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HR WALLINGFORD REPORT – RT012 – ANNUAL AVERAGE CONCENTRATION – DEDICATED DISCHARGE

BRAD/EN/REP/138

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PURPOSE

The purpose of this document is to provide supporting information for the application to the Environment Agency for variations to the non-radioactive effluent permit PR2TS/E10760C/V002, the radioactive substances activities permit EPR/ZP3493SQ/V004 and the Fuel Element Debris (FED) treatment facility permit EPR/DP1327XB.

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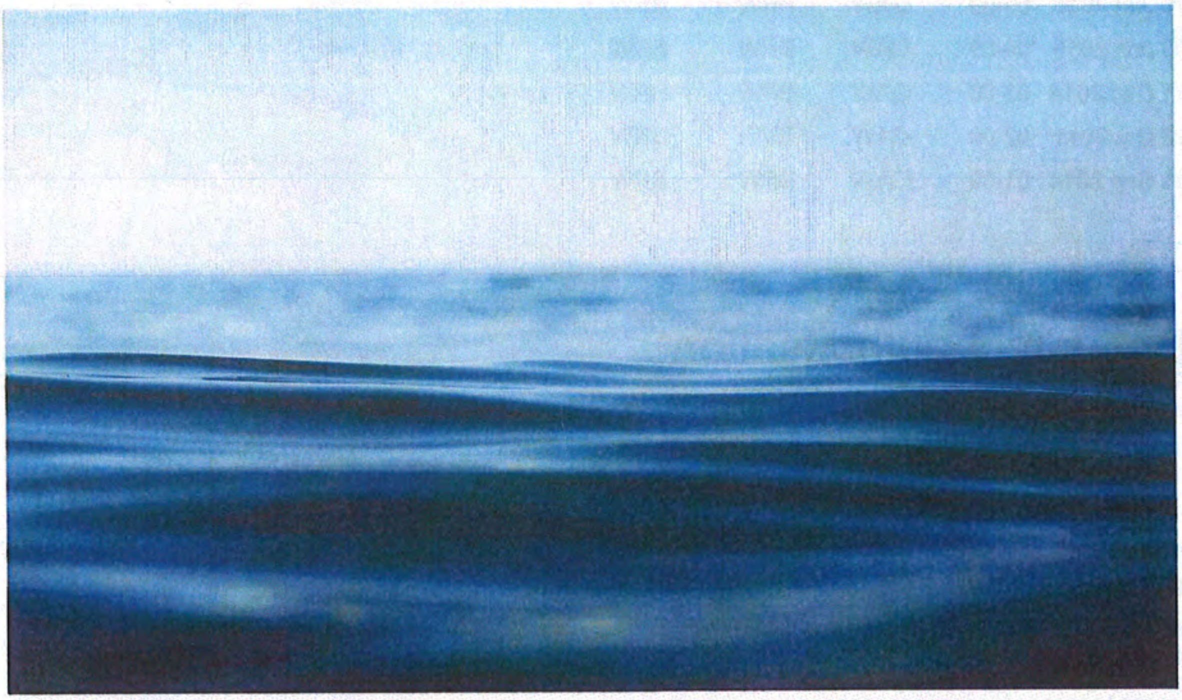
Y:\readona\DOCS1\ENvironment\ENREP\EN-REP-138 APPENDIX

HR Wallingford
Working with water

Bradwell Power Station

Annual average concentration - dedicated discharge



EBR4908-RT012-R05-00

January 2015

Document information

Document permissions	Confidential - client
Project number	EBR4908
Project name	Bradwell Power Station
Report title	Annual average concentration - dedicated discharge
Report number	RT012
Release number	R05-00
Report date	January 2015
Client	Magnox Ltd
Client representative	Martina Mullarkey
Project manager	Graham Watt
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Document history

Date	Release	Prepared	Approved	Authorised	Notes
15 Jan 2015	05-00	GAW	BRW	BRW	
09 Jan 2015	04-00	GAW	BRW	BRW	
11 Dec 2014	03-00	GAW	BRW	BRW	
20 Oct 2014	02-00	GAW	BRW	BRW	
11 Sep 2014	01-00	GAW	BRW	BRW	

Document authorisation

Prepared	Approved	Authorised
Graham	B.R. Wild	B.R. Wild

Summary

Magnox is undertaking a decommissioning programme at Bradwell nuclear power station. The site lies on the south side of the Blackwater Estuary in Essex, about 1 kilometre seaward of Bradwell Marina, and has been occupied as a power station since the early 1960s.

The main aim of this study was to identify the optimum times for discharging FED, NOx scrubber liquor and AE through the new discharge line.

The FED and NOx scrubber liquor have similar hydrodynamic properties. Based on the modelling work undertaken, we suggest that Magnox request consent to discharge during a window from HW+1 to HW+2.5 when submitting their EPR permit application as this will give good initial dilution and good flushing from the estuary.

The AE has different properties from the FED and NOx scrubber liquor, but the results shown here lead to a similar conclusion. Therefore we suggest that Magnox should request the same discharge window as for the other effluents – from HW+1 to HW+2.5.

This discharge window would allow the effluents to be discharged at the best time under normal circumstances, but would allow some flexibility that might be necessary from time to time without compromising the dilution and flushing of the effluent.

During decommissioning, the magnesium alloy that comprises the fuel element debris (FED) is being dissolved in nitric acid, abated to reduce certain constituents and released in a controlled batch operation to the Blackwater Estuary. A modelling study (report EX6399) was carried out in 2011 to investigate the dispersion in the estuary of FED effluent discharged though the existing outfall tunnel and tower. This study was updated in 2014 (Report EBR4908-RT011) to consider the combined effect of the released effluent with a gradual build-up in the estuary over time; this report presented estimates of the near field dilution of the effluent at the edge of a mixing zone that extended 100 m from the discharge point.

Due to the degree of silting within the existing discharge arrangements, Magnox has installed a new dedicated discharge system within the existing outfall structure. This removes the pumping of seawater prior to discharge. This dedicated outfall was described in report EBR4908-RT009. It is estimated that during the half-hour discharge period for FED effluent, the dilution ratio (concentration in the undiluted effluent divided by concentration in the estuary) at 100 m from the dedicated outfall would vary between about 240:1 on a typical neap tide and 1200:1 on a typical spring tide. The average over a spring-neap cycle (which is used here as the first step towards a long-term average) is calculated to be around 1000:1. These calculations were made assuming an effluent discharge rate equivalent to 40 m^3/h.

The same outfall will be used at times to discharge active effluent (AE) and another effluent associated with the FED process. The discharges are intermittent, so the average concentration of effluent at the edge of the mixing zone is very much less than the concentration during the discharge periods. This report presents a basis for assessing compliance against the Environmental Quality Standard (EQS) Annual Average (AA) concentration and Maximum Allowable Concentration (MAC) by establishing a dilution factor at the edge of the mixing zone (100 m from the discharge tower) that can be used to assess each discharge's contribution to the EQS AA and MAC.

The discharges may include an occasional discharge of effluent containing treated NOx scrubber liquors. This discharge is likely to occur around twice a year, but the modelling is based on a frequency of 28 days; this assumption is pessimistic because should the discharge of NOx scrubber liquor be on a longer interval the dilution factor will increase accordingly. The discharge will be made on separate days to the FED dissolution discharges, which will usually be made on a daily basis. The working assumption is that the intermittent discharge will be made within the same volume of effluent as the FED (20 m^3) and its density is similar; we have therefore assumed that its initial dilution will be the same as for the FED.

