROADMAP FOR ETHANOL BLENDING IN INDIA 2020-25, Report of the Expert Committee, NITI Aayog | Ministry of Petroleum and Natural Gas (Date: 03 June 2021)

- Major infrastructure modification.
- Materials are drop-in compatible, but plants are not.
- Some sections / linings lining are aging faster than the rest of the surface.
- Non uniform degradation reduces the life-cycle.
- Heavy maintenance cost in operating conditions.



EBP Production and Roll out Plan

Significance & Problem Identification

Corrosion Mechanism	Main Cause	Potential Areas	Identification
CO_2	Fatigue Loads, Fuel Property	Area Adjacent to Pump	Uniform pitting
H_2S	Fuel Property	-	
Microbiological (MIC)	Moisture, H_2S	Near Storage Tanks	Localized pitting
TOLC (Top of The Line Corrosion)	Evaporation Rate, moisture, temperature distribution	Underground sections	10-12-2 O' clock positions
UDC (Under Deposit Corrosion)	Oxygen Deficiency, flow regime	Trapped sections, Underground Passings	4-6-8 O' clock positions
PWC (Preferential Weld Corrosion)	Dissimilar Metallic Crystal	Weld joints	Pitting around weld joints

Significance & Problem Identification

- Purpose is to study the spatial variability of corrosion in the branched pipe network.
- Achieving RMSE <= 3 % {Compared to time series ML models}
- Quantification of differential aging.
- Identification of prevailing oxidation mechanism { RSQ > 0.81 & Corr. >0.9}
- Machine learning-based classification of most affected zones.
- Selection of optimal in-plant orientation.
- Note: Present study evaluates the uniform rate of oxidations. Localized heavy pitting, hydrogen blistering, or induced lamination are excluded.

Methods & Material – Key Methodology

Collection of Data from Oil Handling Terminal

- Pipe – API 5L
- Fluid – Motor Spirit (Gasoline) E0
- Pure Ethanol E100
- & Ethanol Blended MS (Gasohol) E10

Refining of data

- Segregation of noise and signal
- Box and whisker method
- Normalization

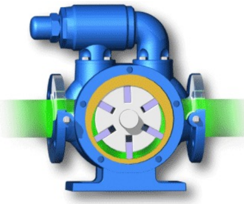
Training and Testing

- Defining The Problem
- Identification of Input Parameters
- Dependence Correlation
- Results
- Testing & Evaluation

