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GDNS GD3 REPEX DETERIORATION ANALYSIS

Deterioration prediction and replacement scenario analysis for GD3 mains and services

SGN

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Applicable contract(s) governing the provision of this Report:

Objective: To undertake analysis of cast, spun, ductile iron and steel failures and Gas in Building events, and to analyse future replacement scenarios and their impact on risk.

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George Wells Consultant		

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1 EXECUTIVE SUMMARY

The end of the iron mains risk reduction programme (IMRRP) will occur in 2032 and there is a need to ensure that risk is managed and funded effectively in the next price control period and beyond. Considerations to fulfil this objective include extending the REPEX programme to include Tier 2 (9”-17”) and Tier 3 (≥ 18”) iron mains, steel services and steel mains. In order to compare these options, an understanding of historical failure trends and future deterioration rates is required. To facilitate this, asset and failure data has been obtained from the Gas Distribution Networks (GDNs). Historic failure rates have been determined for cast and spun iron mains, ductile iron mains, steel mains and steel services. From these data, distributions for pipe age, failure rate and Gas in Building (GiB) rate have been derived for 21 permutations of pipe material, diameter tier and failure mode. These have then been used to generate deterioration curves using a Monte Carlo analysis to predict the annual risk of failure until 2055. Annual GIB rates have also been calculated to enable predicted GiBs to 2055 to be derived, by combining the failure and GiB analyses.

The results of the individual failure and GiB analyses have been combined to enable the impact of different replacement scenarios to be compared. The scenarios considered are as follows:

A. No future replacement – reactive maintenance only

B. Continuation of the Tier 1 programme to complete by 2032

C. In addition, replacement of steel services on PE mains by 2046

D. As per C, but with the addition of remaining Tier 1 iron (>30m from buildings) and all Tier 2 and 3 iron being decommissioned under an extended REPEX scheme by 2046

E. In addition to the above, decommissioning unprotected steel by 2046

For each scenario, the number of GiBs per year up to 2055 is predicted, by modelling the replacement lengths and reducing the associated number of failures and GiBs that would then occur. The outputs of the modelling for the first four scenarios are detailed in the figures below; scenario E just additionally demonstrates the impact of replacing all steel mains and thereby reducing the ferrous pipe length to zero by 2046.

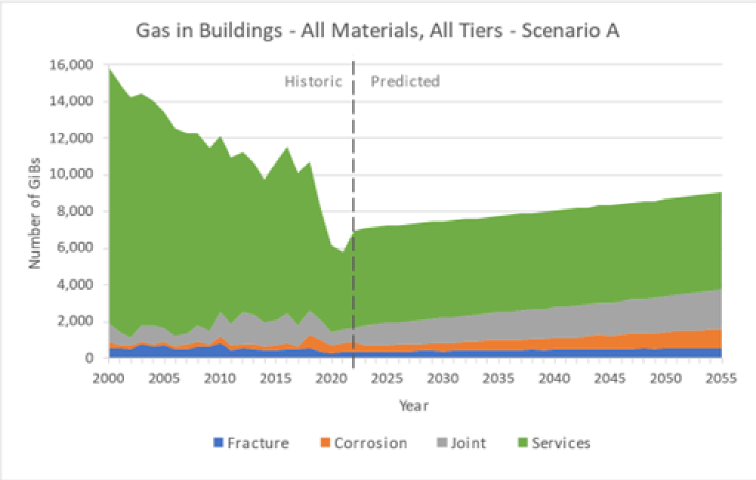
It should be noted that presenting the output in terms of number of GiBs does not take into account the risk of ignition or fatalities; this metric has been used as it is not possible to predict ignition or fatality rates with sufficient precision for each failure mode and material type. Nearly all historic domestic gas explosions have been due to leakage from fractures. Pipes prone to fracture have been the target of the Iron Mains Risk Reduction Programme (IMRRP) so now represent a relatively low proportion of GiBs, but the remaining population of iron pipes should not be negated in terms of their potential for explosion.

If no further replacement is undertaken, it is predicted that by 2055 GiBs from Tier 1 cast and spun iron fractures would be at a similar level to the numbers seen in the decade from 2000-2009 at the start of the IMRRP, with much larger numbers of GiBs also coming from joint failures. Similar trends are seen for Tier 2 and Tier 3 cast and spun iron mains, although the rate of increase is greater, with GiBs from fractures being nearly double the 2000-2009 rate, and GiBs from corrosions and joints predicted to be over six times and over three times the 2000-2009 rates, respectively. For ductile iron mains, total GiBs are expected to rise by 66% from current levels (10-year average) by 2055, with GiBs from corrosion failures having the highest rate of increase. For steel mains, total GiBs are predicted to increase by 108% from current levels (10-year average) by 2055.

The analysis demonstrates that stopping all proactive replacement is not a viable option as the level of GiBs in distribution mains would gradually return to and surpass the level seen at the start of the IMRRP. Completing the IMRRP in its current form has the greatest impact in terms of reducing risk, largely because it targets both steel service pipes and the Tier 1 cast and spun iron mains that fracture most; these two modes of failure have historically caused the highest number of explosions. For further risk reduction, the replacement of all steel services and the replacement of all remaining iron have similar benefits in terms of the reduction in GiBs, with the greatest benefit gained from each km of

Tier 3 cast or spun iron replaced. A full cost benefit analysis would be required to understand the costs involved in replacing the different categories of pipe and the relative benefits of such expenditure. Use of a risk model (such as the current Mains Replacement Prioritisation Scheme) may also be beneficial in targeting specific high-risk mains within these categories to optimise the benefit.

A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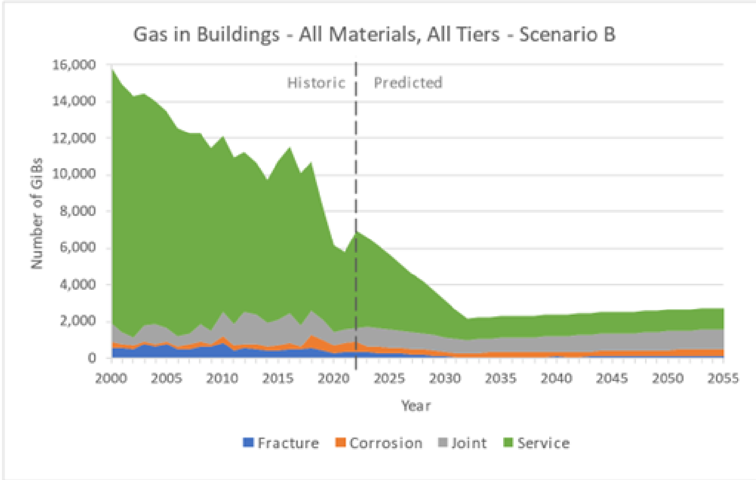
Historic
Predicted
Number of GiBs
Year
Fracture
Corrosion
Joint
Services

B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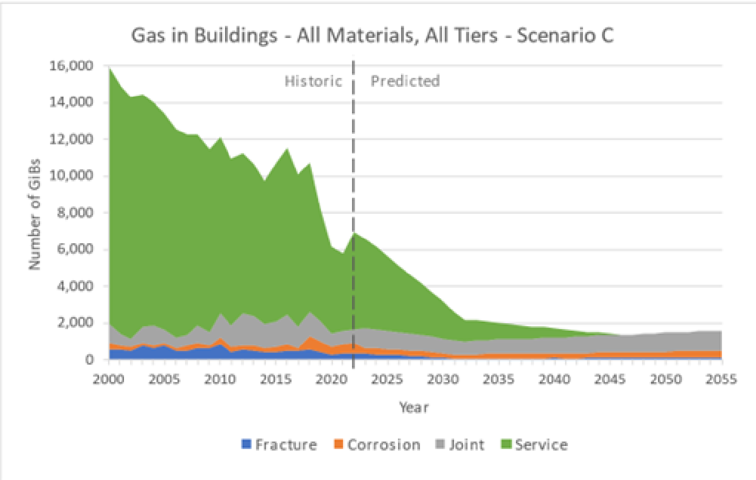
Predicted
Number of GiBs
Year
Fracture
Corrosion
Joint
Service

C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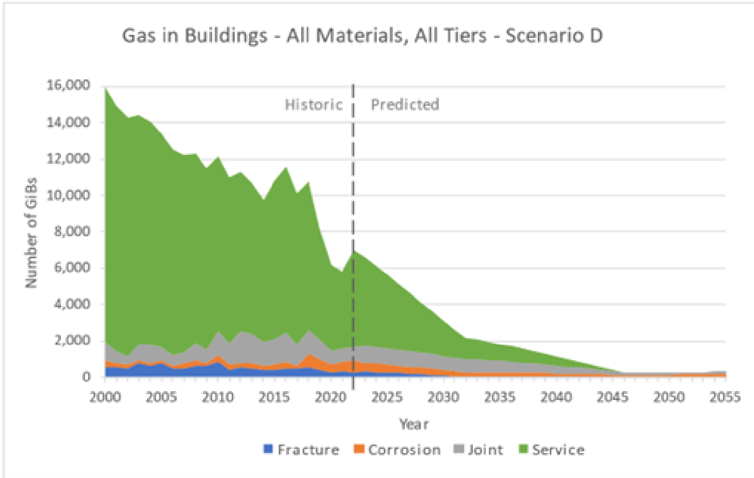
Predicted
Number of GiBs
Year
Fracture
Corrosion
Joint
Service

D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Historic
Predicted
Number of GiBs
Year
Fracture
Corrosion
Joint
Service

2 INTRODUCTION

The end of the iron mains risk reduction programme (IMRRP) will occur in 2032 and there is a need to ensure that risk is managed and funded effectively in the next price control period and beyond. Considerations to fulfil this objective include extending the REPEX programme to include Tier 2 (9”-17”) and Tier 3 (≥ 18”) iron mains, steel services and steel mains. In order to compare these options, an understanding of historical failure trends and future deterioration rates is required. To facilitate this, asset and failure data has been obtained from the Gas Distribution Networks (GDNs). Historic failure rates have been determined for cast and spun iron mains, ductile iron mains, steel mains and steel services. From these data, distributions for pipe age, failure rate and Gas in Building (GiB) rate have been derived for 21 permutations of pipe material, diameter tier and failure mode. These have then been used to generate deterioration curves using a Monte Carlo analysis to predict the annual risk of failure until 2055. Annual GIB rates have also been calculated to enable predicted GiBs to 2055 to be derived, by combining the failure and GiB analyses. This approach is documented is Section 3.

The results of the individual failure and GiB analyses have been combined to enable the impact of different replacement scenarios to be compared. The scenarios considered are as follows:

A. No future replacement – reactive maintenance only

B. Continuation of the Tier 1 programme to complete by 2032

C. In addition, replacement of steel services on PE mains by 2046

D. As per C, but with the addition of remaining Tier 1 iron (>30m from buildings) and all Tier 2 and 3 iron being decommissioned under an extended REPEX scheme by 2046

E. In addition to the above, decommissioning unprotected steel by 2046

For each scenario, the number of GiBs per year up to 2055 is predicted, by modelling the replacement lengths and reducing the associated number of failures and GiBs that would then occur. The analysis is presented in Section 4.

3 APPROACH AND DATA

Asset and failure data has been obtained from all four GDNs (detailed in section 3.1). The data has been cleansed and used to fit distributions describing the age of the total network and probability of failure with age, for each material type and failure mode. A Monte Carlo approach is used to model predicted failure rates over the period 2023 - 2055. It is not possible to predict ignition or fatality rates with sufficient precision for each failure mode and material type, so results are presented as GiBs per year.

3.1 Data sources

The mains asset data contains information on currently live and previously decommissioned pipes, namely the pipe ID, material, pressure, diameter, length, installation year, and decommissioning date (where applicable). The failure data contains all failures that were recorded from January 2000 to December 2022 with the pipe ID, leakage date, leakage codes (cause, component, and corrective action) and GiBs (Y/N).

Intermediate Pressure (IP) and High Pressure (HP) pipes have been removed from both data sources leaving just Low Pressure (LP) and Medium Pressure (MP) mains and their failures. Steel pipes with a diameter less than 3" diameter and duplicate failures (same pipe ID, leakage date, leakage cause and component) have also been removed.

There is limited asset data digitised for steel services so instead annual length data as supplied to Ofgem as part of the Regulatory Reporting Pack (RRP) has been used. Services failure data has been supplied by the GDNs but has deteriorated in quality with increasing length of time. As such, only the past five years' data has been used.

3.2 Mains failures – Monte Carlo analysis

The approach taken to predict annual GiB rates from the mains data is mapped in Figure 1. The data is first divided into nine unique asset groups based on material type and diameter tier, each of which has either two or three corresponding failure groups based on the failure mode (fracture, corrosion, or joint failure); these are given in Table 1.