The annual average relative concentration at 100 m distance from the discharge tower (that is, the concentration in the estuary divided by concentration in the final monitoring and delay tank) will in general include contributions from: a series of spikes in the concentration as the discharged effluent passes over the edge of the mixing zone; a series of lower humps in concentration as some of the most recent discharge returns as a diffuse patch on the following flood tide; and a low level background that will build up over time through the estuary.

The calculations presented here show that (within the accuracy of reporting) the returning concentrations are negligible compared with the 'fresh' discharge.

Results for FED effluent/ NOx Scrubber Liquor

Summary of FED effluent and NOx Scrubber Liquor dilutions at 100 m from the outfall

discharge	average instantaneous dilution (during discharge)	long-term average (compare EQS AA)	minimum (compare EQS MAC)
daily	1000	48,000	240
17 days	1000	800,000	240
28 days	1000	1,300,000	240

It should be noted that the dilution values given above at 100 m from the discharge point refer to the dilution at the core of the discharge plume. They apply, therefore, to a region a few tens of metres across and up to two metres thick, close to the estuary bed. The depth-average dilution would be significantly higher (so depth-average concentration would be lower).

The annual average relative concentration and dilution at the point of discharge can be estimated from the time average of the discharge concentration. Whilst there is no initial dilution at this point, the effluent will mix rapidly with the estuary water over a small area, due to the high turbulence produced by its exit velocity. The contribution from returning patches and background is again negligible.

- For discharge every day, the long-term average dilution at the point of discharge is estimated as 50:1.
- For discharge every 17 days, the long-term average dilution at the point of discharge is estimated as 800:1.
- For discharge every 30 days, the long-term average dilution at the point of discharge is estimated as 1,400:1.

Results for AE

Active effluent (AE) will be discharged through the same structure as FED, but using a different discharge period of 45 minutes (and on different tides). The AE has a different density from FED and its initial dilution has been considered previously in Report EBR4908-RT009. The working assumption for the volume of the AE discharge batch is 28 m^3 (compared with 20 m^3 for the FED) and it will be discharged over a longer period of 45 minutes. A reference discharge period starting at HW+1 and running to HW+1.75 gives the dilutions summarised below.

Summary AE dilutions at 100 m from outfall

discharge	average instantaneous dilution	long-term average (compare EQS AA)	minimum (compare EQS MAC)
AE daily	700	22,400	250

Contents

Summary

Figures

Tables

1. Introduction

Magnox is undertaking a decommissioning programme at Bradwell nuclear power station. The site lies on the south side of the Blackwater Estuary in Essex, about 1 kilometre seaward of Bradwell Marina, and has been occupied as a power station since the early 1960s. This report provides a basis for assessing compliance of various waste streams produced during decommissioning against the relevant Environmental Quality Standard (EQS) concentrations. Ultimately, we present a dilution factor at the edge of the mixing zone (100 m from the discharge tower) that could be used to assess each discharge against the EQS values.

Three effluent streams are considered in this report:

- effluent from the dissolution of fuel element debris (FED discharge);
- liquors arising from the removal of oxides of nitrogen (NOx scrubber liquors);
- active effluent (AE).

The discharges are intermittent, so the average concentration of effluent at the edge of the mixing zone is less than the concentration during the discharge periods. It is shown in this report that to a very good approximation the reduction factor is the ratio of the discharge time to the total time. For a discharge of 0.5 hour each day, the additional factor is 0.5/24=1/48. (1/32 for a 45-minute discharge.)

The discharges are now expected to include an occasional discharge of effluent containing treated NOx scrubber liquors taking place a few times a year. The discharge will be made on separate days to the FED dissolution discharges, which will usually be made on a daily basis.

1.1. The discharges

1.1.1. FED

During decommissioning, the magnesium alloy that comprises the fuel element debris (FED) is being dissolved in nitric acid, abated to reduce certain constituents and released in a controlled batch operation to the Blackwater Estuary. A modelling study (report EX6399) was carried out in 2011 to investigate the dispersion in the estuary of FED effluent discharged though the existing outfall tunnel and tower. This study was updated in 2014 (Report EBR4908-RT011) to consider the combined effect of the released effluent with a gradual build-up in the estuary over time; this report presented estimates of the near field dilution of the effluent at the edge of a mixing zone that extended 100 m from the discharge point.

Due to the degree of silting within the existing discharge arrangements, Magnox has installed a new dedicated discharge system within the existing outfall structure. This removes the pumping of seawater prior to discharge. This dedicated outfall was described in report EBR4908-RT009. It is estimated that during the half-hour discharge period for FED effluent, the dilution ratio (concentration in the undiluted effluent divided by concentration in the estuary) at 100 m from the dedicated outfall would vary between about 240:1 on a typical neap tide and 1200:1 on a typical spring tide. The average over the spring-neap cycle is expected to be around 1,000:1. These values apply at the core of the discharge plume, which (again averaged over the spring-neap cycle) is expected to be about 20 m wide and 1.4 m thick.

1.1.2. NOx scrubber liquors

During the commissioning trials of the FED dissolution plant, improvements have been identified to optimise the NOx scrubber liquor arisings. The liquor contains trace radioactive 20-25%w/w nitric acid with metal constituents. It arises from the abatement of NOx emissions that are generated during the FED dissolution process. The liquor will be used as a part of the acid charge for the FED dissolution process, rather than having a separate waste effluent arising. This has no material change to the methodology described in this report; the same dilution factors apply to the FED effluent, and the pH of the discharge to the estuary will not be affected.

1.1.3. AE

Active effluent (AE) will be discharged through the same structure, over 45 minutes, but on different tides. The AE has a different density from FED and its initial dilution has been considered previously in Report EBR4908-RT009.

1.2. Discharge times

Times during the tide are generally described in hours after high water (HW). For example, 'HW+1' refers to the time one hour after high water.

Magnox's existing discharge permit defines a discharge window 'during the first 90 minutes of the ebb tide': HW to HW+1.5. This report shows that discharge periods during the latest part of this window give more favourable dilutions than are obtained closer to high water for discharges made through the new dedicated discharge system. To differentiate between them, we refer to the consented time as the 'discharge window' and the actual time when discharge occurs as the 'discharge period'. Several discharge periods are considered, some of which go outside the existing consented discharge window which relates to effluent that is pre-diluted with sea water prior to discharge.

1.3. Report structure

Section 2 of this report describes the general method used to establish background concentrations and applies to all the discharges. Section 3 presents the long-term average concentrations obtained using this method and Section 4 discusses the annual average values. Section 5 gives maximum predicted concentrations. Section 6 interprets these predictions in the context of nitrate concentrations.

Because the FED and NOx scrubber liquor discharges have similar hydrodynamic properties, they are considered together in Sections 3 to 6. Section 7 presents the equivalent results for the AE.

2. Assessment method for long-term averages

2.1. Contributions to the annual average

If the material that entered the estuary during one discharge were carried out into the North Sea and did not return, it would be possible to calculate the annual average simply by multiplying the average concentration during the discharge periods by the fraction of the total time that the discharge takes place. This simple approach would – in general – underestimate the average concentration because the discharged effluent forms a diffuse patch, some of which returns (at a much lower concentration) on the next flood tide, as illustrated in Figure 2.1.