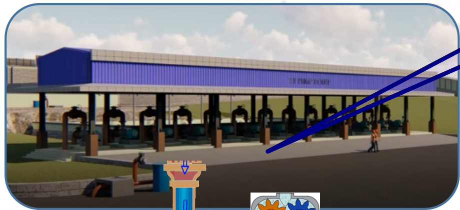
Methods & Material – Plant Layout

Wagon Receipt → Storage in AG Tankages → Dispatch

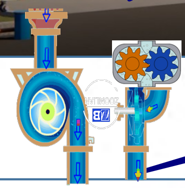
MS / HSD Receipt



Ethanol / BD Receipt



TLF Pump House



TLF Gantry

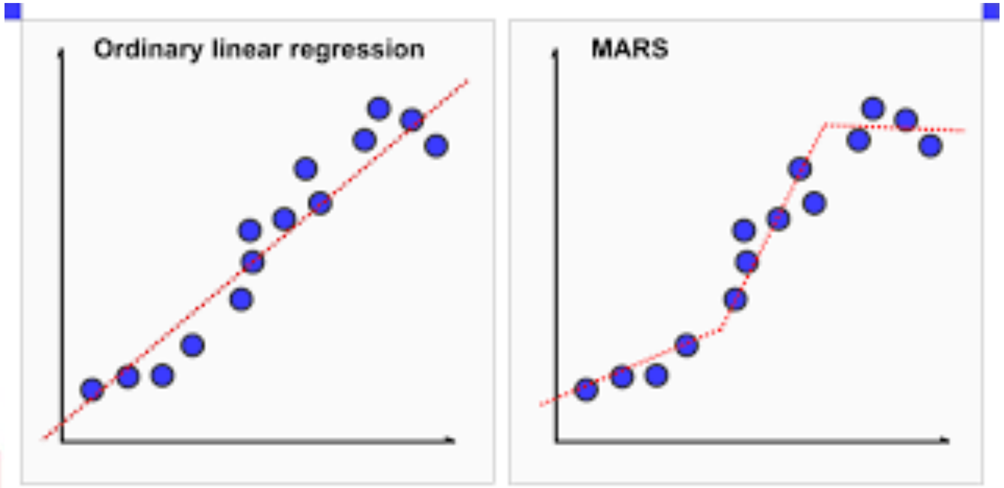
Dispatch 12KL, 18KL, 20KL. 25KL TTs

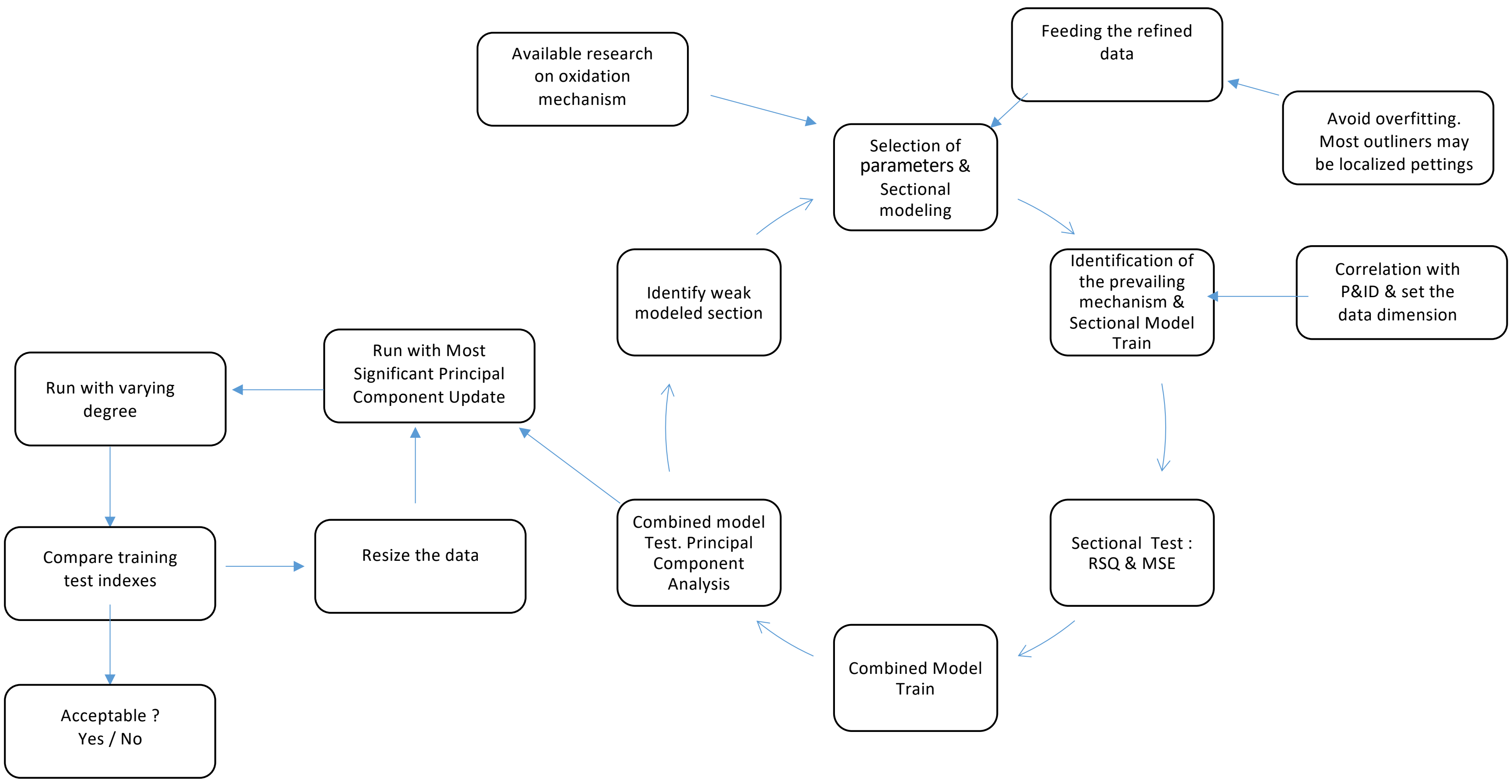
Methods & Material – Variables

Independent Variables	Dependent Variables
Distance from Source (Nx)	Reduction in pipe wall thickness (Ndt)
Reynolds Number (NRN)	Ndt at 12,2,4,6,8 & 12 O Clock Positions (t12, t2, t4, t6, t8 & t10)
Heat Affected Zone (HAZ)	Maximum Ndt around the cross section (dtmax)
Flow Direction (GA & FA)	Average Ndt around the cross section (dtavg)
Fuel Properties (FP)	
Relative Elevation (Ht)	
Pressure (Vf)	
Relative Distance (Dlen)	

Methods & Material – MARS

- Multivariate Adaptive Regression Splines, or MARS, is an algorithm for complex non-linear regression problems. Introduced by Jerome H. Friedman in 1991
- It is a supervised machine learning algorithm suitable for highly volatile data.
- The algorithm involves finding a set of simple linear functions that in aggregate result in the best predictive performance.




Available research on oxidation mechanism
Feeding the refined data
Avoid overfitting. Most outliners may be localized pettings
Selection of parameters & Sectional modeling
Identification of the prevailing mechanism & Sectional Model Train
Correlation with P&ID & set the data dimension
Identify weak modeled section
Run with Most Significant Principal Component Update
Run with varying degree
Compare training test indexes
Resize the data
Combined model Test. Principal Component Analysis
Sectional Test : RSQ & MSE
Combined Model Train
Acceptable ? Yes / No

Results & Discussion

Corrosion Mechanism	Main Cause	Potential Areas	Identification
CO_2	Fatigue Loads, Fuel Property	Area Adjacent to Pump	Uniform pitting
H_2S	Fuel Property	-	-
Microbiological (MIC)	Moisture, H_2S	Near Storage Tanks, U sections	Localized pitting
TOLC (Top of The Line Corrosion)	Evaporation Rate, moisture, temperature distribution	Underground sections	10-12-2 O' clock positions
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PWC (Preferential Weld Corrosion)	Dissimilar Metallic Crystal	Weld joints	Pitting around weld joints

Results & Discussion

Moisture content

FA

Localized Factors

GA

Velocity, flow regime, pressure, Weld zone.