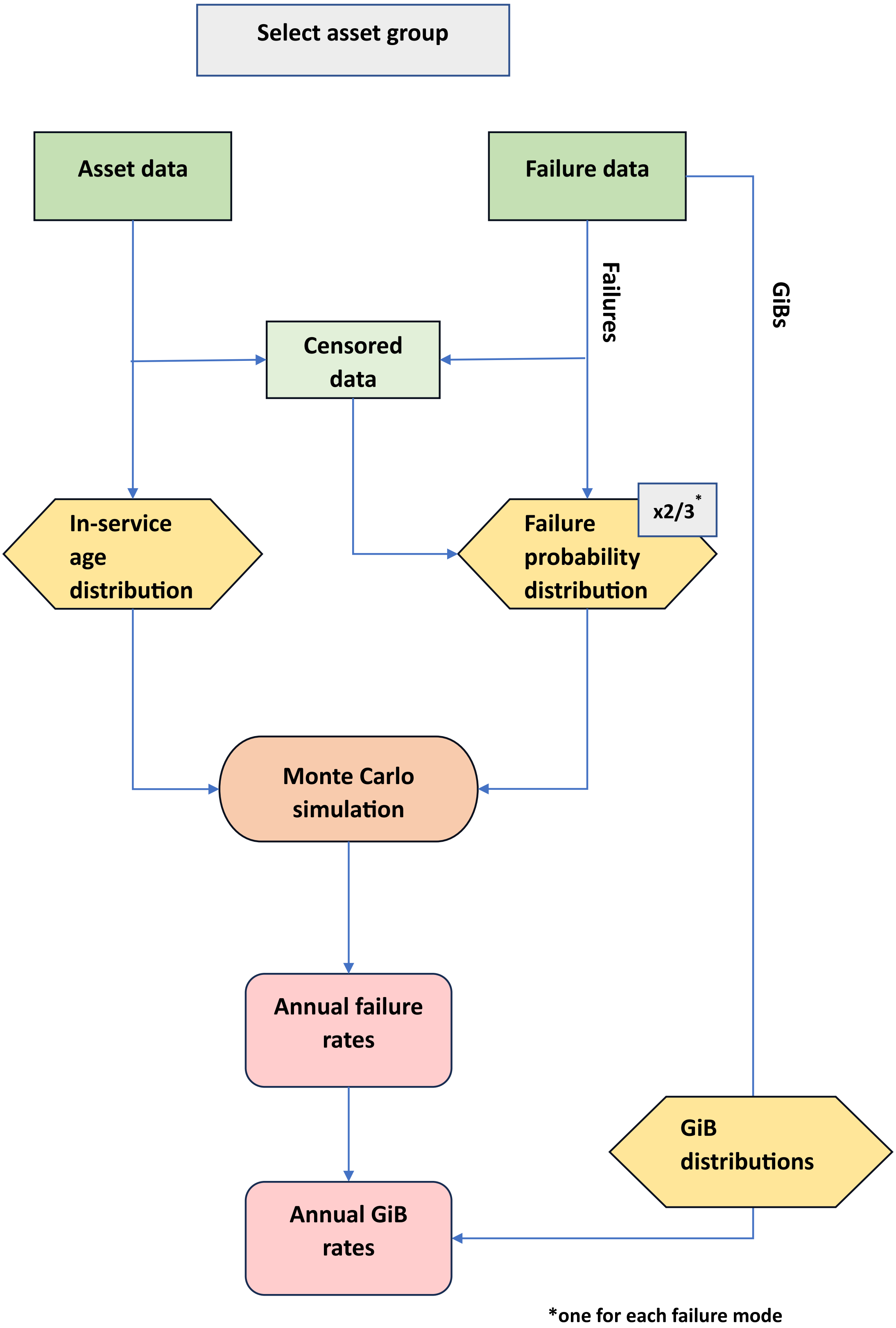

Figure 1: Map of Monte Carlo simulation process

Table 1: Material, diameter and failure mode cohorts for Monte Carlo analysis

Material	Diameter Tier	Asset Group	Failure Mode	Failure Group
Cast / Spun Iron	1	**C1**	Fracture	**C1_F**
			Corrosion	**C2_F**
			Joint	**C3_F**
	2	**C2**	Fracture	**C1_C**
			Corrosion	**C2_C**
			Joint	**C3_C**
	3	**C3**	Fracture	**C1_J**
			Corrosion	**C2_J**
			Joint	**C3_J**
Ductile Iron	1	**D1**	Corrosion	**D1_C**
			Joint	**D2_C**
	2	**D2**	Corrosion	**D3_C**
			Joint	**D1_J**
	3	**D3**	Corrosion	**D2_J**
			Joint	**D3_J**
Steel	1	**S1**	Corrosion	**S1_C**
			Joint	**S2_C**
	2	**S2**	Corrosion	**S3_C**
			Joint	**S1_J**
	3	**S3**	Corrosion	**S2_J**
			Joint	**S3_J**

During the failure data period (2000 – 2022) the number of failures is known and recorded. To account for failures that (i) could have occurred before the period but were not captured (all pipes) and (ii) failures that could have gone onto occur (decommissioned pipes) or might go onto occur in the future (live pipes), left and right censored data is used respectively, combining both asset and failure data.

Failures are tabulated by age at failure and combined with the censored data to fit a failure distribution for each failure group using parametric distribution analysis. Weibull and lognormal distributions have been used (either two or three parameter); both are standard distributions used in reliability analysis and the type is chosen depending on the best fit to the data. An in-service age distribution is fitted for each asset group from the asset data.

For each asset group, the in-service age distribution and appropriate failure distributions are fed into a Monte Carlo simulation. Monte Carlo techniques involve repeated random sampling of probability distributions and can be used to perform statistically robust analyses to predict future outcomes for a process involving uncertainty (such as leakage from a pipe). The simulation runs from 2023 – 2055. Starting in 2023, a pipe age is selected from the age distribution and a probability of failure for each mode is drawn from the failure distributions. Each probability is compared to a pseudo-random number; if the random number generated is less than the probability of failure, then a failure is assigned to this year. This process is repeated each year until 2055, and then starts again with a new pipe. The simulation runs for

1,000,000 pipes for each pipe cohort (material and diameter tier) to ensure a truly representative population has been sampled and a stable output achieved. The output is summarised as the percentage of failures each year to give annual failure rates for each failure mode. Conversion to GiB rates is described in Section 4.

3.3 Confidence intervals, mean and variance

The confidence around the modelling is detailed in this section, to confirm the robustness of the analysis. The Monte Carlo model gives one output for up to three failure modes (fracture, corrosion and joint) for each material / diameter tier for every year from 2023 to 2055. This gives a maximum of 99 outputs. Each output represents the predicted number of failures of that type in a given year. To calculate confidence intervals and determine if convergence of the model has occurred, the sum of the number of failures for each failure mode is calculated and results presented for these three outputs.

Convergence monitoring of the mean identifies whether the model is producing stable outputs. This is particularly relevant in the case where failure rates are very low. The model has been run with 1,000,000 simulations and analysis shows that outputs have converged to a tolerance of 5% with a confidence level of 95%; i.e. there is a 95% chance that the mean of each of the outputs is within 5% of its true value. Table 2 gives the convergence and 95% confidence intervals for each material and diameter tier. For cast iron tier 3, additional analysis has been undertaken due to the convergence values. These are detailed in Table 3. It can be seen that whilst convergence to 5% hasn't happened at a 95% confidence level, it has happened at a 90% level. There is 90% confidence that the result is within ±5% tolerance. Alternatively, there is 95% confidence that the result is within ±10% tolerance.

Table 2: Confidence intervals and convergence by material and diameter tier (5% tolerance, 95% confidence)

Material / Cohort	Convergence	Confidence intervals		
		Fractures	Corrosions	Joints
Cast iron Tier 1	100%	0.004955	0.002146	0.051804
Cast iron Tier 2	87% - 100%	0.001338 ± 7.603E-05	0.001507 ± 7.165E-05	0.066076 ± 0.000487
Cast iron Tier 3	31% - 100%	0.000491 ± 4.342E-05	0.001330 ± 7.143E-05	0.074148 ± 0.000514
Ductile iron Tier 1	100%	-	0.004736 ± 1.345E-04	0.023644 ± 2.977E-04
Ductile iron Tier 2	100%	-	0.002418 ± 9.626E-05	0.025414 ± 3.085E-04
Ductile iron Tier 3	100%	-	0.002771 ± 1.030E-04	0.041845 ± 3.925E-04
Steel Tier 1	100%	-	0.012308 ± 2.161E-04	0.019774 ± 2.729E-04
Steel Tier 2	100%	-	0.005722 ± 1.478E-04	0.013509 ± 2.263E-04
Steel Tier 3	100%	-	0.003203 ± 1.108E-04	0.014963 ± 2.379E-04

Table 3:Additional confidence intervals and convergence for cast iron tier 3 cohort

Tolerance and confidence	Convergence	Confidence intervals		
		Fractures	Corrosions	Joints
5% Tolerance 95% Confidence	31% - 100%	0.000491 ± 4.342E-05	0.001330 ± 7.143E-05	0.074148 ± 5.140E-04
10% Tolerance 95% Confidence	100%	0.000479 ± 4.288E-05	0.001319 ± 7.113E-05	0.074310 ± 5.140E-04
5% Tolerance 90% Confidence	100%	0.000479 ± 4.360E-05	0.001319 ± 7.105E-05	0.074310 ± 5.138E-04

3.4 Service pipe failures

It was not possible to undertake an equivalent Monte Carlo analysis for steel service pipes as failures could not be matched to individual digitised assets. Initially, a five-year trend in failures was used, normalised by the number of assets in service each year, however feedback from the GDNs has requested additional analysis to extend the period of failures under consideration. As such, analysis has been undertaken using Cadent service data from 2014 – 2021 (as this is the only robust data available for an extended period) which has then been scaled using the ratio of Cadent mains failures compared to that of the other GDNs. This has extended the analysis from five years to eight years and is shown in Figure 2: Steel service pipe failures, normalised by number of assets. The overall eight-year failure rate shows a slightly decreasing trend but it is not clear from an engineering perspective why this would be the case. Failures for the two most recent years have levelled off, so the average of the past eight years has been used to calculate a fixed rate of 0.0075 failures/service/year to use in this analysis. It should be noted that the policy for steel service pipe repair states that they must be replaced after first failure, so the deterioration trend for these assets is different for distribution mains, which may fail and be repaired multiple times.

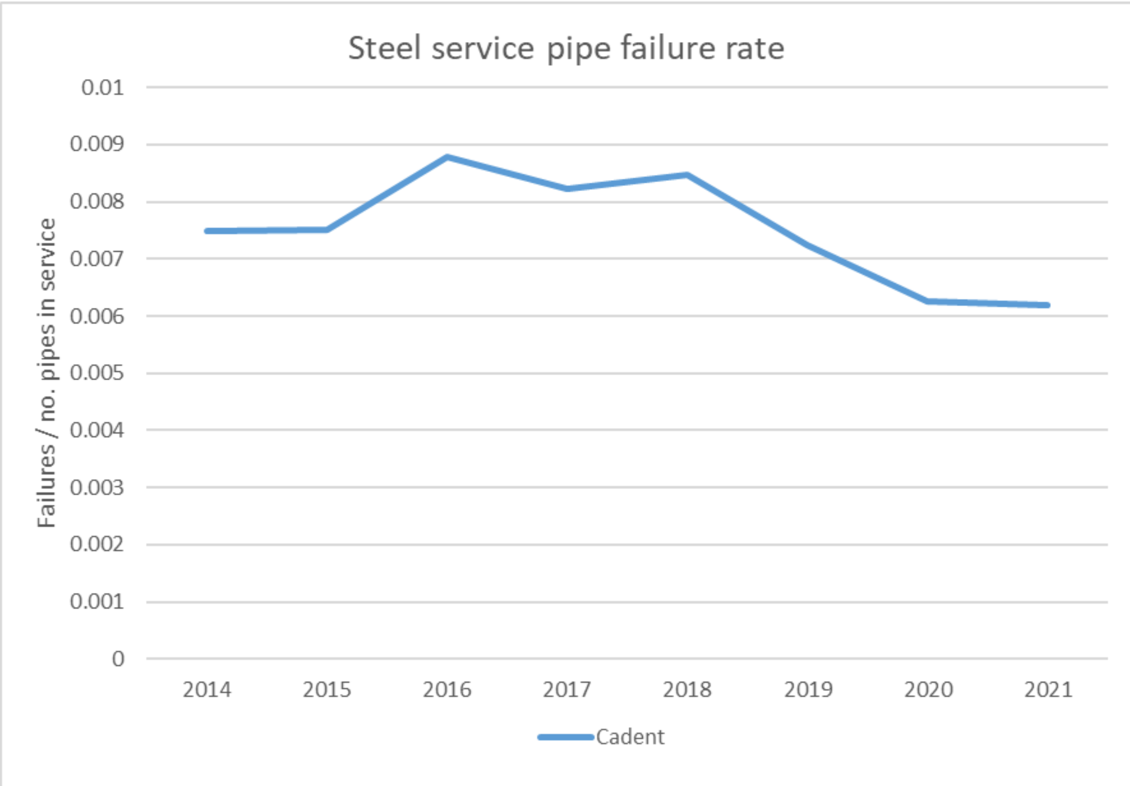

Figure 2: Steel service pipe failures, normalised by number of assets

3.5 Gas in Building rates

Once a distribution main or service pipe has failed, a proportion of these escapes result in gas tracking into one or more nearby buildings. Gas in Building (GiB) rates have been plotted for mains for each of the 21 categories outlined in Section 3.2, using a best fit line to predict forward to 2055. The mean GiB rate, expressed as GiBs per failure, for each failure mode (all materials) and overall is shown in Figure 3, including the prediction to 2055. There is a generally increasing GiB rate over the past 20 years, which is also seen in each of the individual graphs. It is not clear why more GiBs are being recorded but it is believed to be a genuine phenomenon and not an issue with data quality. Note that the irregularity in the predicted GiB rate, seen particularly in the corrosions line, is due to the results of the Monte Carlo failures analysis which have been used to normalise the combined GiB rates.

The predicted GiB rate in 2055 is in excess of what would be considered reasonable by applying engineering judgement. Also, many of the individual plots show a levelling out over the past five to ten years which adds weight to using a lower predicted GiB rate than that derived by extrapolating the past 20 years. As such, for each of the 21 categories the mean of the predicted GiB rate and the fixed 10-year average GiB rate has been used for the risk profiling. An example of this is shown in Figure 4.

For steel services, the Gas in Building rates (GiBs per failure) for Cadent for the past eight years are plotted in Figure 5. A slightly decreasing trend is observed. GSM(R) reports (which document accidental or uncontrolled releases which could cause personal injury, pipeline shutdowns, or other large uncontrolled releases) for service pipe issues have also been reviewed as anecdotal evidence suggests that service pipe failures are increasing which contrasts with the service pipe failure data. GSM(R) reports were available for three GDNs for the past seven to ten years No increase in severe service pipe failure events was identified from the GSM(R) reports. As such, a fixed rate of 0.352 GiBs per failure has been used for all future predictions, which is the mean of the eight years' Cadent data that has been analysed.