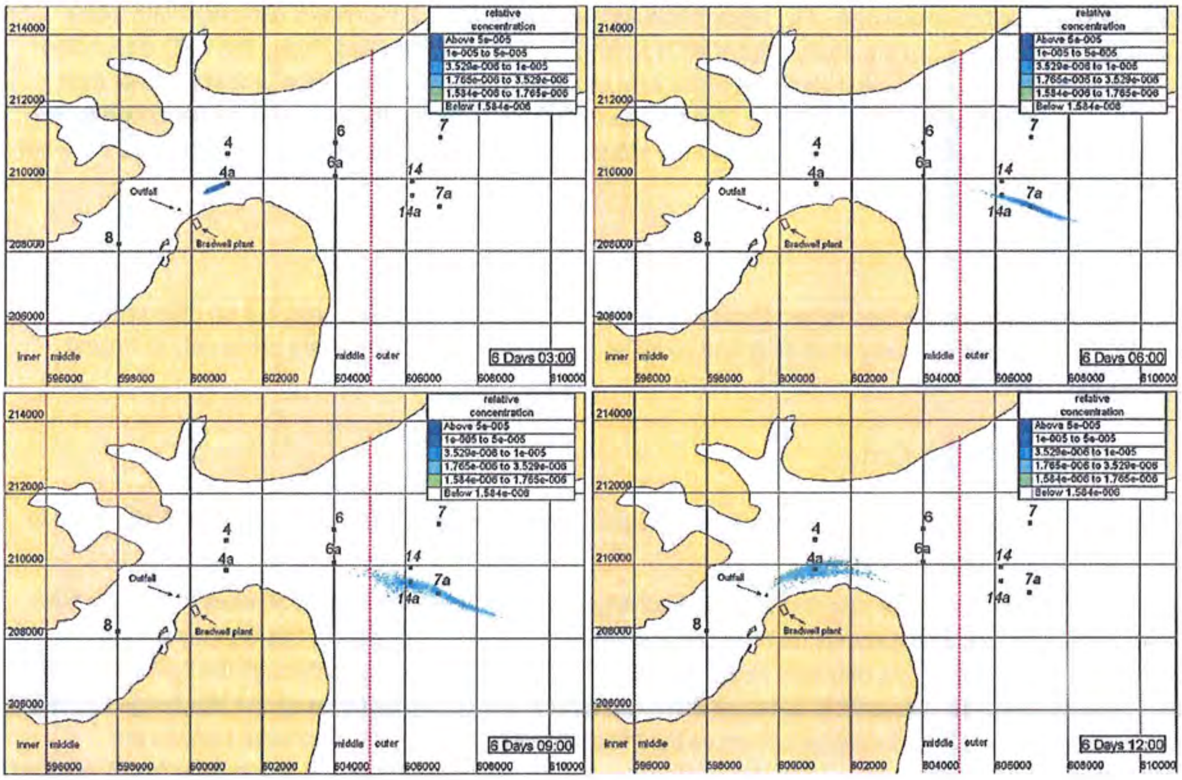

Figure 2.1: Representative movement of a single discharge patch during one tide

Source: Report EX6399

Over time, material may spread at an even lower concentration over much of the estuary, forming a low level background. As a result, the concentration at a point 100 m downstream of the discharge in the seaward direction has a sharp peak as the plume passes over, a lower broader increase as the returning patch passes over, and a low background concentration. This is illustrated in the sketch in Figure 2.2, which is derived from the same dispersion model as was used in report EX6399, using the revised pumping rate of 40 m^3/h. Figure 2.2 shows the variation with time of the relative concentration. Relative concentration is the concentration expressed as a fraction of the concentration in the final delay tank: a relative concentration of 1×10^{-3} corresponds to a dilution of 1,000:1. As there is one discharge per day, but two tides, the patch returns once about mid-way between the discharges and once just before the next discharge.

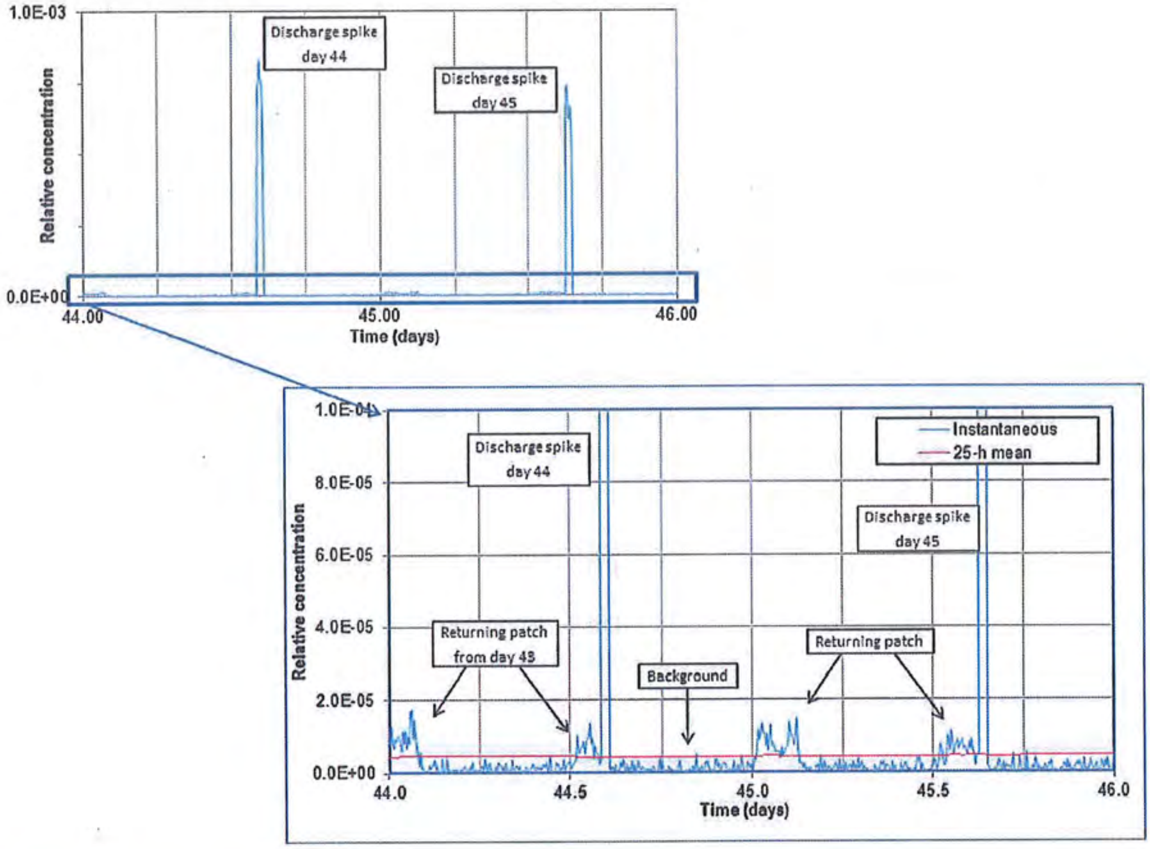

Figure 2.2: Variation of relative concentration 100 m from the discharge tower, after 1.5 months with daily discharge

2.2. Variation through the spring-neap cycle

As the range of the tide and the strength of the tidal streams vary through the spring-neap cycle, the dilution of the discharge also varies, leading to higher concentrations during neap tides and lower concentrations during spring tides. Also the extent to which the returning patch affects the concentration at the edge of the mixing zone varies with the tide, in particular with the relative ranges of successive tides. The overall pattern of daily peaks and background at the point 100 m downstream from the discharge point is shown in Figure 2.3, which is derived from the same dispersion model as was used in report EX6399, using the revised pumping rate of 40 m^3/h.