Space Dependent Factors

Corrosion Mechanism	Main Cause
CO2	Fatigue Loads, Fuel Property
H2S	Fuel Property
Microbiological (MIC)	Moisture, H2S
TOLC (Top of The Line Corrosion)	Evaporation Rate, moisture, temperature distribution
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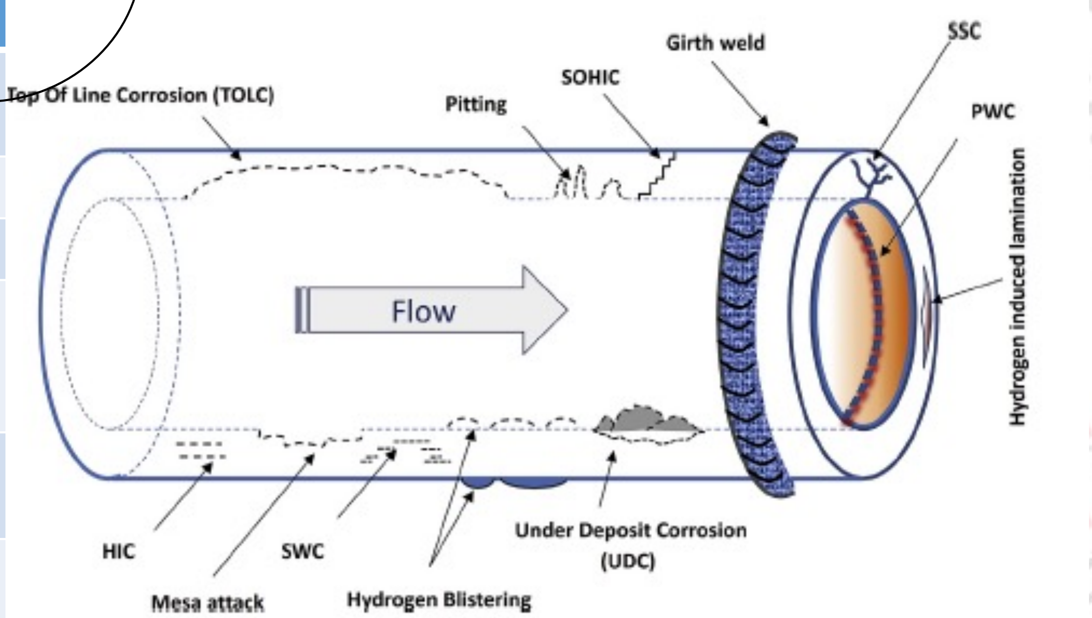
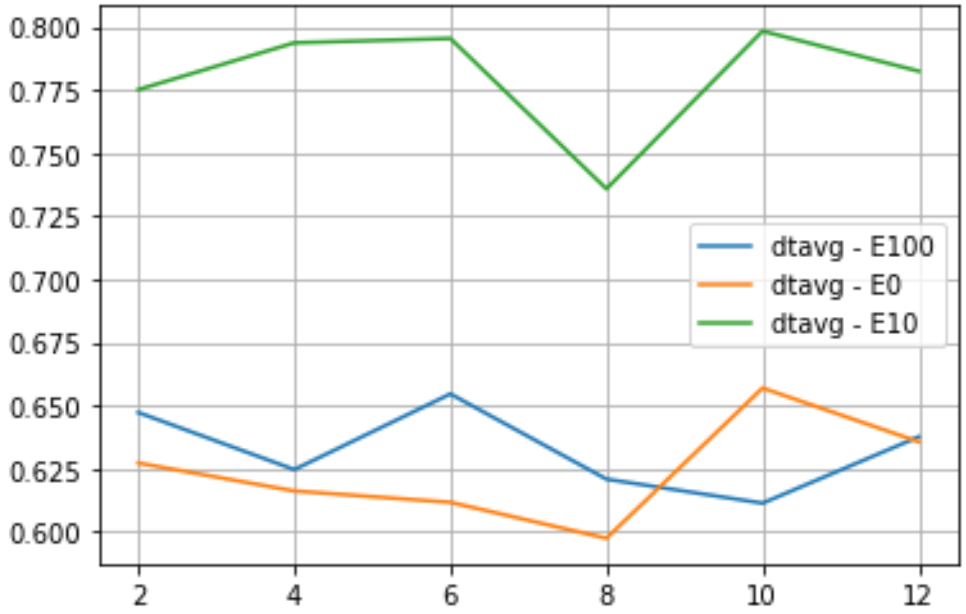
PWC (Preferential Weld Corrosion)	Dissimilar Metallic Crystal



Results & Discussion – Localized Factors

- The present study is in good agreement with product handling experience at oil terminals.
- Water enters the network with MS and causes aggressive scale formation when mixed with ethanol. The bottom position (6 O clock) is found to be more corroded in the case of ethanol.
- In case of E100 & E0, relative variation of thickness not significant.



Results & Discussion – T Test & Correlation

- Relatively weak correlation between angular positions suggests the influence of localized factors is more than space-dependent factors in the case of E0.
- Opposed to that, E100 data depicts a stronghold of localized variables.

	t12	t2	t4	t6	t8	t10
t12	1.000000	0.302718	0.481450	0.414873	0.472922	0.634665
t2	0.302718	1.000000	0.444815	0.487345	0.364073	0.391372
t4	0.481450	0.444815	1.000000	0.600676	0.522788	0.622316
t6	0.414873	0.487345	0.600676	1.000000	0.653122	0.592229
t8	0.472922	0.364073	0.522788	0.653122	1.000000	0.781738
t10	0.634665	0.391372	0.622316	0.592229	0.781738	1.000000