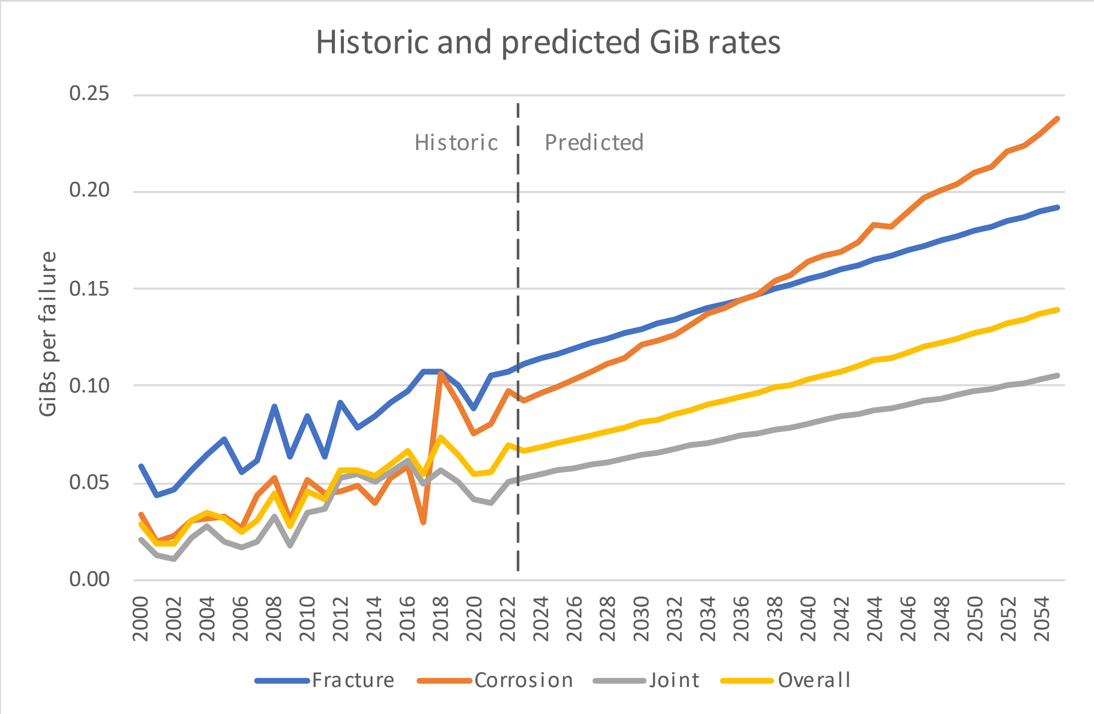

Figure 3: Historic and predicted Gas in Building rates for all failures combined

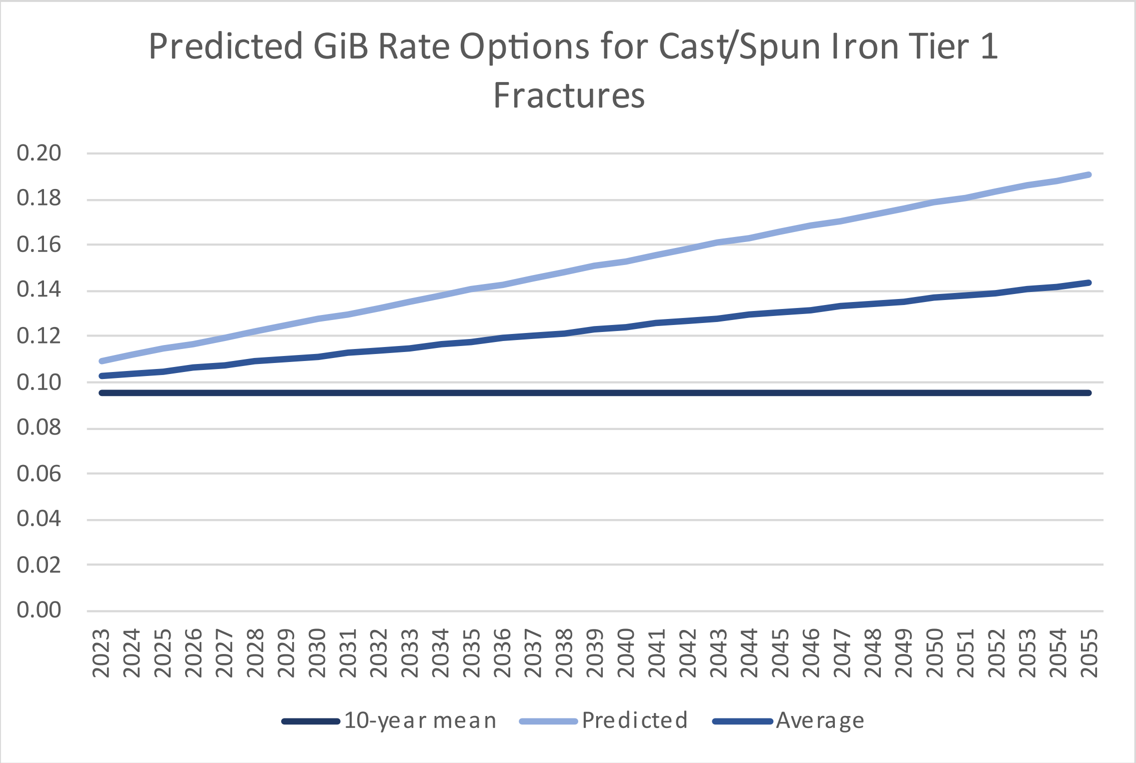

Figure 4: Predicted, 10-year average, and mean GiB rates

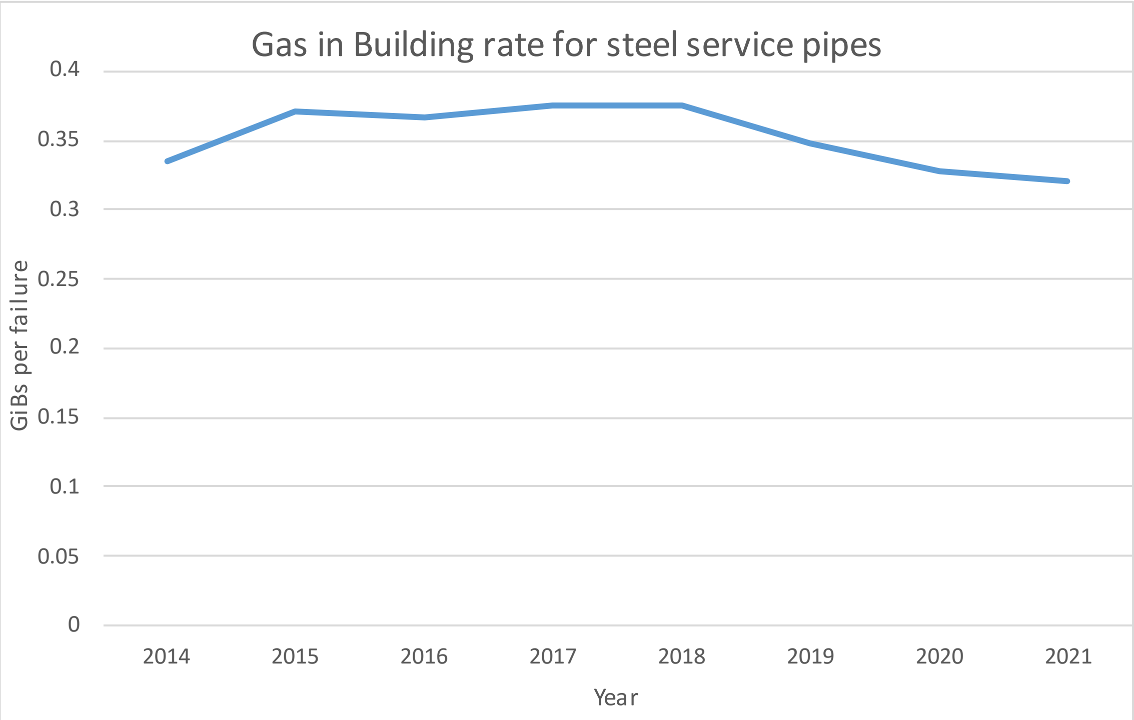

Figure 5: Historic Gas in Building rates for Cadent steel services

4 RESULTS

The results of the analyses described in Section 3 have been combined to determine the number of GiBs that would be predicted each year to 2055, for each material, diameter tier and failure mode. The default position is a 'do nothing' scenario, assuming that any replacement work had ceased at the end of 2022 and that the length of all pipes then remains constant until 2055. Adjustments have then been made to the length data and associated GiBs to present the following scenarios:

A. No future replacement – reactive maintenance only

B. Continuation of the Tier 1 programme to complete by 2032

C. In addition, replacement of steel services on PE mains by 2046

D. As per C, but with the addition of remaining Tier 1 iron (>30m from buildings) and all Tier 2 and 3 iron being decommissioned under an extended REPEX scheme by 2046

E. In addition to the above, decommissioning unprotected steel by 2046

Note that 2046 was selected by the GDNs as an appropriate target for completing further programmes of pipe replacement.

The results are a combination of the predicted failures, which are a measure of the deterioration of the pipeline assets, and the predicted GiB rates, which also show an increasing trend (see Section 3.5). The results are presented as stacked charts for each material and diameter tier, showing the number of GiBs predicted for all relevant failure modes for each permutation; this results in ten graphs (comprising three graphs for each pipe material, and one graph for steel services). Figure 6 shows an example of just the failures plotted, using the output from the Monte Carlo simulation. In Figure 7 the failures have been multiplied by the predicted GiB rate for each year, to give a predicted number of GiBs. The rest of the results are presented in the form of the GiB graph shown in Figure 7, but these two plots are shown together here to demonstrate the data analysis process.

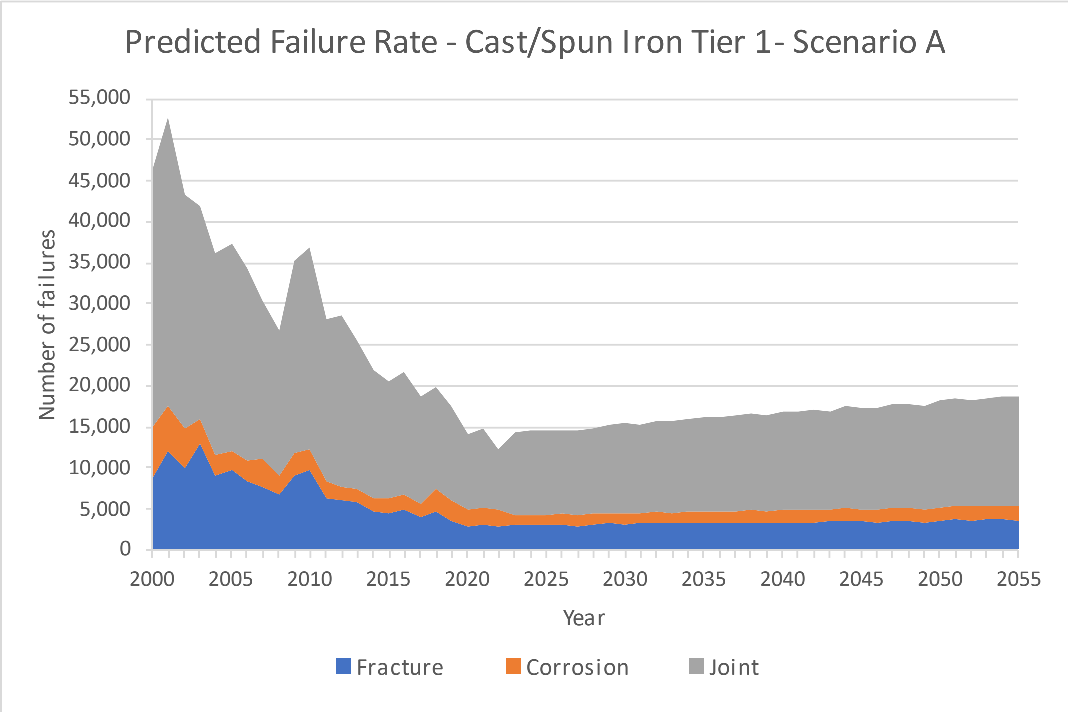

Figure 6: Example of stacked failure graph (cast/spun iron tier 1)

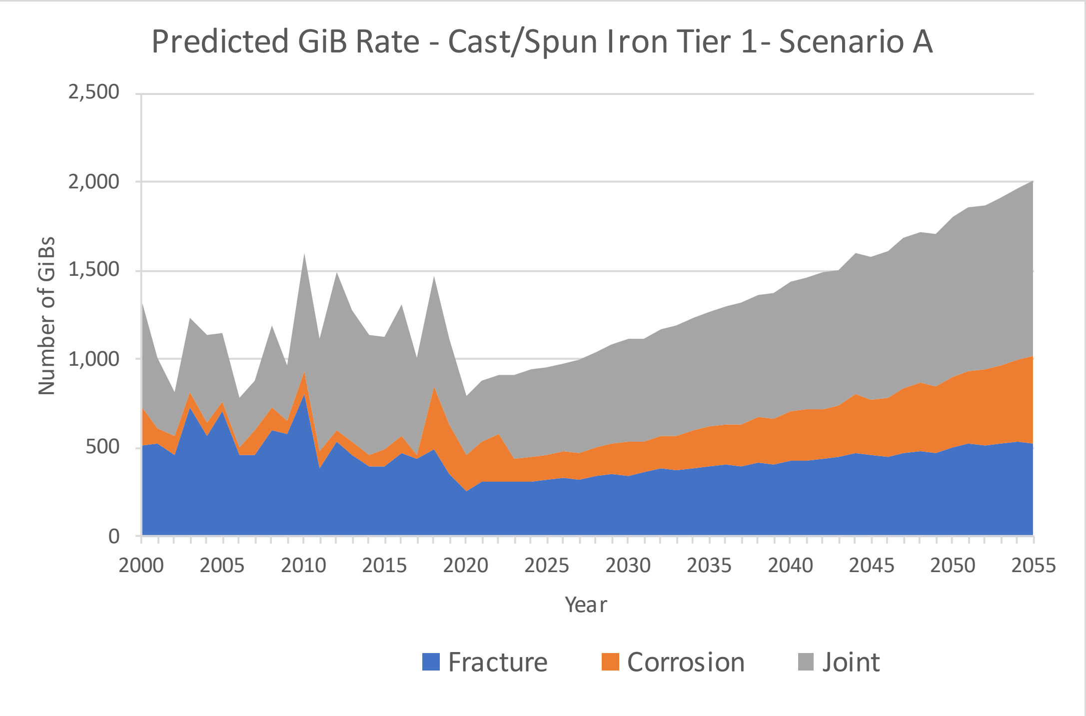

Figure 7: Example of stacked GiB graph (cast/spun iron tier 1)

4.1 Scenario A - 'Do nothing'

In this section the individual graphs for each permutation of material and diameter tier are shown for completeness. For each subsequent scenario, only one graph for each material is shown, combining all three diameter tiers. The graphs for each diameter tier are shown with the same scale on the y-axis as the others for that material, so that direct comparisons can be made.

Plots for cast iron are shown in Figure 8 to Figure 11; the plots for ductile iron are shown in Figure 12 to Figure 15; the plots for steel are shown in Figure 16 to Figure 18; and the single plot for steel services is shown in Figure 19.