Note that there are two sets of spring tides and two sets of neap tides during a lunar month of approximately 28 days, but in general within one month the first set of springs has a different range from the second set of springs, and similarly for the neaps. In this report the phrase 'spring-neap cycle' is used to refer to the (approximately) 28-day cycle, which is closer to a truly repetitive cycle.

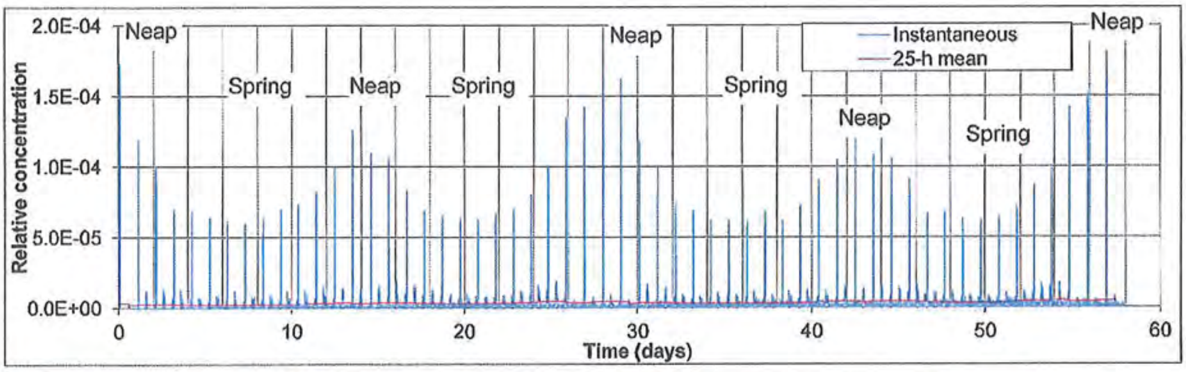

Figure 2.3: Variation of relative concentration 100 m from the discharge tower through the spring-neap cycle

In this assessment the effect of the contributions to the overall average, in particular the returning patch and background, is calculated using the same dispersion model as was used in report EX 6399, using the revised pumping rate of 40 m^3/h.

2.3. Contributions from successive spring-neap cycles

An approach was developed in report EX6399 to estimate the build-up of total nitrate in the estuary during the operation of the FED discharge. A dispersion model was used to simulate the dispersion of discharges over two spring-neap cycles and the total amount of effluent present in the estuary was monitored through the simulation. Simulations were carried out for a single discharge and for successive (daily) discharges. The two spring-neap cycles were, in fact, a single (approximately 28-day) spring-neap cycle repeated. This is a reasonable approximation to two successive natural 28-day spring-neap cycles and, importantly, using the repetition approach allows the contribution of the first cycle's discharge to the effluent concentrations predicted during the second month to be evaluated.

Approximately 78% of the material discharged during one spring-neap cycle was lost to the North Sea during that cycle. Approximately 36% of what remained was lost during the second cycle. Extrapolating forward using this loss rate of 36% per month generated a geometric series in which the content at a particular time includes the material discharged during that month plus a set of decreasing contributions from the previous months. The approach enabled estimation of the total amount of nitrate at the end of the FED process (6% of the total amount discharged) and the rate of reversion to normal. The loss rate of 36% per month corresponds to a characteristic exponential decay time (τ in the expression $C = C_o e^{-t/\tau}$) of about 2.75 months ($1/0.36 \approx 2.75$). This is equivalent to a residence half-life in the estuary of 2 months and a time to lose 90% of the material, T_{90}, of 6.5 months. This is illustrated in Figure 2.4.

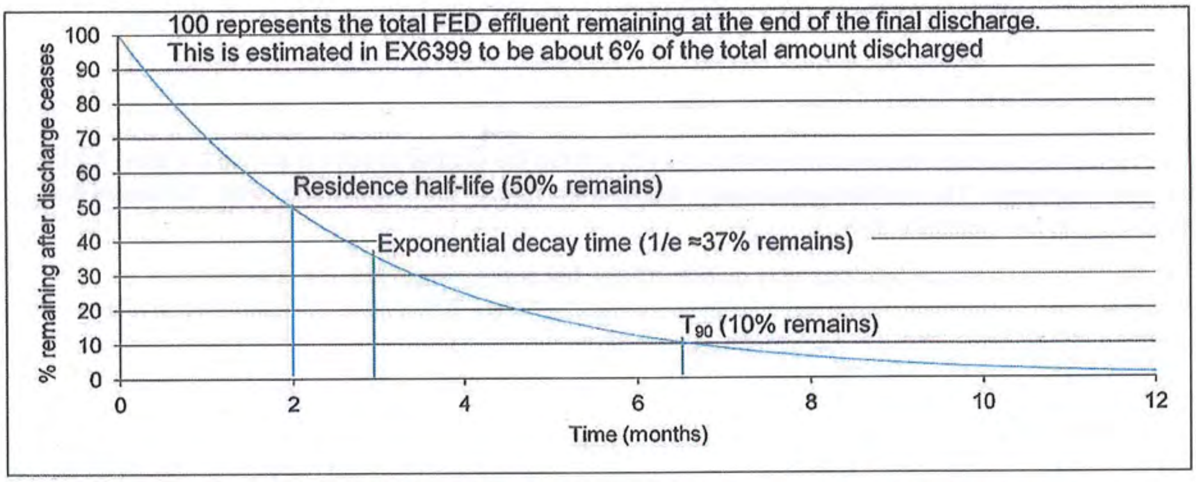

Figure 2.4: Illustration of exponential loss of FED material from the estuary after discharge ceases

A similar 'decay time' approach has been adopted here, but based on re-analysis of the dispersion model results at a location 100 m downstream of the discharge point. In this case the measure used in the geometric series is the cumulative average concentration at the 100-m point, rather than the total amount of material in the estuary.

The effect of discharging at intervals of 17 or 28 days was considered on the basis of the loss of material from a single discharge, which is also presented in report EX6399, and additional model runs.

Because the initial dilution obtained by the dedicated discharge structure is lower than that provided by the predilution used with the existing outfall structure (Report EBR4908-RT011) the concentrations predicted for each fresh discharge at 100 m from the outfall are higher than in the previous case. In fact, they are sufficiently high that the returning concentrations may now be neglected when presenting the dilution factors to a reasonable level of accuracy. This is discussed in Section 4.2.

2.4. Summary

- The discharge will be washed out to sea by the tide, but some of it will return when the tide turns. The total effluent concentration at a point 100 m downstream of the discharge has 3 components:
  - a 'spike' from the fresh discharge (during discharge only);
  - a smaller contribution from the 'patch' formed by previous discharges returning with the tide;
  - a very small background contribution from diffused older discharges.
- The spikes will vary with the size of the tide – higher concentrations on smaller tides – but the patch and background concentrations vary only a little.
- Over the operational period, concentrations will build up as more FED effluent is released – at the end of the process about 6% of the total effluent will remain, spread over the estuary. After that, it will gradually be washed out, with just over 1/3 of the remaining effluent being removed each month.
- After 6.5 months, around 10% (of the original 6%) remains; after a year it is almost completely removed.

3. Results for FED effluent / NOx Scrubber Liquor

3.1. Daily discharges

The cumulative average relative concentration at 100 m from the discharge point is shown in Figure 3.1 for the daily discharge. The cumulative average is the time-average of the concentration from the start of the discharges to any particular time.