E0

	t12	t2	t4	t6	t8	t10
t12	1.000000	0.708854	0.728421	0.768252	0.758921	0.729874
t2	0.708854	1.000000	0.638623	0.694664	0.690983	0.739495
t4	0.728421	0.638623	1.000000	0.668278	0.722390	0.725223
t6	0.768252	0.694664	0.668278	1.000000	0.713732	0.699986
t8	0.758921	0.690983	0.722390	0.713732	1.000000	0.828457
t10	0.729874	0.739495	0.725223	0.699986	0.828457	1.000000

E100

	t12	t2	t4	t6	t8	t10
t12	1.000000	0.006751	0.242201	0.151301	0.346815	-0.312149
t2	0.006751	1.000000	0.653653	0.133076	-0.152234	0.669241
t4	0.242201	0.653653	1.000000	-0.099240	0.080381	0.284281
t6	0.151301	0.133076	-0.099240	1.000000	0.233001	0.225101
t8	0.346815	-0.152234	0.080381	0.233001	1.000000	-0.420736
t10	-0.312149	0.669241	0.284281	0.225101	-0.420736	1.000000

E10

Results & Discussion – T Test & Correlation

- The coefficient of correlation is either close to zero or negative in most of the cases for E10.
- This suggests non-uniform oxidation on the inner walls of the pipe.
- 12 O'clock lining is aging faster than the rest of the surface.

	t12	t2	t4	t6	t8	t10
t12	1.000000	0.302718	0.481450	0.414873	0.472922	0.634665
t2	0.302718	1.000000	0.444815	0.487345	0.364073	0.391372
t4	0.481450	0.444815	1.000000	0.600676	0.522788	0.622316
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E0

	t12	t2	t4	t6	t8	t10
t12	1.000000	0.708854	0.728421	0.768252	0.758921	0.729874
t2	0.708854	1.000000	0.638623	0.694664	0.690983	0.739495
t4	0.728421	0.638623	1.000000	0.668278	0.722390	0.725223
t6	0.768252	0.694664	0.668278	1.000000	0.713732	0.699986
t8	0.758921	0.690983	0.722390	0.713732	1.000000	0.828457
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E100

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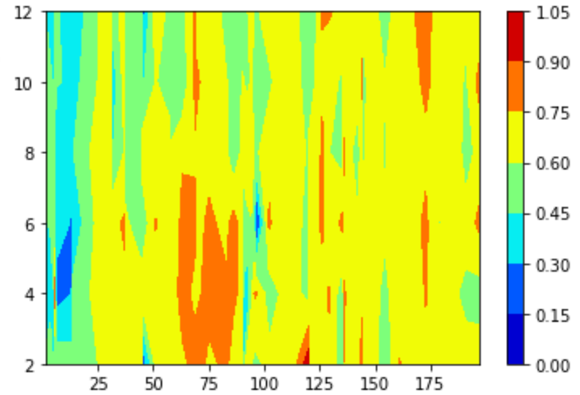
t10	-0.312149	0.669241	0.284281	0.225101	-0.420736	1.000000

E10

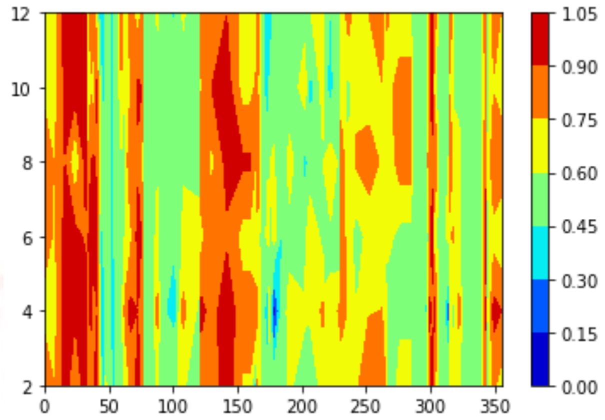
Results & Discussion – Over The Length

- It can be derived that presence of HAZ, highly turbulent area (near pumps), and buffer storage tanks governs the length distribution of the corrosion.

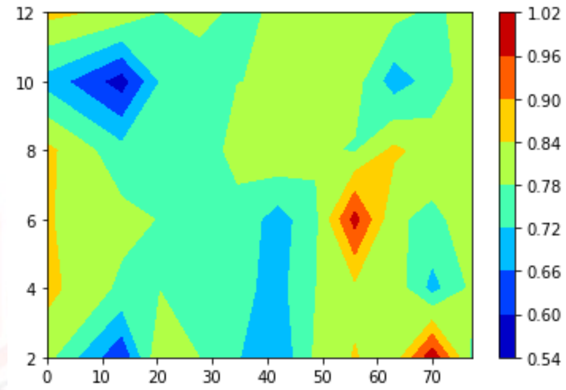
- Surface are severely attacked near weld joints and storage tanks.