4.1.1 Cast/spun iron

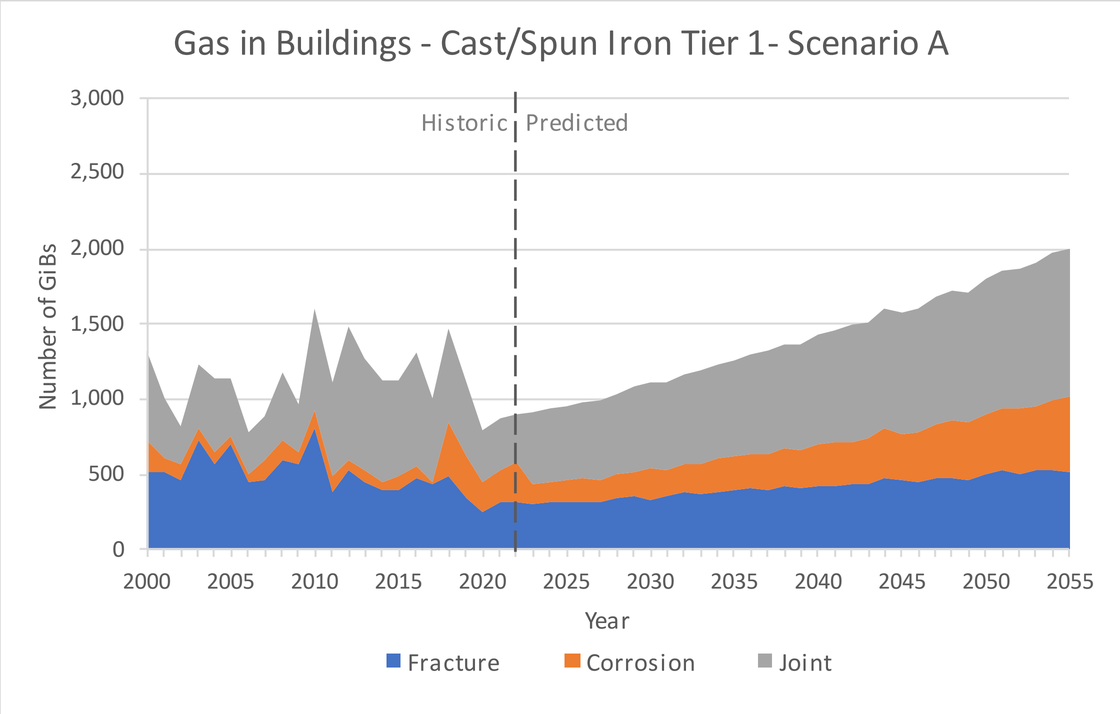

Figure 8: Gas in Buildings for cast/spun iron, tier 1, no replacement

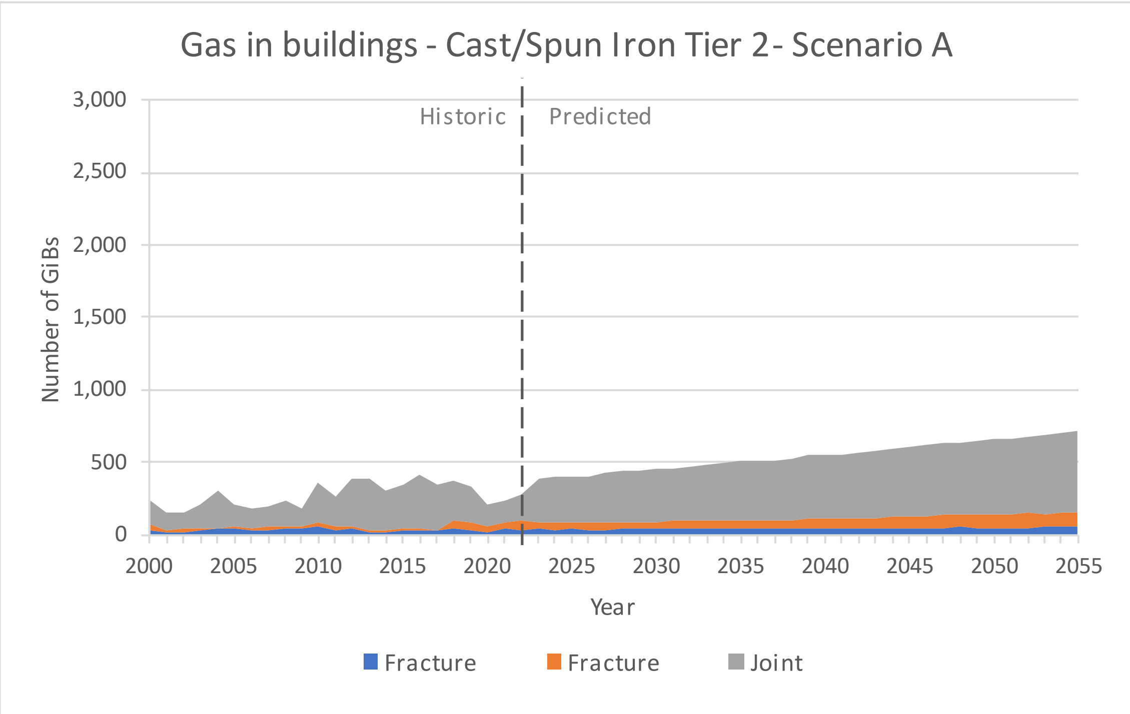

Figure 9: Gas in Buildings for cast/spun iron, tier 2, no replacement

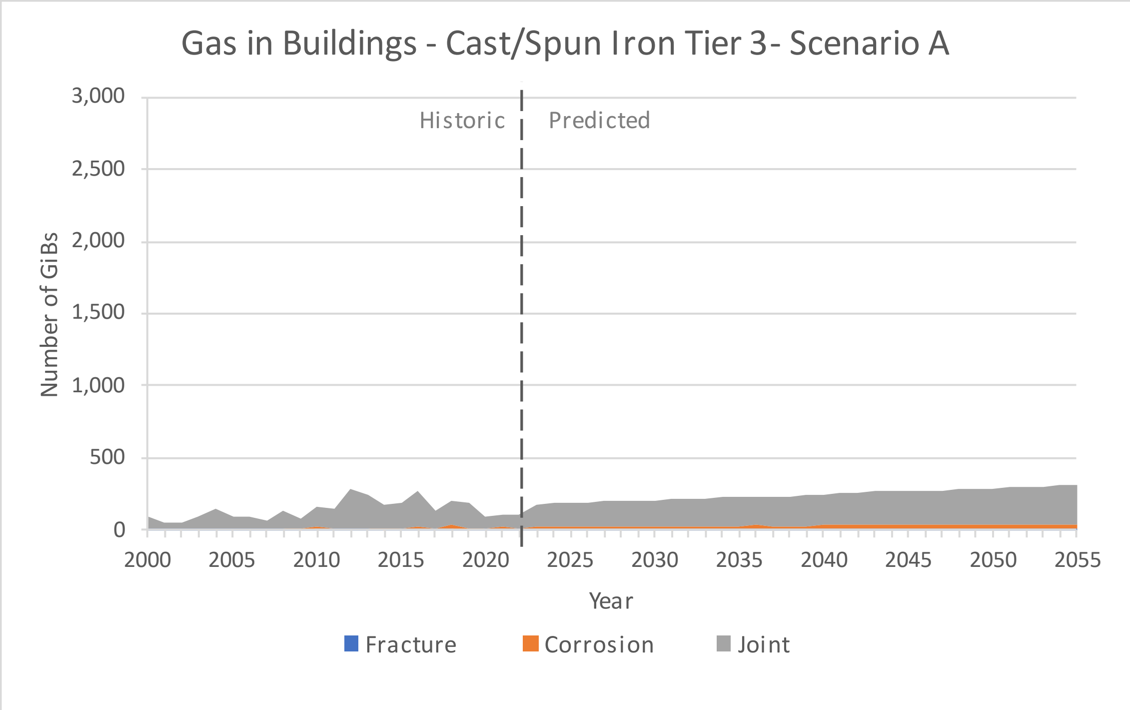

Figure 10: Gas in Buildings for cast/spun iron, tier 3, no replacement

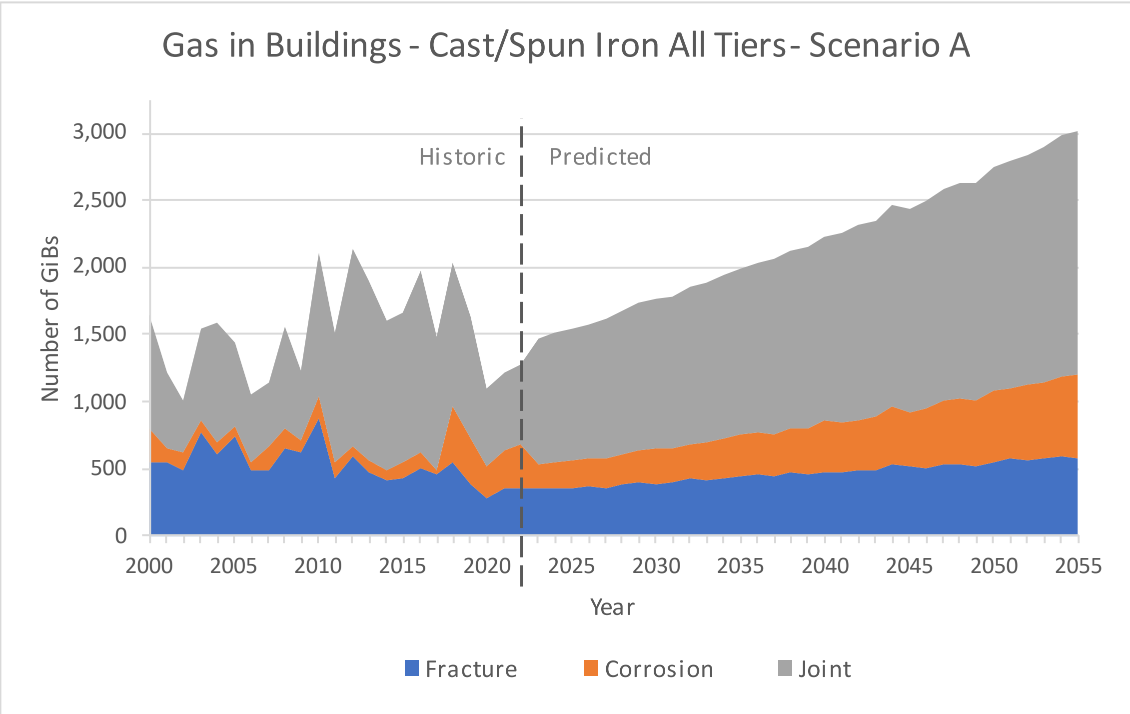

Figure 11: Gas in Buildings for cast/spun iron, all tiers, no replacement

4.1.2 Ductile iron

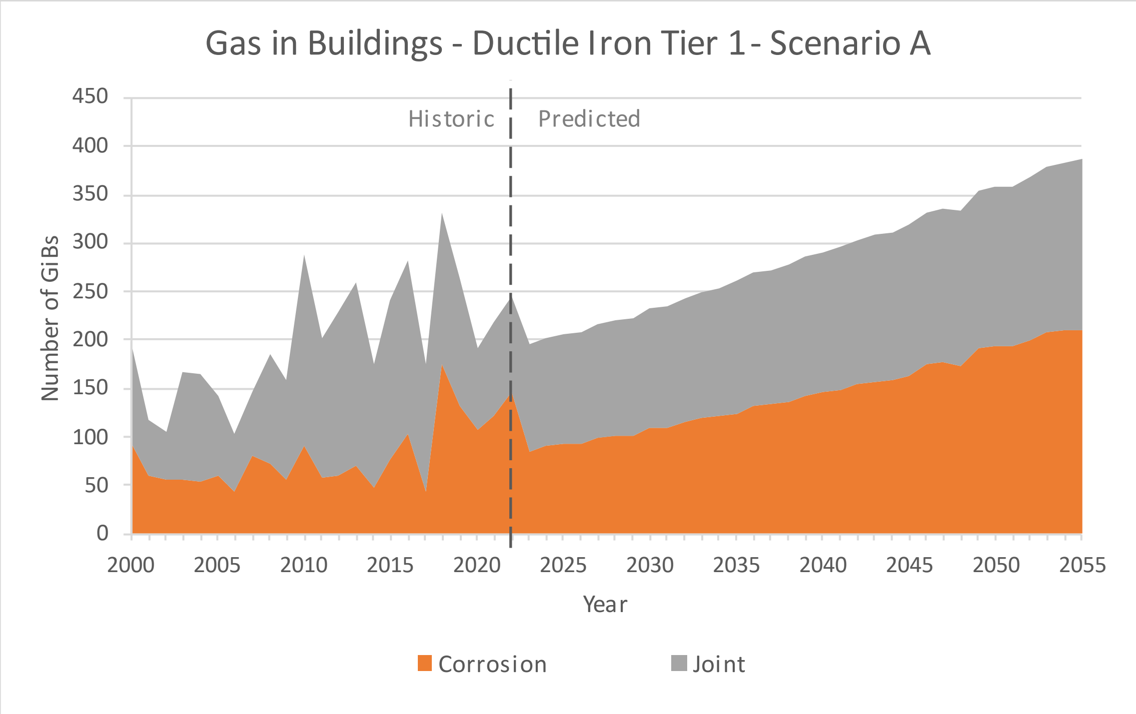

Figure 12: Gas in Buildings for ductile iron, tier 1, no replacement

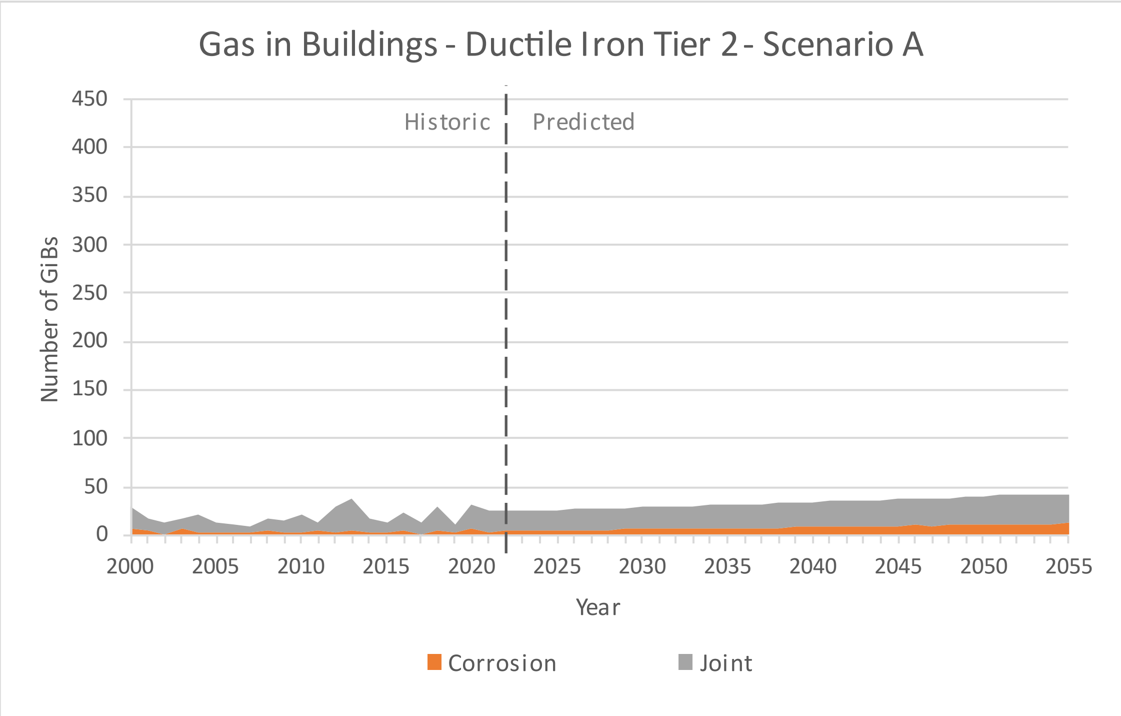

Figure 13: Gas in Buildings for ductile iron, tier 2, no replacement

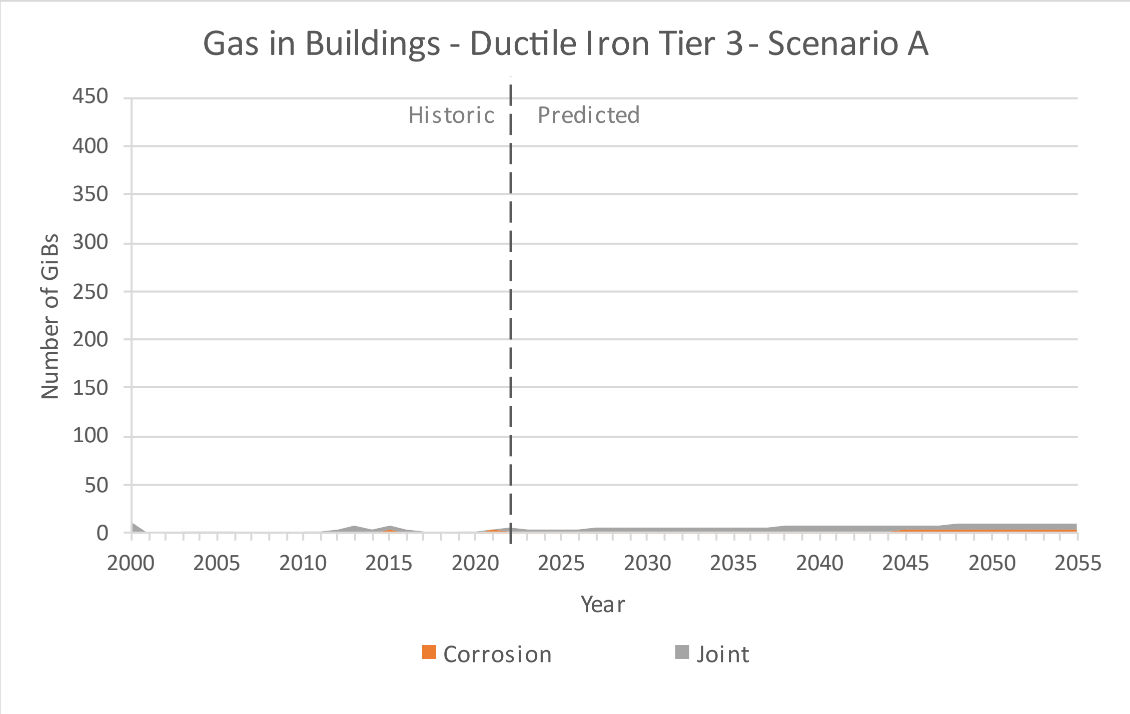

Figure 14: Gas in Buildings for ductile iron, tier 2, no replacement