It is seen that the average builds up very quickly initially, because to begin with the concentration is averaged over a short time, which includes the very first discharge. Thereafter, the cumulative average builds up much more gradually to approach a true long-term average.

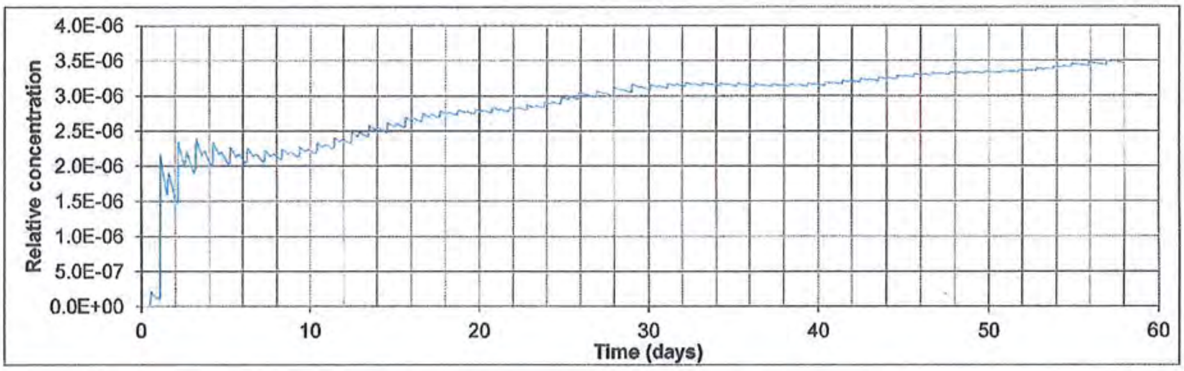

Figure 3.1: Cumulative average relative concentration at 100m from the discharge tower for a daily discharge

For the daily discharge, the cumulative average relative concentration increases from 3.15×10^{-6} at the end of the first spring-neap cycle to 3.47×10^{-6} at the end of the second, an increase of 11.8%. Since the second cycle in the model is a repeat of the first, the contribution from the second cycle to the average is (to a very good approximation) the same as the average after one cycle. Therefore the 11.8% increase is the contribution from the residual material discharged in the first cycle that is still present during the second cycle (i.e. the background build-up). Using the geometric series increase approach, as established in report EX6399, we then assume that in the third cycle the contribution from background will increase a further 11.8% (of the 11.8%). The overall concentration after the third cycle will therefore be:

$$1 \text{ (from cycle 3)} + 11.8\% \text{ (from cycle 2)} + (11.8\%)^2 \text{ (from cycle 1)}$$

times the concentration after the first cycle. Extrapolating forward again generates a geometric series of the form $1 + 0.118 + 0.118^2 + 0.118^3 + \ldots$ The sum to infinity of this series is $1/(1-0.118) = 1.13$. This suggests that the equilibrium cumulative average after many spring-neap cycles would be 1.13 times the value after one cycle which corresponds to a relative concentration of approximately 3.5×10^{-6} (dilution of 285,000:1). The extrapolation forward is shown in Figure 3.2.

The figures above were calculated assuming discharge during the preferred discharge period (HW+1 to HW+1.5). For discharges later in the tide (up to HW+2.5), more of the effluent may be retained in the estuary – up to twice as much for any individual release. If – in a very pessimistic assumption – all of the releases were to be later (still up to HW+2.5), the limiting relative concentration would then be around 5.0×10^{-6} (dilution of 200,000:1).

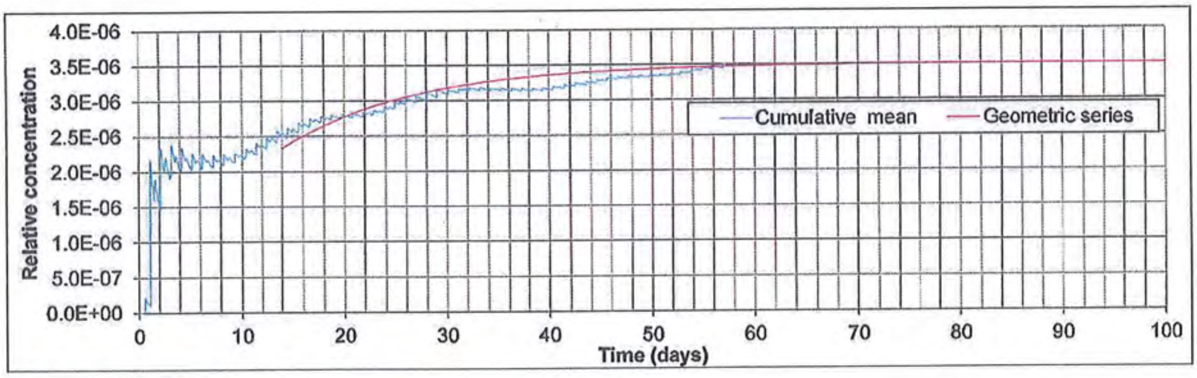

Figure 3.2: Extrapolation forward of the average concentration

3.1.1. Improved estimate

If we examine the average concentration at a location southwest of the discharge (i.e. the upstream direction during the FED discharges) we see the effect of returning patch and background without the spikes caused by the individual discharges. This shows that the background builds up in a similar way to the concentration at the downstream point, as shown in Figure 3.3. The final equilibrium value is lower than at the point 100 m downstream because the discharge spikes do not influence the concentration directly. The average concentration downstream of the discharge can be estimated by calculating the weighted average of the upstream (background) concentration from Figure 3.3 (24 hours out of 24) and the intermittent spikes (0.5 hours out of 24). This alternative calculation indicates that the long term average dilution is 96 times the dilution during discharge on a neap tide.

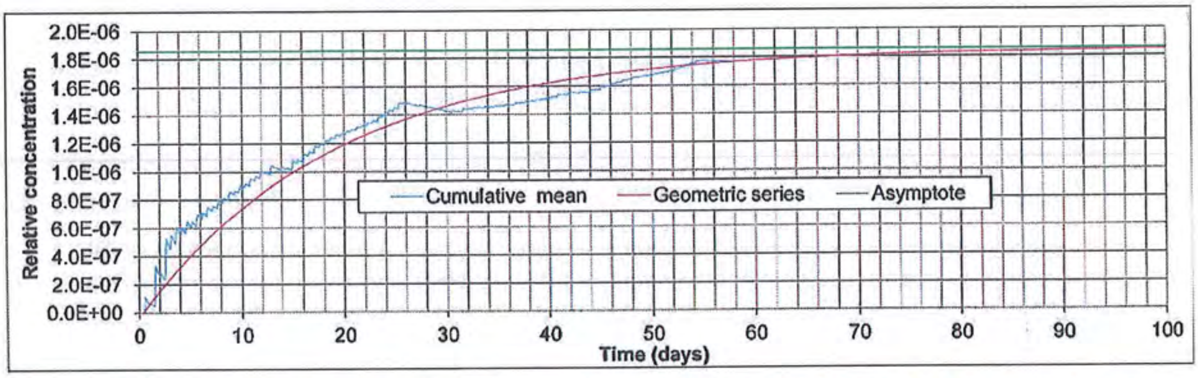

Figure 3.3: Average concentration and extrapolation forward at a point upstream of the discharge tower

As with the downstream values, the returning concentrations are somewhat higher for later discharge periods, but the increase is less than a factor of two. For the calculations presented in Table 3.1 this change is negligible.