E0



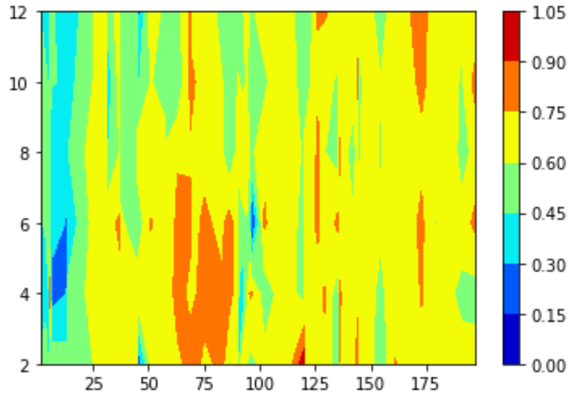
E100



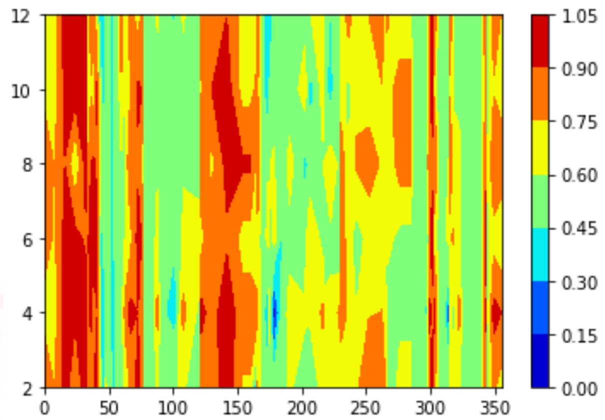
E10

Results & Discussion – Over The Length

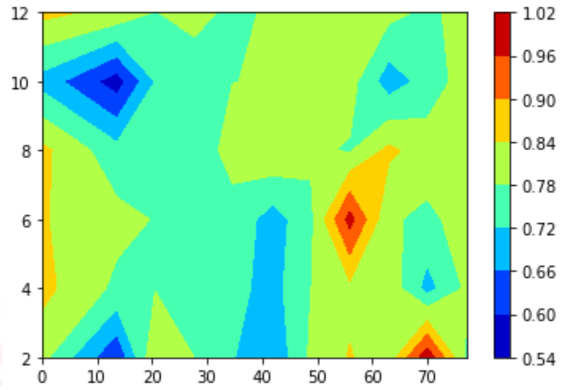
- E100 is more corroded than E0. The figure shows a similar pattern for gasohol (E10) regarding spatial distribution.
- Nevertheless, the magnitude of corrosion is more as compared to the former 2 cases.



E0



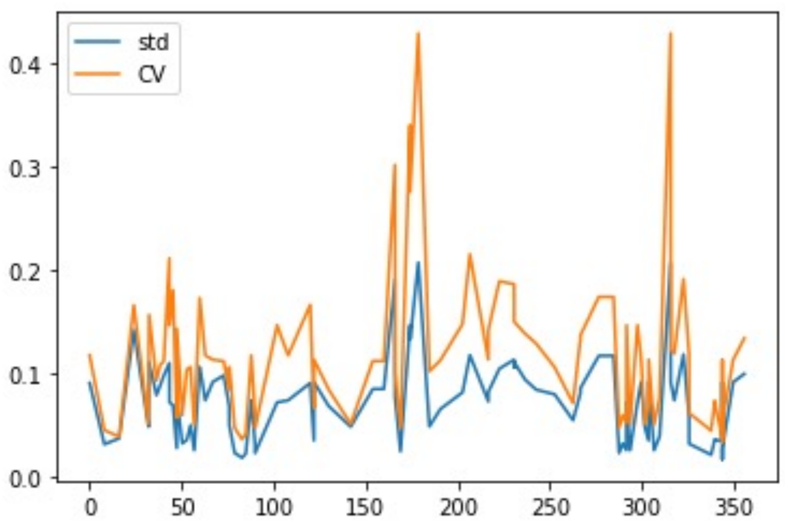
E100



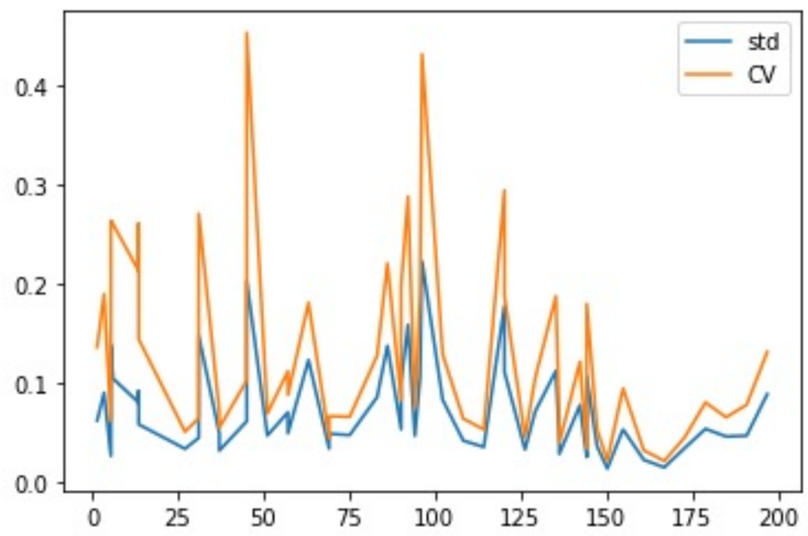
E10

Results & Discussion - Fluctuations

- Change in thickness around the section of pipe over the entire length is plotted. As expected, the standard deviation is higher near the tankage and pumps.
- One mechanism is out racing the others.