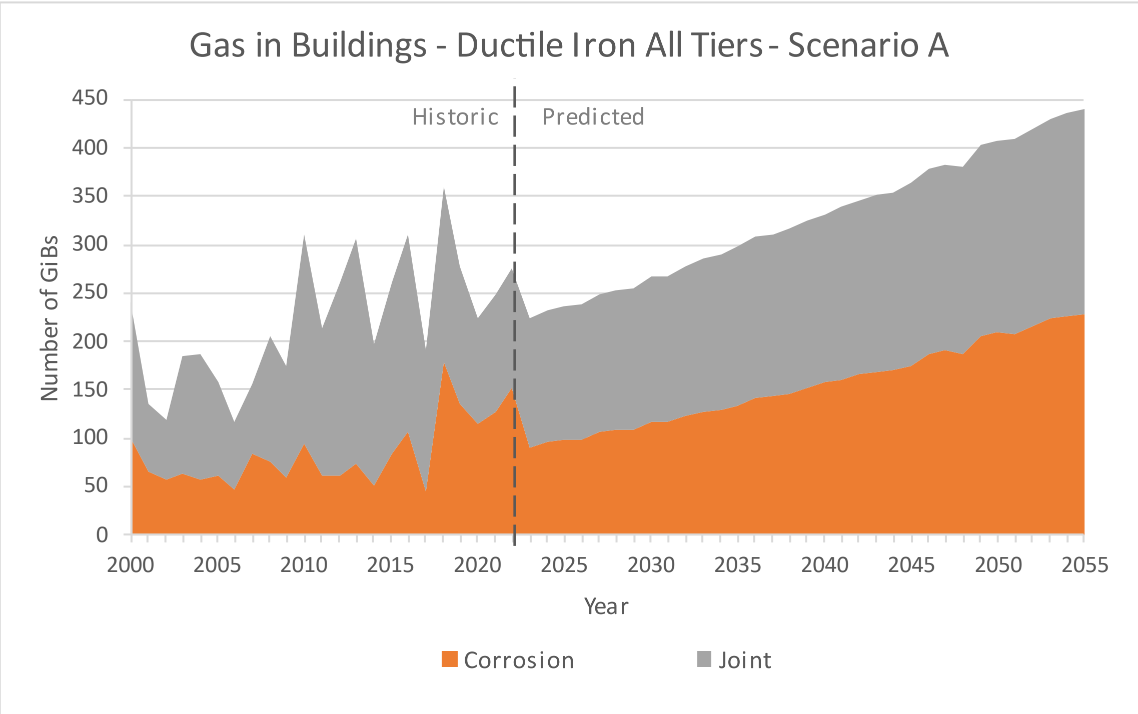

Figure 15: Gas in Buildings for ductile iron, all tiers, no replacement

4.1.3 Steel

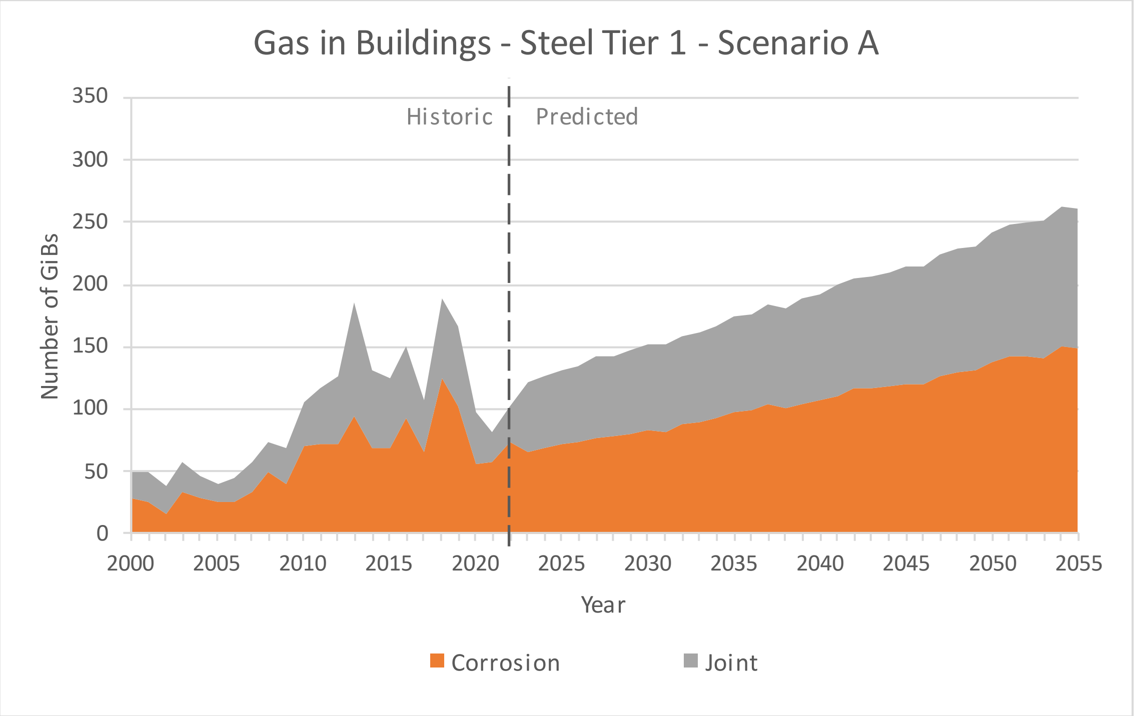

Figure 16: Gas in Buildings for steel mains, tier 1, no replacement

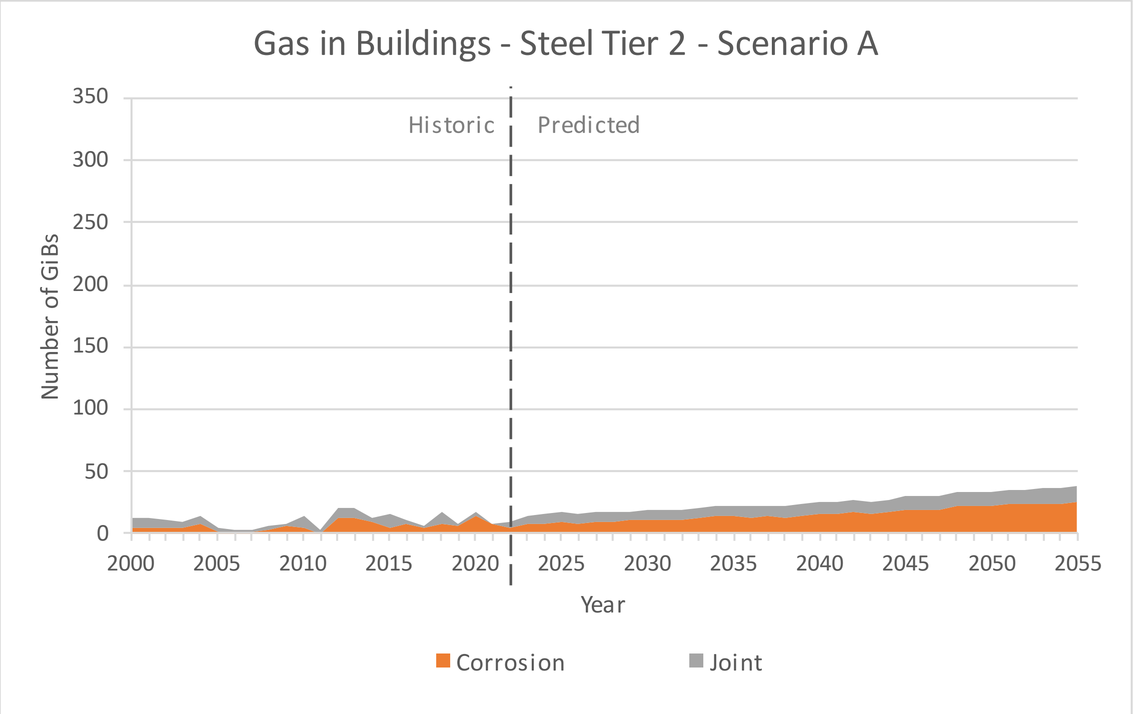

Figure 17: Gas in Buildings for steel mains, tier 2, no replacement

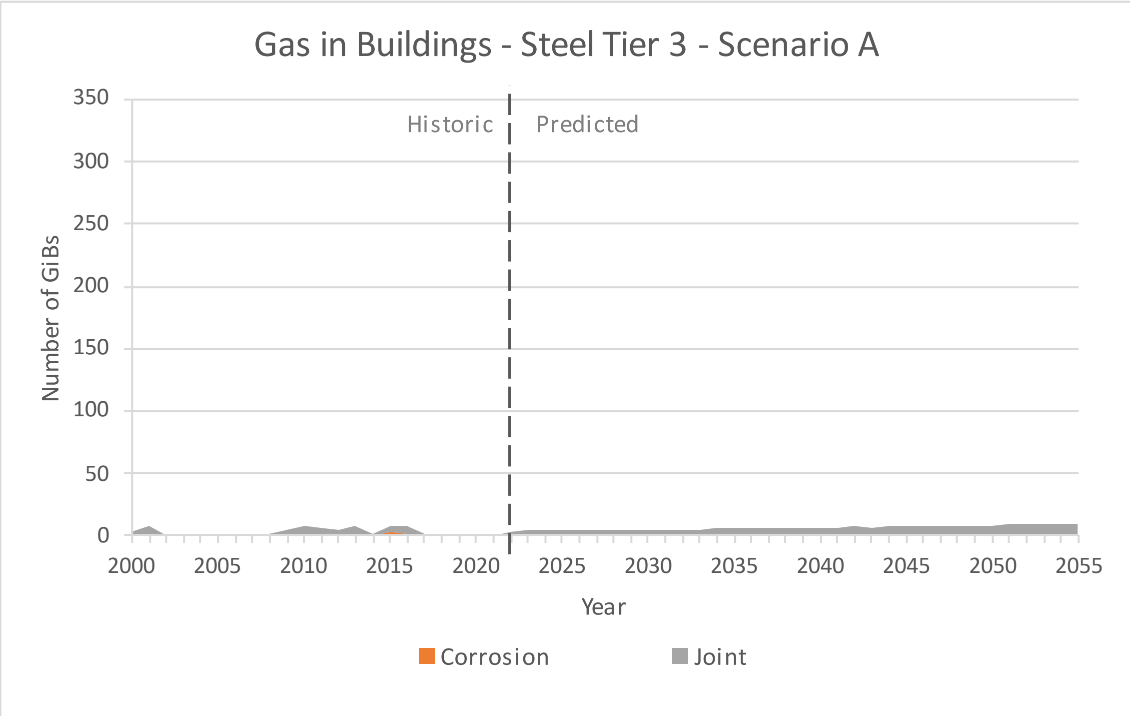

Figure 18: Gas in Buildings for steel mains, tier 3, no replacement

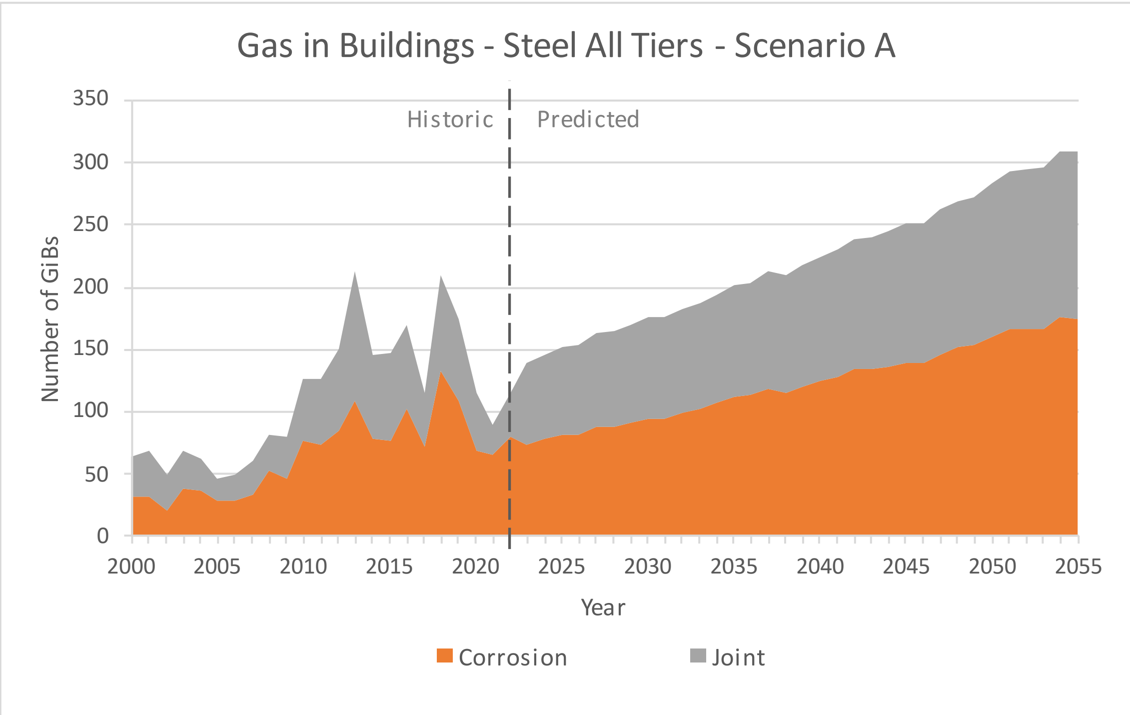

Figure 19: Gas in Buildings for steel mains, all tiers, no replacement

4.1.4 Steel services

Failure modes for steel services are not defined in the same way as for steel distribution mains. Most of the failures relate to corrosion of the pipe itself but some failures of joints and fittings have also been included. Interference damage has been excluded.