3.2. Discharges at 17- and 28-day intervals

The dispersion model was also run for discharges at 17- and 28-day intervals. The concentration at the point 100 m downstream from the discharge tower is shown in Figure 3.4 and Figure 3.5. The discharge in both cases is at an interval of several days and nearly all the discharged material has cleared the estuary by the time of the next discharge. It was shown in report EX6399 that about 15% of material from a single discharge remains in the estuary after 17 days and about 12% after 28 days. Therefore, the build-up of background concentration and impact of previous returning patches is very much reduced compared with the daily discharge. The heights of the spikes and the number of times the patches return will depend on the stage in the spring-neap cycle that the discharges occur.

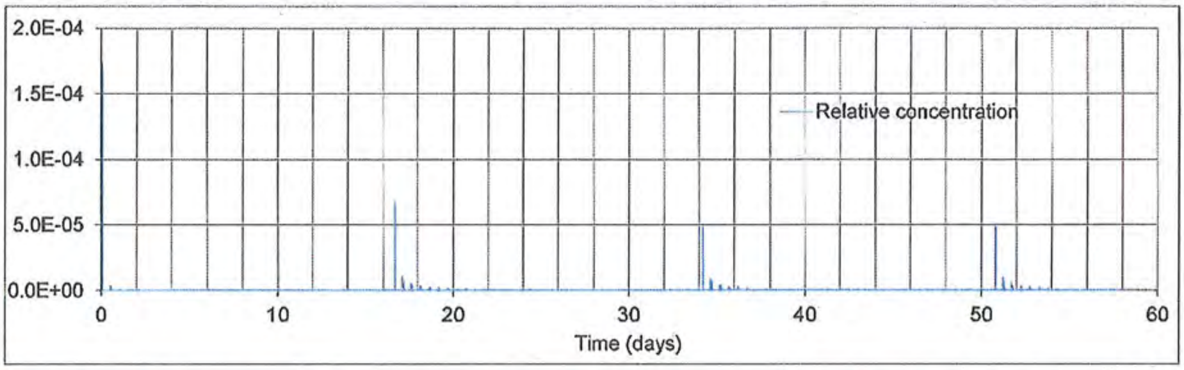

Figure 3.4: Variation of relative concentration 100 m from the discharge tower for a 17-day discharge interval

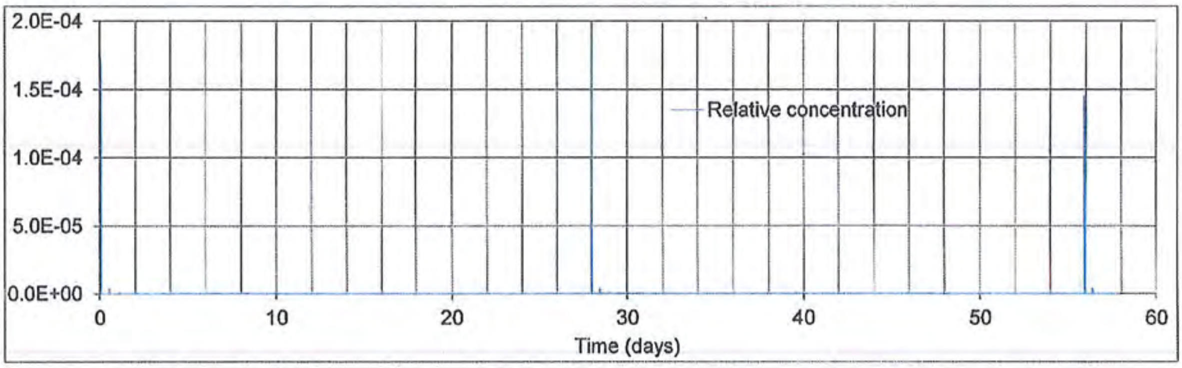

Figure 3.5: Variation of relative concentration 100 m from the discharge tower for a 28-day discharge interval

For the 17- and 28-day discharge intervals, the geometric series approach cannot be applied so readily because the discharge interval does not fit in with the spring-neap cycle, and also there are only a few discharges within the simulation. However, it would still be expected that on average the concentration would build up (from a lower level) in a similar decreasing increments to those identified in Section 3.1: 11.8% on the first spring-neap cycle, 1.4% on the second, etc. This rate of build-up is also consistent with the rate of loss from a single discharge mentioned above.

These values refer to the intermittent discharges in isolation, and would be appropriate for any component of the intermittent discharge that was not present in any other effluent stream. This is not the case, as the metals in particular are also present in the FED. The interaction between the FED and NOx scrubber discharges is discussed in section 4.1.1.

3.3. Summary

Table 3.1 summarises the (instantaneous) initial dilutions obtained at 100 m from the outfall.

In the table:

- 'Background relative concentration' is the concentration value described in the sections above; that is, the returning concentration of effluent.
- 'Equivalent background dilution' is the dilution factor corresponding to this relative concentration.
- 'Tidal-average initial dilution' is the initial dilution obtained by the outfall structure during discharge, averaged over the discharge periods of the full spring-neap tidal cycle.
- 'Effective relative concentration' is the relative concentration at 100 m, obtained by combing the initial dilution with the background relative concentration.
- 'Equivalent dilution' is the dilution factor corresponding to the effective relative concentration.

This table illustrates clearly that the returning concentrations are negligible within the accuracy of reporting the dilution values; this observation is true for discharge at any point in the proposed discharge window.

Table 3.1: Predicted average FED effluent/NOx Scrubber Liquor initial dilutions at 100 m

discharge	background relative concentration	equivalent background dilution	tidal-average initial dilution	effective relative concentration	equivalent dilution
daily	1.87×10^{-6}	534,800	1000	1.00×10^{-3}	1000
17 days	1.60×10^{-7}	6,250,000	1000	1.00×10^{-3}	1000
28 days	5.80×10^{-8}	17,241,400	1000	1.00×10^{-3}	1000

Note: These 'equivalent dilution' values are instantaneous values predicted during discharge.

4. Annual Average predictions

4.1. Average dilution 100 m downstream from the discharge tower

The minimum initial dilution predicted for FED effluent / NOx scrubber liquor during the discharge period with the dedicated discharge is around 240:1 (on neap tides). The average over a spring-neap cycle is expected to be around 1,000:1.

Applying the time-average factors for a half-hour discharge period (48 for daily discharge, 816 for a 17-day interval and 1,344 for a 28-day interval) and rounding the result, compliance against the EQS annual average (AA) may be calculated by assessing the discharge concentration contribution to the AA. This is done by dividing the concentration in the final monitoring and delay tank by the relevant dilution factor. The determination of the long term average provides a reasonable basis for assessing the EQS AA because this represents the exposure of the biota to accumulation (although as noted above the returning concentrations may in fact be neglected). For discharges:

- Every day, the long-term average dilution at 100m is estimated as 48,000:1.
- Every 17 days, the long-term average dilution at 100m is estimated as 800,000:1.

- Every 28 days, the long-term average dilution at 100m is estimated as 1,300,000:1.

Dilution values are relative to the concentration in the liquors. These may be used to convert the discharge concentrations into values which can be compared with EQS AA limits.

A discharge interval of about 14 or 28 days for the NOx scrubber liquor would allow the operators always to discharge on spring tides, which would provide further increases in the average dilution ratio.