E100



E0

Results & Discussion - MARS

- Model is trained with the available data set. Input variables are grouped in various combinations to identify the significant factors.
- Train-to-test ratio is 80:20
- Higher degree of regressions were simulated to get the best results for the scattered data
- Sample data -

Nx	NRN	HAZ	FA	GA	Dia	Dlen	Ht	FP	Vf	dtmax
0	0.155216	1	0.7071	0	0.25	20	-0.45	1	0.423	0.395161
0.013195	0.155216	0	0	0	0.25	16	-0.45	1	0.432	0.330645
0.02639	0.155216	0	0	0	0.25	12	-0.45	1	0.432	0.443548
0.039584	0.155216	0	0	0	0.25	6	-0.45	1	0.432	0.432796
0.052779	0.155216	0	0	0	0.25	2	-0.45	1	0.432	0.443548

Results & Discussion - MARS

MARS	RMSE Value		
Clustering of Variables	E100	E0	E10
NX, NRN, HAZ, FA, GA, FP, Vf	0.0247	0.0082	0.0063
NX, NRN, HAZ, FA, GA, FP, Ht, Dlen	0.0170 (1)	0.0055(2)	0.0023(3)
NX, NRN, HAZ, FA, GA, FP, Ht, Vf, Dlen	0.0247	0.0082	0.0063
NX, NRN, HAZ,FA Ht, Dlen	0.0247	0.0082	0.0063
NX, NRN, HAZ, Ht, Vf	0.0247	0.0062	0.0063
NRN, HAZ, GA	0.0289	0.0099	0.0067
NRN,HAZ, FP	0.0289	0.0082	0.0063
NX, NRN, FP	0.0247	0.0062	0.0063
NX, FA, GA	0.0247	0.0070	0.0063
NX, NRN, FA, GA	0.0247	0.0062	0.0063

- RMSE of the model is tabulated with reactive input clustering
- Pearson correlation coefficient for models marked as 1, 2, and 3 in the table is 0.9011, 0.9452, and 0.9434 respectively

Results & Discussion – Fitting the curve

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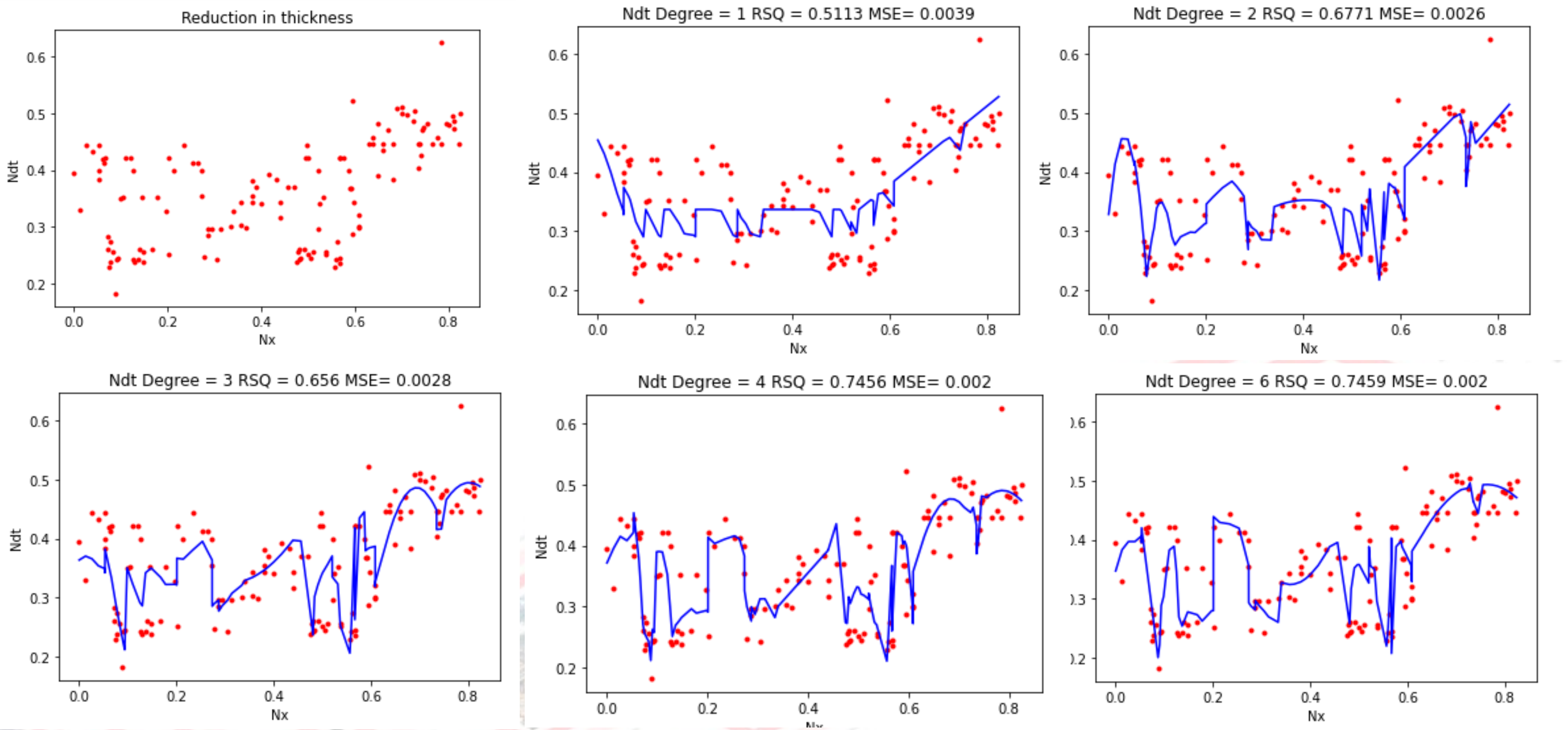
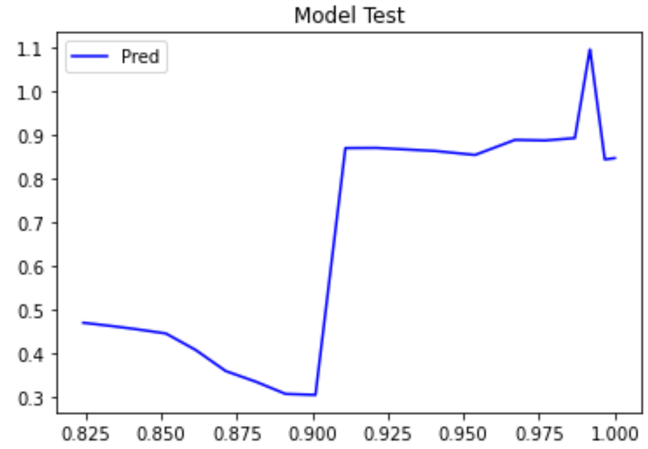
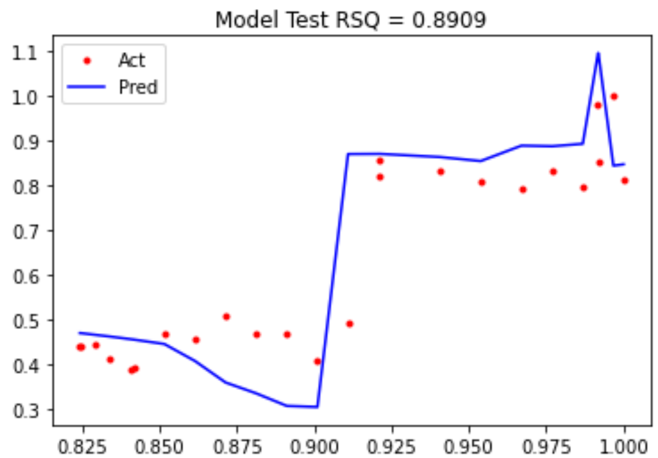
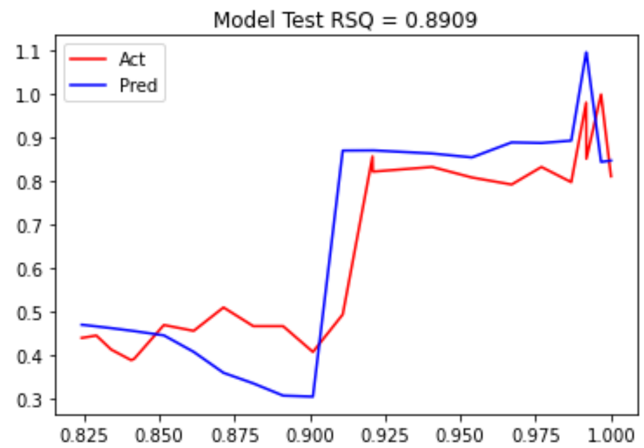