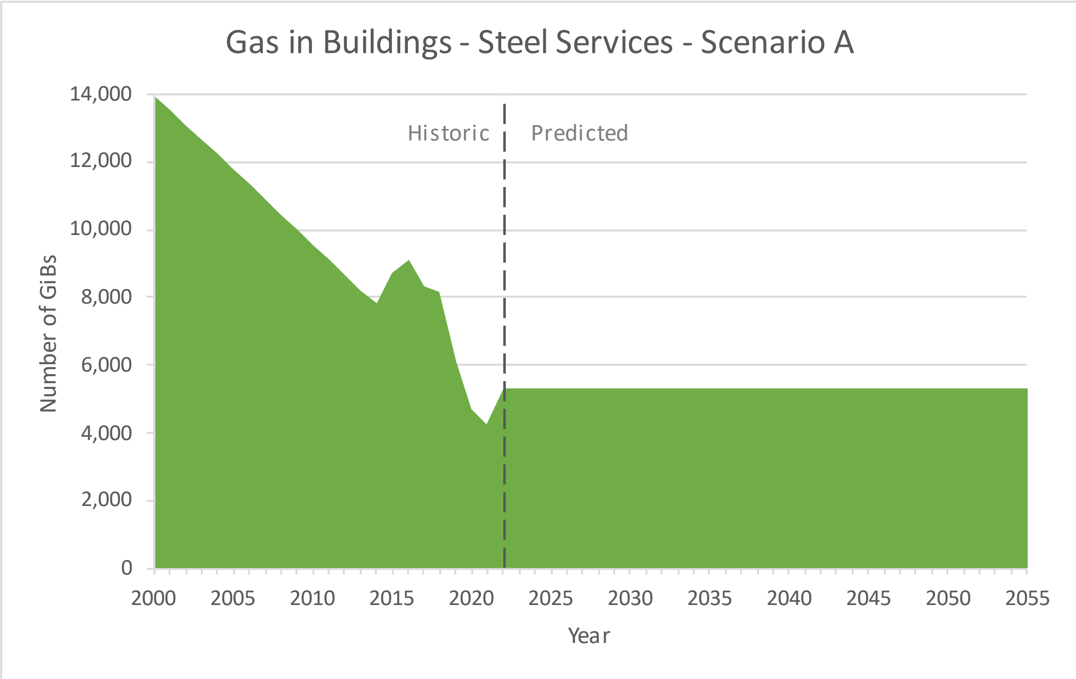

Figure 20: Gas in Buildings for steel services, no replacement

Note that the number of GiBs from 2000 to 2013 has been estimated based on recorded GiB numbers for 2014 to 2021 and historic replacement rates.

4.1.5 All materials

A combined graph for historic and predicted Gas in Buildings for all materials, diameter tiers and failure modes is shown in Figure 21. The highest number of GiBs comes from the failure of steel services, followed by distribution main joint failures. However, it should be noted that nearly all historic domestic gas explosions have been due to leakage from fractures. Pipes prone to fracture have been the target of the Iron Mains Risk Reduction Programme (IMRRP) so now represent a relatively low proportion of GiBs, but the remaining population of iron pipes should not be negated in terms of their potential for explosion.

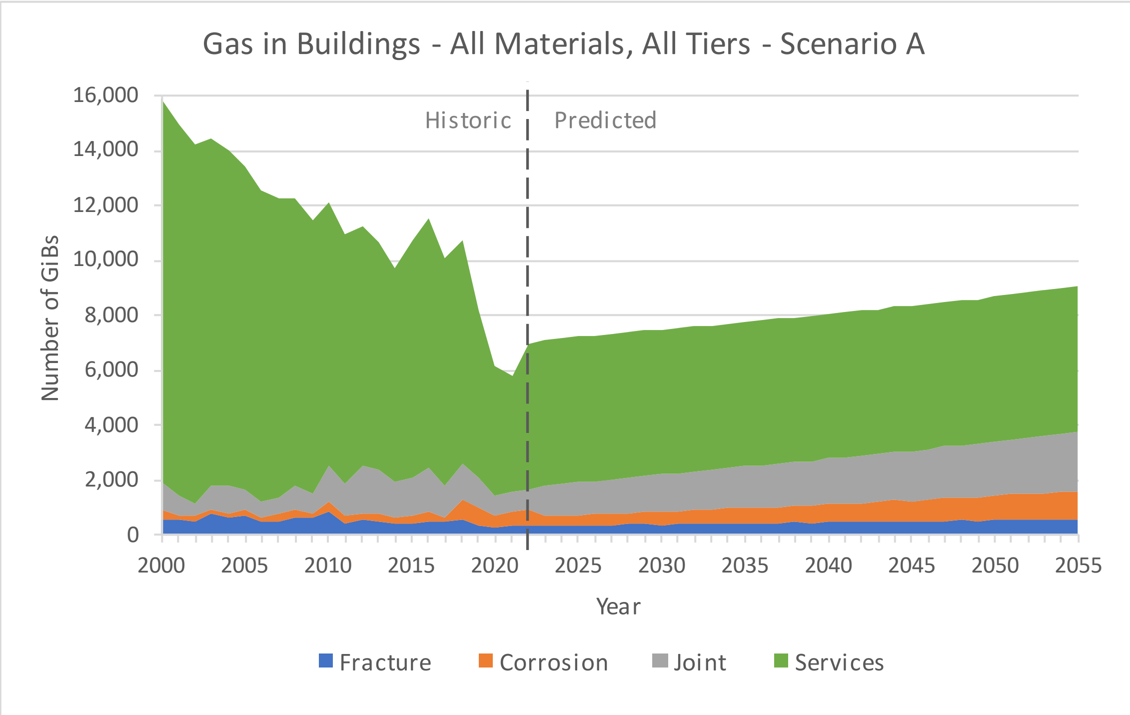

Figure 21: Gas in Buildings for all materials, no replacement

4.2 Scenario B – Complete IMRRP

The Iron Mains Risk Reduction programme (IMRRP) is due to complete in 2032 and will result in the replacement with polyethylene pipe of all tier 1 (<8") cast, spun and ductile iron mains within 30m of a building. This has been simulated in the following graphs (Figure 22 to Figure 25) by removing an appropriate length of pipe and its associated failures and GiBs for each year from 2023 to 2032. Note that tier 2 and tier 3 are excluded from this programme, as are steel mains; as such the graph for steel mains has not been replicated here as it remains the same as for Scenario A.

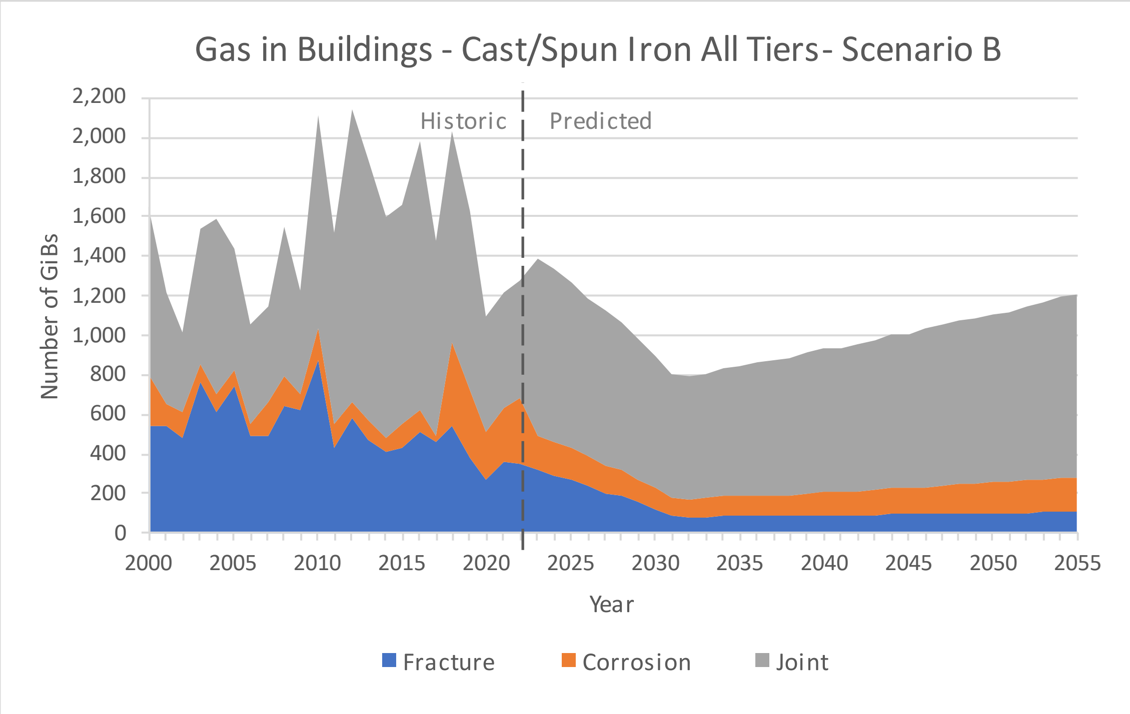

Figure 22: Gas in Buildings for cast/spun iron, all tiers, completion of IMRRP

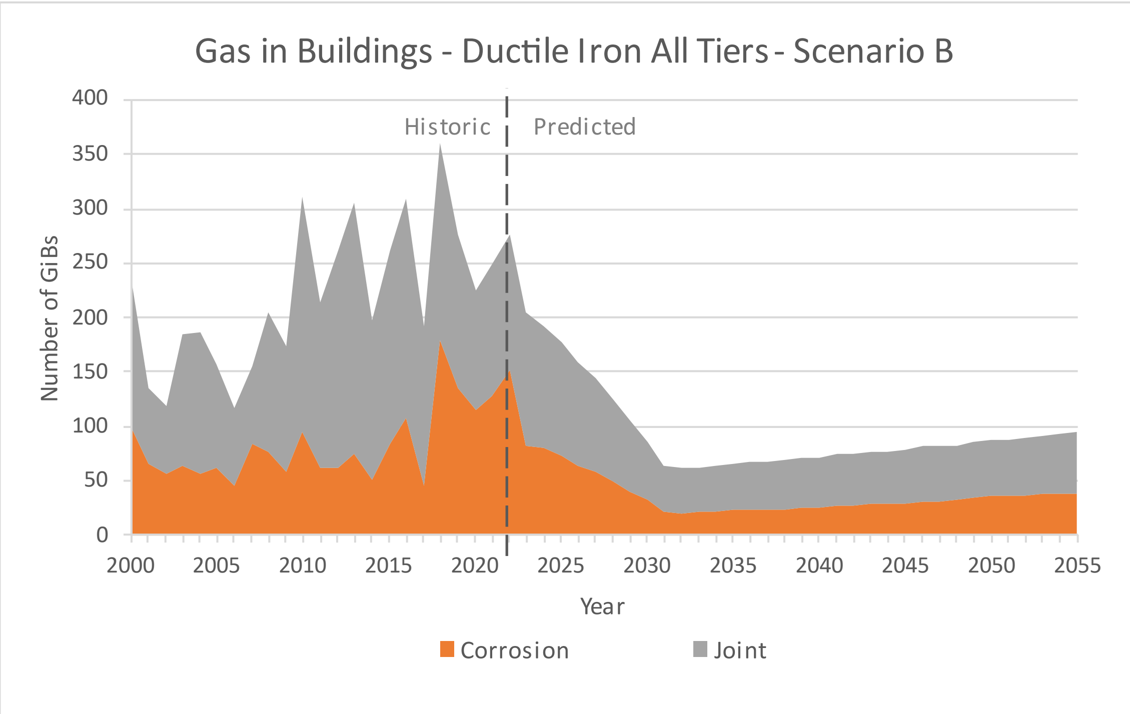

Figure 23: Gas in Buildings for cast/spun iron, all tiers, completion of IMRRP

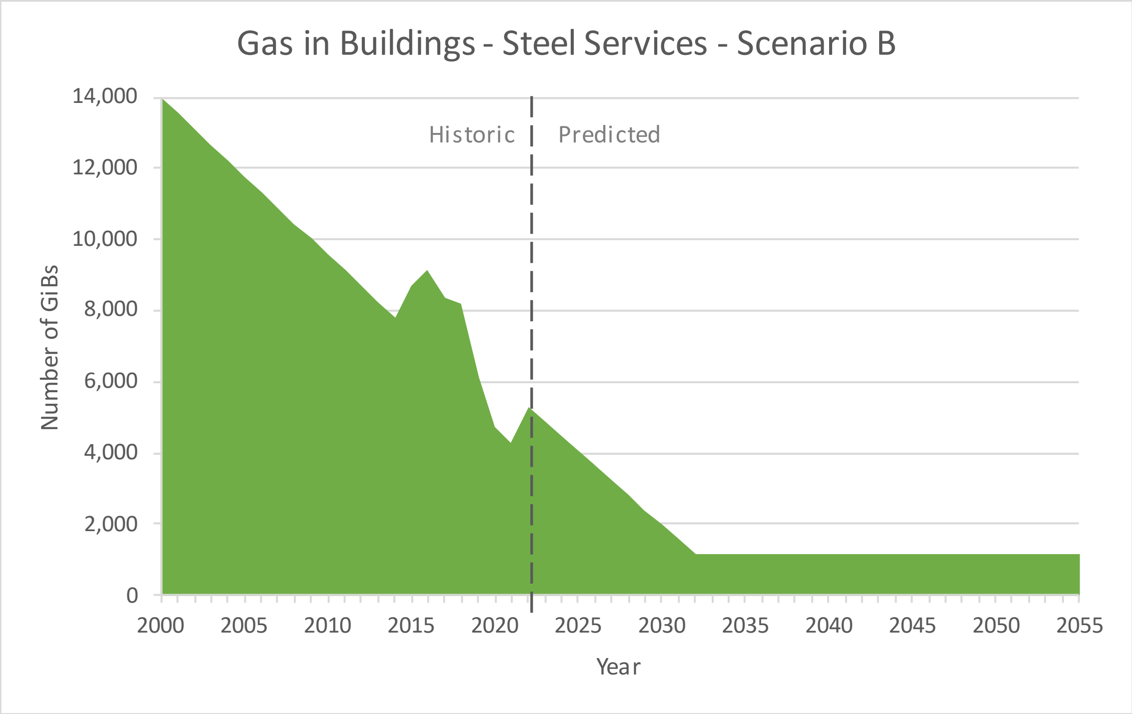

Figure 24: Gas in Buildings for steel services, completion of IMRRP

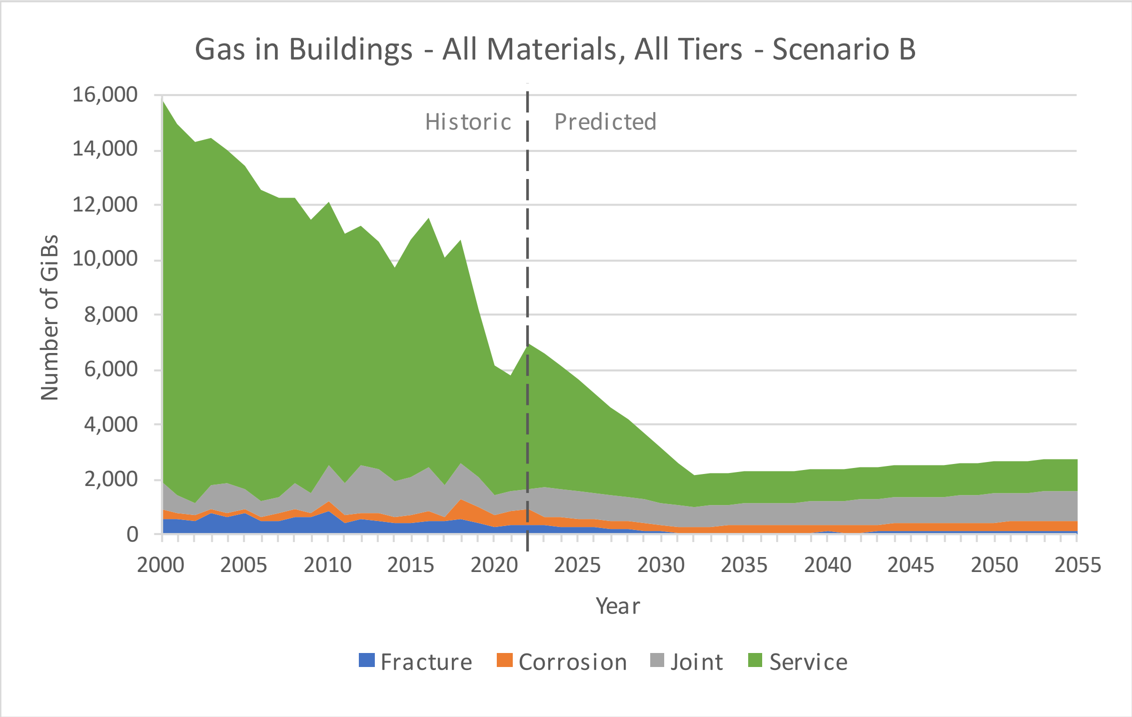

Figure 25: Gas in Buildings for all materials, all tiers, completion of IMRRP

4.3 Scenario C – Replace steel services

This scenario models the additional impact of replacing all remaining steel services by 2046. Only the specific graph for steel services is shown below (Figure 26), as well as the updated combined graph (Figure 27).