Table 4.1: Predicted long-term average FED effluent/NOx Scrubber Liquor dilutions at 100 m

discharge	tidal-average initial dilution	long-term average dilution
daily	1000	48,000
17 days	1000	800,000
28 days	1000	1,300,000

4.1.1. Combined effect of FED and NOx discharges

Instead of looking at the NOx scrubber liquor as a separate stream to the FED, discharging at intervals of several days, we can consider a regular daily discharge, but with amended composition. For discharge of the NOx liquor every n days, the average concentration of any metal would be:

$$C_{av} = [(n-1)C_{FED} + C_{NOx}]/n$$

where C_{FED} is the concentration in the FED liquor and C_{NOx} is the concentration in the NOx scrubber liquor. (This assumes the volume of the FED batch discharge is equal to the volume of the NOx scrubber liquor batch. If this were not the case a simple adjustment could be made to the equation.)

Assuming the NOx scrubber liquor is discharged at random in the spring neap cycle (though always just after high water), the annual average concentration of this metal at the edge of the mixing zone would then be C_{av} divided by the long-term average dilution for the daily discharge, D_{av}, estimated above as 48,000:1.

If the target for annual average concentration of the process contribution is less than 4% of the EQS concentration, C_{EQS}, (i.e. the insignificance threshold defined by the Environment Agency), then for compliance:

$$C_{av} / D_{av} < 0.04\ C_{EQS}$$

$$[(n-1)C_{FED} + C_{NOx}]/(n\ D_{av}) < 0.04\ C_{EQS}$$

$$C_{NOx} < 0.04\ n\ D_{av}\ C_{EQS} - (n-1)C_{FED}$$

As long as the concentration in the FED liquor is known, the equation above gives the maximum concentration in the NOx liquor for compliance at the edge of the mixing zone.

For extra conservatism, the long-term average dilution D_{av} can be replaced with the time-average of the minimum (neap tide) dilution. In this case the resulting dilution factor would be 240:1 x 48 which is around 11,500:1.

Combined effect of FED and NOx scrubber liquor

The simplest way to ensure compliance with the regulations is to ensure that the diluted concentration of each constituent in every discharge is below the Environment Agency's no-significance threshold of 4% of the EQS value.

If this is not possible for a particular batch of NOx scrubber liquor discharge, the maximum allowable concentration of any constituent is:

$$n \times D_{av} \times 0.04 \times C_{EQS} - (n-1) \times C_{FED}$$

where:

n is the number of days since the last NOx scrubber liquor discharge;

D_{av} is the long-term time-average dilution, 48,000;

$0.04 \times C_{EQS}$ is the Environment Agency's no-significance threshold (4% of the EQS value);

C_{FED} is the concentration of the relevant constituent in the FED discharge – if this varies from day to day, the average value since the previous NOx scrubber liquor discharge should be used.

4.2. Average dilution at the outfall

The previous sections estimate the annual average dilution at a point 100 m downstream of the outfall. During the discharge period, the effluent will emerge at the same concentration as in the final delay and monitoring tank. It will then mix rapidly with the estuary water over a small area, due to the high turbulence produced by its exit velocity.

The water that the new effluent mixes with has a slightly raised concentration from the previous releases. This is estimated (from the concentration upstream of the tower described in report EBR4908-RT011) as a relative concentration of 1.9×10^{-6} for a daily discharge, 1.6×10^{-7} for a 17-day discharge interval and 5.8×10^{-8} for a 28-day interval.

- The annual average relative concentration at the point of discharge (that is, the effective time-averaged concentration in the estuary divided by concentration in the final monitoring and delay tank) is estimated as 24 hours per day (100% of the time) of the background concentration plus 0.5 hours per day, per 17 days or per 28 days of the discharge concentration (2.1%, 0.12% or 0.074% of the time). For FED discharge every day the average relative concentration at the point of discharge is estimated as $1.9 \times 10^{-6} + 1 \times 0.021 = 0.021$ and the dilution is around 50:1.
- For NOx scrubber liquor discharge every 17 days the average relative concentration at the point of discharge is estimated as $1.6 \times 10^{-7} + 1 \times 0.0012 = 1.2 \times 10^{-3}$ and the dilution is 800:1 at the edge of the mixing zone (i.e. 100 metres from the point of discharge).
- For NOx scrubber liquor discharge every 28 days the average relative concentration at the point of discharge is estimated as $5.8 \times 10^{-8} + 1 \times 0.00074 = 7.4 \times 10^{-4}$ and the dilution is 1,300:1 at the edge of the mixing zone.

In fact within the accuracy of reporting of these numbers, the background concentration is negligible.

4.3. Other discharge periods

As noted previously, we have considered a discharge period for FED effluent / NOx scrubber liquor from HW+1 to HW+1.5. For practical reasons, it is desirable to have some flexibility in the discharge time. Therefore we have considered the effects of discharging at other periods in the early phase of the ebb tide. Table 4.2 summarises the results. As before, the average values are calculated over all the equivalent discharge periods in a spring-neap cycle. The maximum and minimum values are instantaneous, and calculated over a spring-neap cycle. Earlier in the ebb tide, poorer initial dilutions are predicted, while later in the tide they are much the same, or better, at least until HW+2.5.

The initial dilution for a discharge starting at High Water (the beginning of the existing consented discharge window) is poorer for discharges made through the new dedicated discharge system, than in the 'preferred' discharge period, because the low current speeds at High Water give little mixing of the effluent. In particular, the minimum dilution is rather low.

The average initial dilution in the period HW+0.5 to HW+1 is only slightly lower than that in HW+1 to HW+1.5. It may therefore be acceptable to adopt HW+0.5 as the preferred start of the discharge period. Then a short delay (up to 30 minutes) in starting the discharge stream would be accommodated within the existing discharge window. The retention of effluent within the estuary is broadly similar for any of these discharge times.

Alternatively, it may be preferable to apply to use the later phase of the tide, which offers initial dilutions comparable to those in HW+1 to HW+1.5. For example, retaining the same length of discharge window (90 minutes) but starting one hour after High Water (that is, HW+1 to HW+2.5) instead of at High Water would allow the 'preferred' discharge period to be used under normal conditions but allow flexibility to accommodate minor operational hitches such as pump trips, and achieve essentially the same initial dilution performance.

We note that the existing discharge period (HW to HW+1.5) was established for the original discharge method, which used a pre-dilution system to mix the effluent with a large volume of seawater prior to discharge. In that case, initial dilution in the estuary was not required and it was possible to discharge at HW to obtain the best possible flushing from the estuary. Therefore the existing discharge window from HW to HW+1.5 was appropriate for that configuration. With the proposed dedicated discharge, pre-dilution is not available, and it is better to delay the discharge time so that the ebb current speeds can build up enough to provide initial dilution, while still maintaining good flushing from the estuary.

Table 4.2: FED dilution at 100 m for different discharge periods

Discharge period		Dilution		
Start	End	Minimum	Average	Maximum
HW	HW+0.5	10	400	1000
HW+0.5	HW+1.0	100	800	1200
HW+1.0	HW+1.5	240	1000	1200
HW+1.5	HW+2.0	500	1000	1200
HW+2.0	HW+2.5	500	1000	1200
HW+2.5	HW+3.0	500	900	1200

Note: *Minimum and maximum values are instantaneous and calculated over a full spring-neap cycle.*
Average values are calculated over all equivalent discharge periods for a spring-neap cycle.