Results & Discussion

- The spatial variability of corrosion predicted in the specific research dedicated to TOLC, PWC and UDC matches the observed data.
- The developed model is successfully predicting spatial variability of corrosion reaction in line with pre-established corrosion mechanisms.

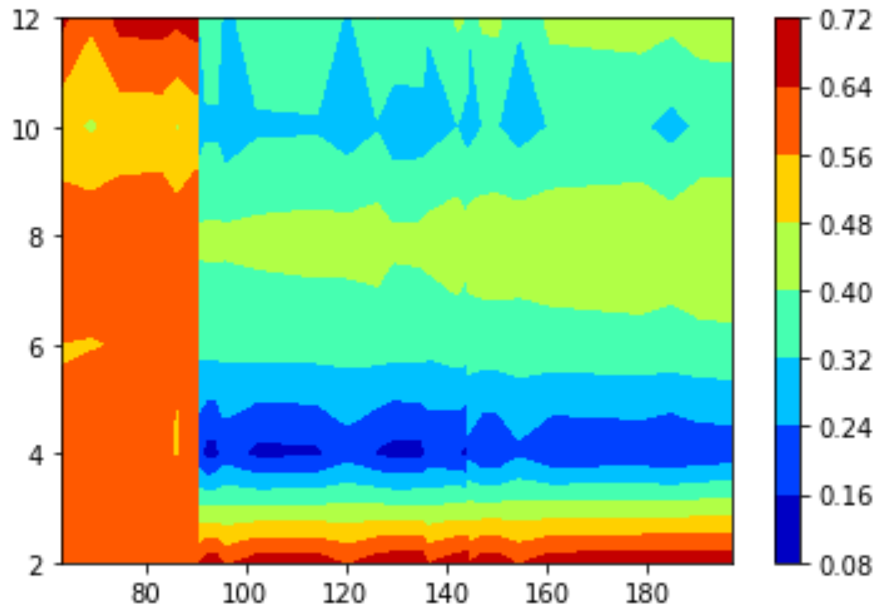






Testing & Evaluation – Worked Example

- Model prepared for E100 using NX, NRN, HAZ, FA, GA, FP & Vf as input variable. Expected MAE = 0.0247.
- Pipe configuration is same as what we have taken for E0.
- Corrosion behavior of the network is predicted.