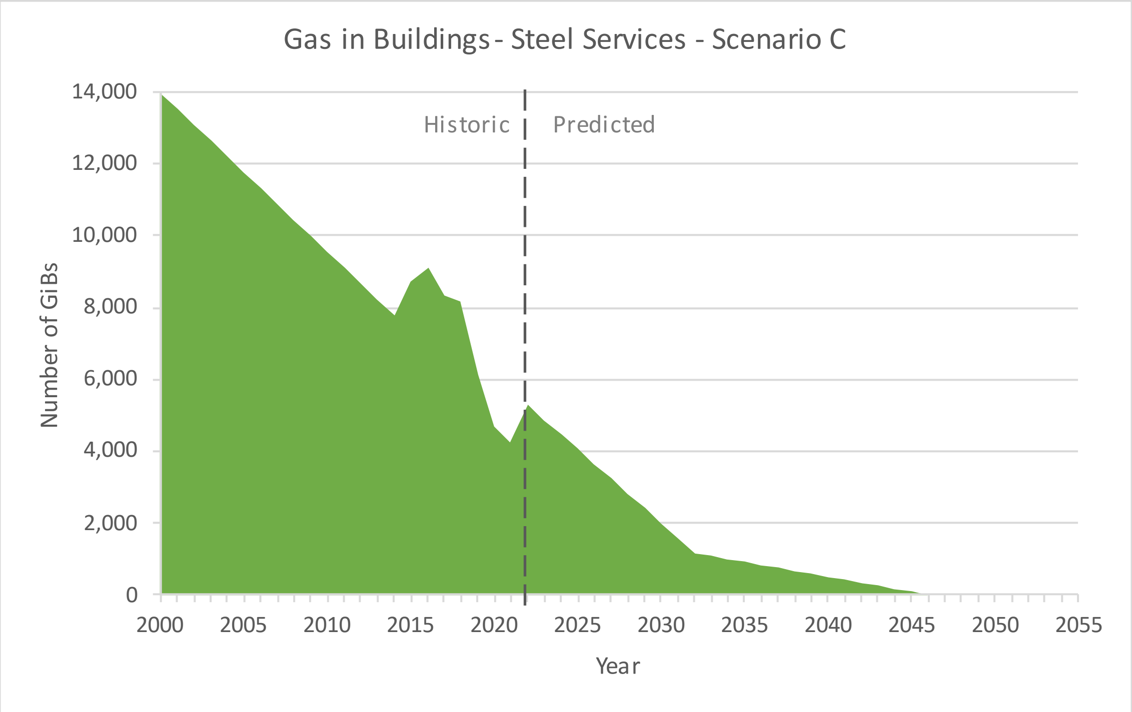

Figure 26: Gas in Buildings for steel services, replace all steel services by 2046

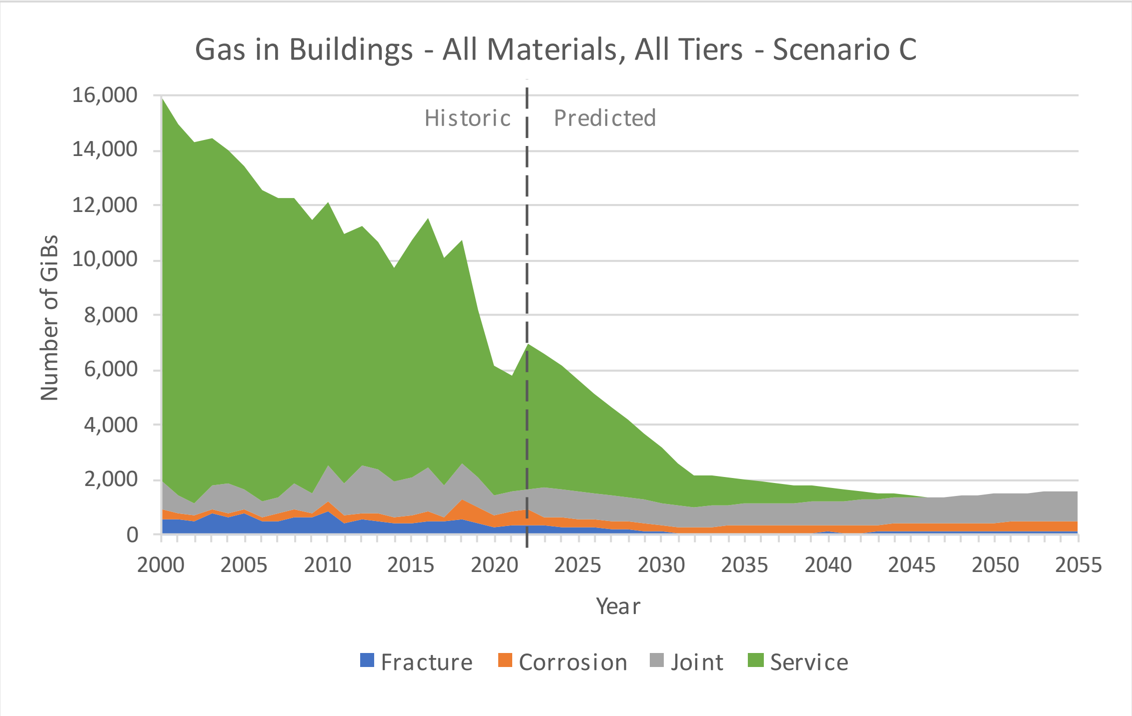

Figure 27: Gas in Buildings for all materials, all tiers, IMRRP and replace all steel services

4.4 Scenario D – Replace all iron

This scenario models the additional impact of replacing all remaining iron mains, as well as steel services, by 2046. The iron mains remaining after the conclusion of the IMRRP comprise cast, spun and ductile iron tier 1 pipes >30m from a building, and all cast, spun and ductile iron tier 2 and tier 3 mains. Only the specific graphs for cast/spun iron (Figure 28) and ductile iron (Figure 29) are shown below, as well as the updated combined graph (Figure 30).

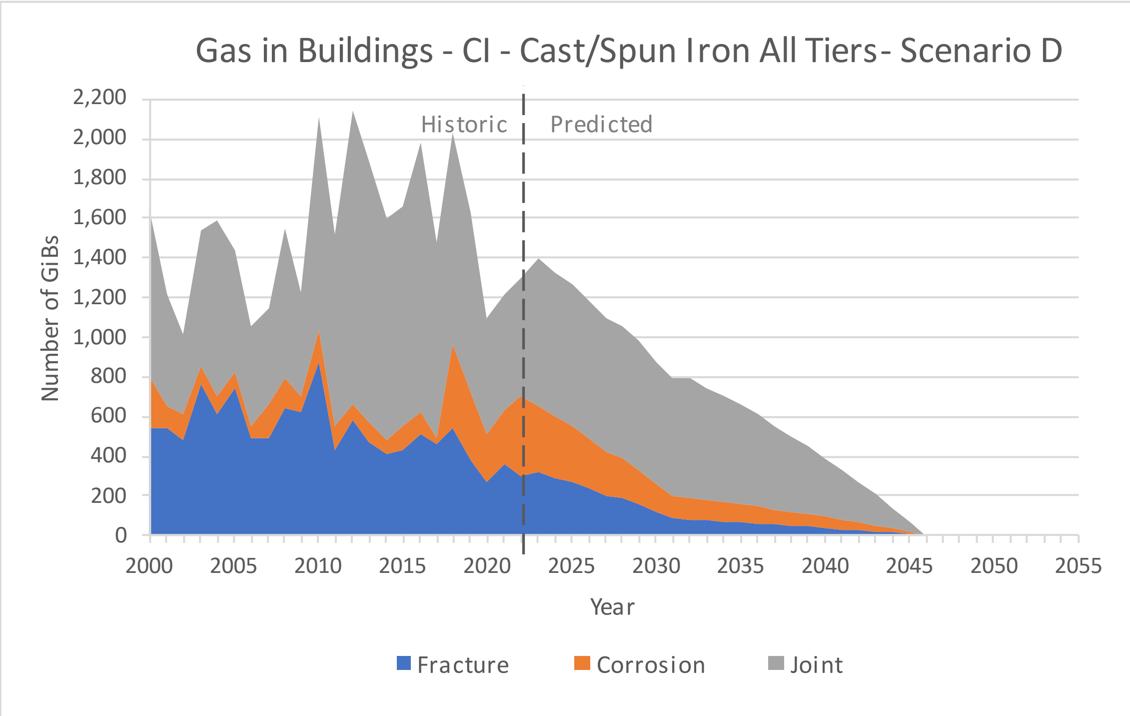

Figure 28: Gas in Buildings for cast/spun iron, all tiers, replace all iron mains by 2046

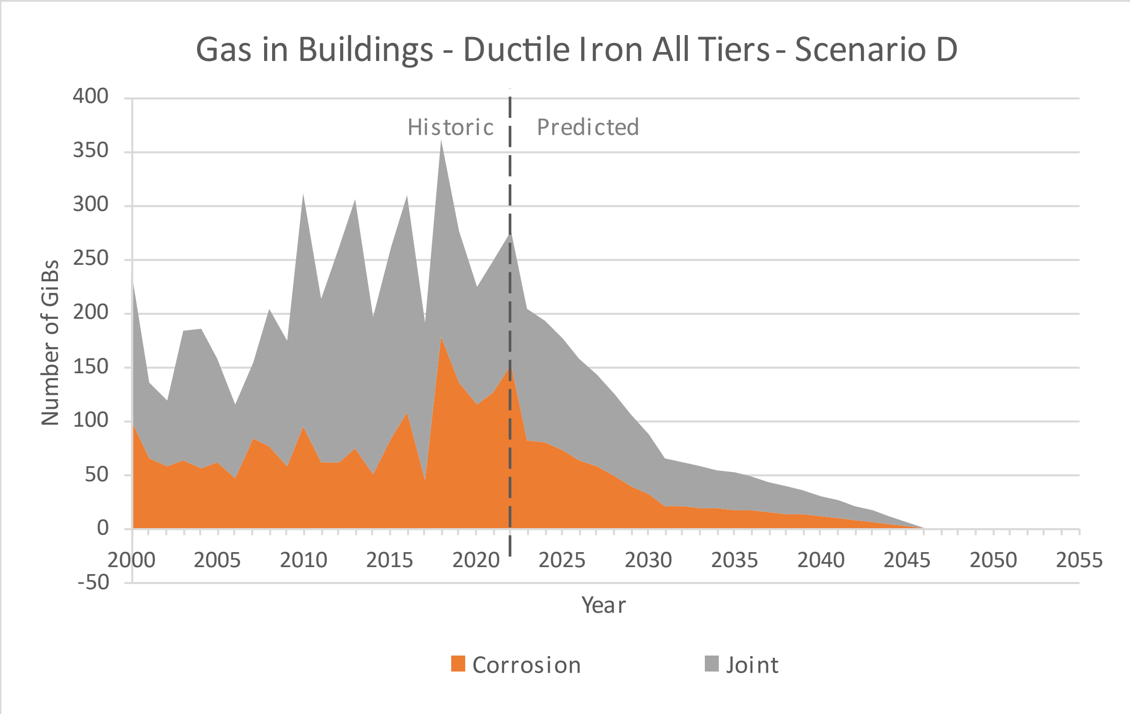

Figure 29: Gas in Buildings for ductile iron, all tiers, replace all iron mains by 2046

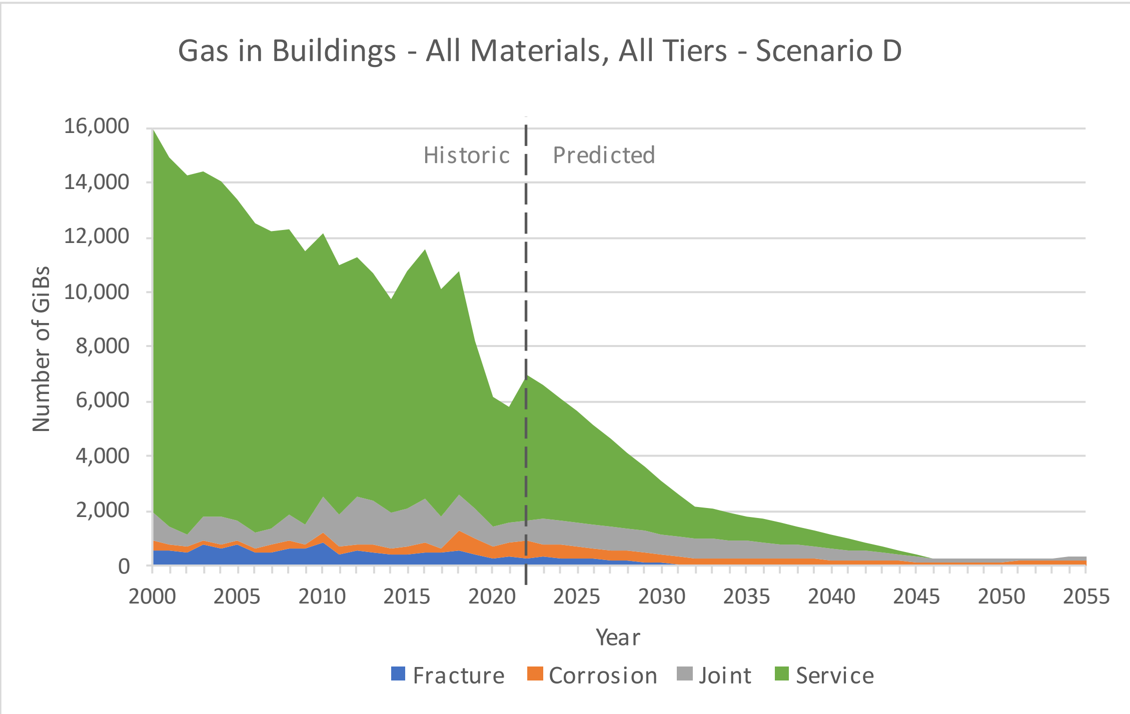

Figure 30: Gas in Buildings for all materials, all tiers, replace all iron mains and steel services by 2046

4.5 Scenario E – Replace all steel

The final scenario considers the additional impact of replacing all steel mains by 2046. Only the specific graph for steel mains (Figure 31) is shown below, as well as the updated combined graph (Figure 32).

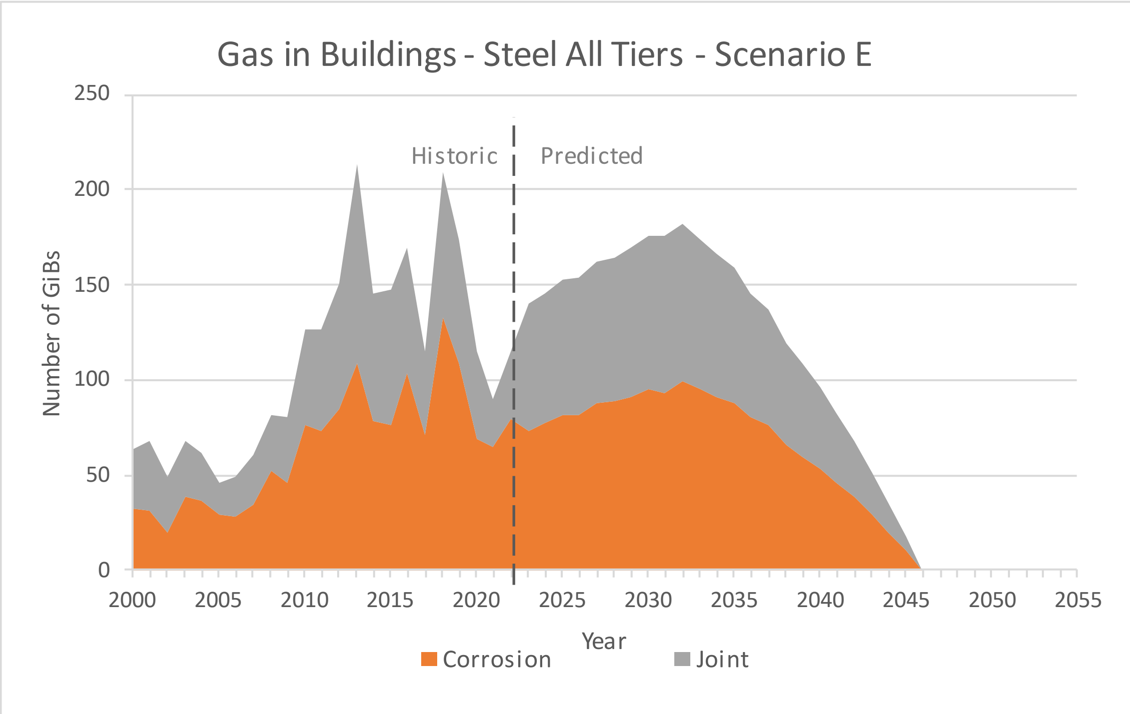

Figure 31: Gas in Buildings for steel mains, all tiers, replace all steel by 2046

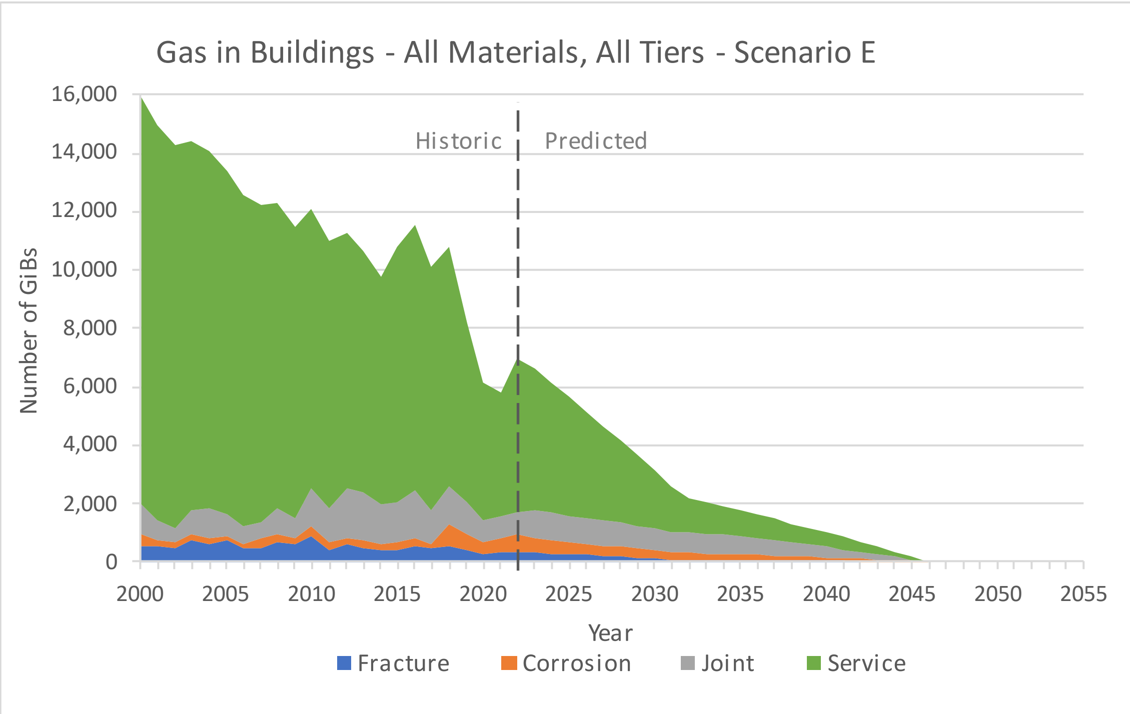

Figure 32: Gas in Buildings for all materials, all tiers, replace all iron and steel mains and steel services by 2046

5 DISCUSSION

5.1 Current state

Analysis of data from the four main gas distribution networks in Great Britain shows that there were just under 7,000 Gas in Building (GiB) events in 2022 from the low pressure and medium pressure networks. Of these, 5,296 GiBs derived from the failure of steel service pipes and 1,672 derived from ferrous distribution main failures. It should be noted that fitting failures and interference damage have been excluded from this analysis, as have the failure of non-ferrous pipe materials, so the total annual number of GiBs will be higher than this. Very few GiBs result in an explosion. Historic explosion events have been predominantly from distribution main fractures, with failures of steel services being the second highest cause of explosions. The relationship between GiBs and explosions is not clearly defined as data on gas readings in properties is not robust, but it is generally accepted that fractures result in a larger release of gas than other failure modes, which in turn results in more explosion events.

Approximately half (54.2%) of GiBs on ferrous distribution mains are currently from Tier 1 cast and spun iron mains. The IMRRP has been particularly successful at targeting the replacement of pipes with a high probability of fracture, so that less than half of the Tier 1 GiBs are now from this mode of failure. GiBs from Tier 2 and Tier 3 cast and spun iron are predominantly from joint failures, and comprise a further 22.4% of current distribution mains GiBs.

GiBs from corrosions and joint failures on ductile iron mains and steel mains account for 16.5% and 6.9% of current occurrences, respectively. For both materials, corrosion failures have the greatest impact for Tier 1, whilst joint failures dominate for Tier 2 and Tier 3 (although absolute numbers for the larger diameter ductile iron and steel pipes are very low).

The data for steel services is less robust than that for ferrous distribution mains. However, it can be seen that failures have reduced considerably over the past five years for which data is available, in line with the replacement carried out under the IMRRP. In addition, the policy for steel services replacement dictates that after a service has failed once it must be replaced, so deterioration of individual services is not as much of an issue as for distribution mains, which may continue to degrade and fail again after an initial failure event.

5.2 Future predictions

A summary of historic and predicted GiB numbers is given in Table 4. If no further replacement is undertaken, it is predicted that GiBs from Tier 1 cast and spun iron joint failures and corrosions will increase at a greater rate than those from fractures. By 2055 total Tier 1 cast and spun iron GiBs would be approximately 2,000 per year, with just over a quarter of those coming from fractures; this would mean that GiBs from fractures would be at a similar level to the numbers seen in the decade from 2000-2009 at the start of the IMRRP, with much larger numbers also coming from joint failures. Similar trends are seen for Tier 2 and Tier 3 cast and spun iron mains. However, the rate of increase is greater for Tier 2 and Tier 3 mains than for Tier 1 cast and spun iron, with GiBs from fractures being nearly double the 2000-2009 rate, and GiBs from corrosions and joints predicted to be over six times and over three times the 2000-2009 rates, respectively.

For ductile iron mains, total GiBs are expected to rise by 66% from current levels (10-year average) by 2055, with GiBs from corrosion failures having the highest rate of increase. For steel mains, total GiBs are predicted to increase by 108% from current levels (10-year average) by 2055.

For steel service pipes, future predictions are currently limited by data quality. It is estimated that future GiB levels would remain constant if no further proactive replacement was undertaken. Whilst there would be no increasing deterioration of individual assets, as is the case for distribution mains, number of GiBs caused by steel service pipe failure is a significant proportion of total GiBs and they are known to occasionally result in explosions.

Table 4: Summary of historic and predicted GiB numbers by pipe category

Pipe material	Diameter tier	Average GiBs 2000-2009 (start of IMRRP)	Average GiBs 2013-2022 (recent 10-year average)	Predicted GiBs 2055, no replacement
Cast and spun iron	Tier 1	1,046	1,100	2,003
	Tier 2	208	322	714
	Tier 3	87	165	308
Ductile iron	Tier 1	149	239	386
	Tier 2	17	23	43
	Tier 3	2	4	11
Steel	Tier 1	53	133	262
	Tier 2	8	13	38
	Tier 3	2	3	10
Steel services		11,998*	7,080**	5,296

*estimated; **2013,2022 estimated, 2014-2021 actual

5.3 Replacement options

The analysis presented above demonstrates that stopping all proactive replacement (Scenario A) is not a viable option as the level of GiBs in distribution mains would gradually return to and surpass the level seen at the start of the IMRRP. Completing the IMRRP in its current form (Scenario B) has the greatest impact in terms of reducing risk, largely because it targets both steel service pipes and the Tier 1 cast and spun iron mains that fracture most; these two modes of failure have historically caused the highest number of explosions. In terms of further risk reduction, the replacement of all steel services (Scenario C) and the replacement of all remaining iron (Scenario D) have similar benefits in terms of the reduction in GiBs, preventing 1,163 and 1,297 respectively per year by 2055.

Beyond the conclusion of the IMRRP in 2032, the benefits in risk reduction per unit length or per service replaced for the other categories of pipe are given in Table 5. It can be seen that the greatest reduction in GiBs gained is from each km of Tier 3 cast or spun iron replaced. Tier 1 and Tier 2 cast and spun iron are the next categories with the most risk reduction, followed by Tier 1 steel. A full cost benefit analysis would be required to understand the costs involved in replacing the different categories of pipe and the relative benefits of such expenditure. Use of a risk model (such as the current Mains Replacement Prioritisation Scheme) may also be beneficial in targeting specific high-risk mains within these categories to optimise the benefit.

Table 5: Annual GiB reduction per km or service replaced for each pipe category

Pipe material	Diameter tier	Annual GiB reduction in 2055 per km replaced (no. of GiBs)	Annual GIB reduction in 2055 per service replaced (no. of GiBs)
Cast and spun iron	Tier 1	0.090	
	Tier 2	0.089	
	Tier 3	0.123	
Ductile iron	Tier 1	0.045	
	Tier 2	0.027	
	Tier 3	0.079	
Steel	Tier 1	0.051	
	Tier 2	0.025	
	Tier 3	0.015	
Steel services			0.003

It should also be noted that this analysis has combined the data for low pressure and medium pressure mains. Whilst the pressure tier has no impact on failure rates, it will affect gas ingress and potentially gas accumulation and ignition within a property. Targeting medium pressure ferrous mains for replacement and/or installing effective cathodic protection on those MP steel mains that cannot easily be replaced would both be effective means of reducing risk.

6 CONCLUSIONS

Asset, failure and Gas in Building data have been collated for mains and services for all four GDNs. Historic failure and GiB trends have been analysed, and future deterioration and GiB trends predicted. Five scenarios are presented that document anticipated numbers of GiBs for each year to 2055, depending on the replacement programme adopted.

It should be noted that presenting the output in terms of number of GiBs does not take into account the risk of ignition or fatalities; this metric has been used as it is not possible to predict ignition or fatality rates with sufficient precision for each failure mode and material type. Nearly all historic domestic gas explosions have been due to leakage from fractures. Pipes prone to fracture have been the target of the Iron Mains Risk Reduction Programme (IMRRP) so now represent a relatively low proportion of GiBs, but the remaining population of iron pipes should not be negated in terms of their potential for explosion.

If no further replacement is undertaken, it is predicted that by 2055 GiBs from Tier 1 cast and spun iron fractures would be at a similar level to the numbers seen in the decade from 2000-2009 at the start of the IMRRP, with much larger numbers of GiBs also coming from joint failures. Similar trends are seen for Tier 2 and Tier 3 cast and spun iron mains, although the rate of increase is greater, with GiBs from fractures being nearly double the 2000-2009 rate, and GiBs from corrosions and joints predicted to be over six times and over three times the 2000-2009 rates, respectively. For ductile iron mains, total GiBs are expected to rise by 66% from current levels (10-year average) by 2055, with GiBs from corrosion failures having the highest rate of increase. For steel mains, total GiBs are predicted to increase by 108% from current levels (10-year average) by 2055.

The analysis demonstrates that stopping all proactive replacement is not a viable option as the level of GiBs in distribution mains would gradually return to and surpass the level seen at the start of the IMRRP. Completing the IMRRP in its current form has the greatest impact in terms of reducing risk, largely because it targets both steel service pipes and the Tier 1 cast and spun iron mains that fracture most; these two modes of failure have historically caused the highest number of explosions. For further risk reduction, the replacement of all steel services and the replacement of all remaining iron have similar benefits in terms of the reduction in GiBs, with the greatest benefit gained from each km of Tier 3 cast or spun iron replaced. A full cost benefit analysis would be required to understand the costs involved in replacing the different categories of pipe and the relative benefits of such expenditure. Use of a risk model (such as the current Mains Replacement Prioritisation Scheme) may also be beneficial in targeting specific high-risk mains within these categories to optimise the benefit.

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