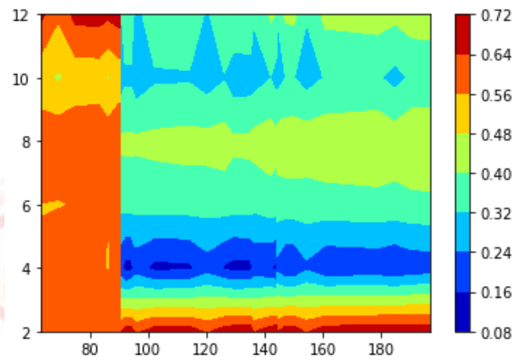
MARS	MAE Value		
Clustering of Variables	E100	E0	E10
NX, NRN, HAZ, FA, GA, FP, Ht, Vf, Dlen	0.0247	0.0082	0.0063

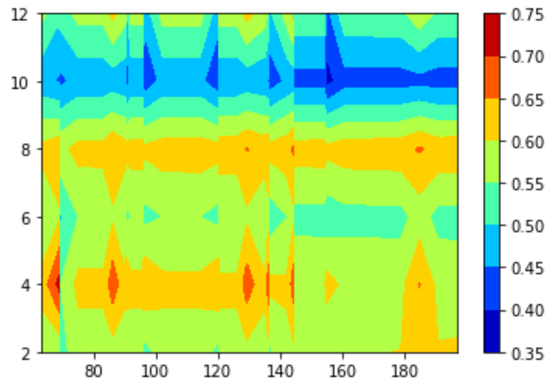
Testing & Evaluation – Worked Example

- Section depicted in the left is remodeled into what is show in the right by alteration of the pipe fitting, fitting locations, pipe diameter and relative valve positioning. RMSE = 2.23 % & 2.65% respectively.
- Economic analysis can be performed to achieve desired level of investment. Similar pre-established methods can be used to perform pipe life span Vs. pipe size analysis.

Nx	NRN	HAZ	FA	GA	Dia	Dlen	Ht	FP	Vf	dtmax
0	0.310432	1	0.7071	0	0.2	42	1.2	1		0.2114
0.44	0.310432	0	0.7071	0	0.2	34	1.2	1		0.2378
0.54	0.310432	0	0.7071	0	0.2	26	1.2	1		0.3502
0.65	0.310432	0	0	0	0.2	18	1.2	1		0.3413
1.2	0.310432	1	0	0	0.2	10	1.2	1		0.2897
1.32	0.310432	1	0.7071	0	0.2	9.95	1.2	1		0.2198
1.75	0.310432	1	0.7071	0	0.2	9.7	1.2	1		0.2052
1.99	0.310432	1	0	0	0.2	5.7	1.2	1		0.0307

Nx	NRN	HAZ	FA	GA	Dia	Dlen	Ht	FP	Vf	dtmax
0	0.293567	1	0.7071	0	0.2	21	0.3	1		0.1323
0.44	0.293567	0	0	0	0.2	13	0.3	1		0.1406
0.54	0.293567	0	0	0	0.2	5	0.3	1		0.3222
0.65	0.293567	0	0	0	0.2	2	0.3	1		0.1316
1.2	0.293567	1	0	0	0.2	1	0.3	1		0.1383
1.32	0.293567	1	0.7071	1	0.2	14	0.6	1		0.1022
1.75	0.293567	0	0.7071	0	0.2	9	0.6	1		0.2473
1.99	0.293567	0	0	0	0.2	2	0.6	1		0.1644





Testing & Evaluation – Comparison

- Comparison is presented with other time dependent machine learning models.

- The cumulative retention of information increases as the data dimension increases, and the RMSE is least for E10 and highest in the case of E100.

- Variable set NX, NRN, HAZ, FA, GA, FP, Ht, Dlen is providing best estimation.

- Maximum RMSE = 2.55% is withing the desired zone.

Error comparison between LR,ANN,PCA-CPSO-SVR, De Waard95(OLGA).

	LR	ANN	PCA-CPSO-SVR	De Waard95(OLGA)
MAE	0.1202	0.149	0.083	0.568
RMSE	2.9%	12.2%	2.7%	61.2%

Error comparison of different algorithms.

	SVR	PCA-SVR	PCA-GA-SVR	PCA-PSO-SVR	PCA-CPSO-SVR
MAE	0.102	0.194	0.098	0.086	0.083
RMSE	5.9%	8.1%	3.1%	2.9%	2.7%

MARS	RMSE Value		
Clustering of Variables	E100	E0	E10
NX, NRN, HAZ, FA, GA, FP, Vf	3.71%	1.23%	0.95%
NX, NRN, HAZ, FA, GA, FP, Ht, Dlen	2.55%	0.83%	0.35%
NX, NRN, HAZ, FA, GA, FP, Ht, Vf, Dlen	3.71%	1.23%	0.95%
NX, NRN, HAZ,FA Ht, Dlen	3.71%	1.23%	0.95%
NX, NRN, HAZ, Ht, Vf	3.71%	0.93%	0.95%
NRN, HAZ, GA	4.34%	1.49%	1.01%
NRN,HAZ, FP	4.34%	1.23%	0.95%
NX, NRN, FP	3.71%	0.93%	0.95%
NX, FA, GA	3.71%	1.05%	0.95%
NX, NRN, FA, GA	3.71%	0.93%	0.95%

Conclusion

- Proposed method provides understanding of internal corrosion distribution over pipe network. Thus enables the design engineer to choose optimal configuration.
- Provides insight on differential aging.
- Able to identify prevailing local oxidation mechanism.
- Classification of spatial distribution.
- Proposed method will not only be helpful for design of new pipe network but can also prove helpful in modification / re-engineering of existing network (as in the case of augmentation job).

Further Works

- Quantification of evaporation rate.
- Processing the outliners.
- Inclusion of temperature gradient to improve model MSE and RSQ.
- System reliability analysis.
- Random field theory to identify pitting.
- Conjunction with time-dependent models.

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Thank You