4.4. Retention of metals in the estuary

Using the retention calculations from report EX6399 (also summarised in Section 2) about 6% of the total material discharged during the FED process will remain in the estuary at the end of the FED programme; it will then be gradually dispersed to the sea. It will take just over 6 months for 90% of this to be lost from the estuary. This estimate neglects all chemical or sedimentation losses.

Therefore for every kilogramme of a particular metal released, 60 grammes is predicted to remain at the end of the FED process, spread widely over the estuary, reducing to about 6 grammes after 6 months.

The figures above were calculated assuming discharge during the preferred discharge period. For earlier discharges flushing of effluent from the estuary is similar or better. For discharges later in the tide (up to HW+3), more of the effluent may be return to the estuary when the tide turns. The results shown in report EBR4908-RT010 suggest this may be up to twice as much for an individual release (about 40% instead of about 20% of the discharged mass). Over the longer term, of course, the effect of an individual late release would be reduced, and the difference is likely to be negligible.

Discharge times for FED and NOx scrubber liquor

The results presented here and in report EBR4908-RT010 suggest that discharge periods starting at HW+1 will give the best compromise between a strong initial dilution and good flushing out of the estuary. Discharge slightly later in the ebb tide will give similar initial dilutions, but would allow more of the effluent to return to the estuary when the tide turns.

We therefore suggest that in its application for revised consent, Magnox should request a discharge window from HW+1 to HW+2.5 (aiming to discharge where practical in the earlier part of this window).

5. Maximum Allowable Concentrations (MAC)

The maximum concentration predicted at 100 m from the outfall corresponds to the minimum predicted dilution (which occurs on the neap tides) corrected for the background build-up. For example, for the FED effluent, the minimum predicted dilution is 240:1 and the background relative concentration for release every day is 1.87×10^{-6}. The overall concentration at the 100-m point is therefore 239 parts of the background plus 1 part of the discharge concentration, giving the weighted average:

$(239 * 1.87\times10^{-6} + 1 * 1) / 240 = 4.17\times10^{-3}$;

which is equivalent to a dilution of 240:1.

Minimum dilution values for the various discharge options are summarised in Table 5.1. These dilution factors may be used to convert the discharge concentrations into values which can be compared with EQS MAC limits.

As with the annual average concentrations, the background build-up is negligible in comparison to the discharge spike.

Table 5.1: Predicted minimum dilutions at 100 m

discharge	background relative concentration	equivalent background dilution	minimum initial dilution	maximum relative concentration	equivalent dilution
daily	$1.87\text{x}10^{-6}$	534,800	240	$4.17\text{x}10^{-3}$	240
17 days	$1.60\ \text{x}10^{-7}$	6,250,000	240	$4.17\text{x}10^{-3}$	240
28 days	$5.80\ \text{x}10^{-8}$	17,241,400	240	$4.17\text{x}10^{-3}$	240

6. Nitrates

The dilution calculations, and the observations on metal concentrations, made in this report, apply equally to nitrates in the effluent streams. However it is discharged, the loading to the estuary remains the same as previously considered in report EBR4908-RT010.

- When FED discharge finishes, the localised peak concentrations near the outfall will immediately be eliminated.
- About 6% of the total material discharged during the FED process will remain in the estuary at the end of the FED programme. For every kilogramme of nitrate released, up to 60 grammes is predicted to remain at the end of the FED process, reducing to about 6 grammes after 6 months. (As before, these values refer to the preferred discharge period.) It will be widely dispersed over the estuary and will then be gradually flushed out to sea. Residual nitrate concentration in the estuary will gradually reduce back to the background concentration.
- The FED discharge is predicted to increase the average nitrate concentration (outside the main plume) in the Blackwater Estuary by less than 10% of the background value.
- Neglecting chemical/biochemical losses such as uptake by plants in the estuary, it would take just over 6 months for 90% of the remaining nitrates to be lost from the estuary.
- Allowing for background processes removing nitrates from the estuary, the period required is estimated at a few (perhaps three) months.

7. AE dispersion

Magnox intends to discharge its Active Effluent (AE) through the same outfall as the FED. Because the AE has different properties from the FED effluent, its dilution behaviour will be different. In particular, the AE is less dense than the ambient water in the estuary, so it will tend to float towards the surface, whereas the FED is more dense and tends to sink, The discharge configuration was previously considered in Report EBR4908-RT009.

The volume of the AE discharge batch is 28 m^3 (compared with 20 m^3 for the FED) and it will be discharged over a longer period of 45 minutes. (Report EBR4908-RT009 considered only 30 minutes.) Calculations were revised using a reference discharge period starting at HW+1 and running to HW+2.5. The minimum initial dilution predicted during this discharge period is predicted as around 250:1 (on neap tides) and the maximum close to 1200:1 (on spring tides). The average over a spring-neap cycle is calculated to be around 700:1.

The tables in this section summarise the dilution and relative concentrations for AE, which have been calculated using the same techniques as the values for FED described in previous sections.

Table 7.1: Predicted average AE initial dilutions at 100 m during discharge

discharge	background relative concentration	equivalent background dilution	tidal-average initial dilution	effective relative concentration	equivalent dilution
AE daily	$2.8\text{x}10^{-6}$	359,000	700	$1.43\text{x}10^{-3}$	700

Note: *These 'equivalent dilution' values are the average values predicted during discharge (i.e. for no more than 45 minutes on any day).*

Table 7.2: Predicted long-term average AE dilutions at 100 m

discharge	tidal-average initial dilution	long-term average dilution
AE daily	700	22,400

Table 7.3: Predicted minimum AE dilutions at 100 m during discharge

discharge	background relative concentration	equivalent background dilution	minimum initial dilution	maximum relative concentration	equivalent dilution
AE daily	$2.8\text{x}10^{-6}$	359,000	250	$4.00\ \text{x}10^{-3}$	250

As for FED, the effects of discharging AE at other times within and outside the presently consented discharge window have been assessed. Table 7.4 shows the results (as before, averaged over the corresponding discharge periods across the spring-neap cycle). These results indicate that discharging later in the ebb tide will give similar dilutions to the preferred discharge period. Discharging earlier is predicted to give similar average dilutions, but the minimum dilutions are poorer - particularly close to HW, as low current speeds are unfavourable for initial dilution.

Table 7.4: Effect of different discharge periods for AE

discharge period		dilution at 100m		
start	end	minimum	average	maximum
HW	HW+0.75	100 *	500	1200
HW+0.75	HW+1.5	200	700	1200
HW+1.0	HW+1.75	250	700	1200
HW+1.75	HW+2.5	300	600	1100

* *Predicted dilutions at HW are uncertain as initial dilution is not well defined at low current speeds.*

Discharge times for AE

As for FED (section 4.3), the results presented here and in report EBR4908-RT010 suggest that discharge periods starting at HW+1 will give the best compromise between a strong initial dilution and good flushing out of the estuary. Discharge slightly later in the ebb tide will give similar initial dilutions, but would allow more of the effluent to return to the estuary when the tide turns.

We therefore suggest that in its application for revised consent, Magnox may request a discharge window from HW+1 to HW+2.5 (aiming to discharge where practical in the earlier part of this window). This is the same definition as for FED / NOx scrubber liquor, but will presumably occur on different tides.

8. Conclusions

Due to the degree of silting within the existing discharge arrangements, Magnox has installed a new discharge system within the existing outfall structure. . This report has described the dilution and dispersion of FED, NOx scrubber and AE effluents through this dedicated outfall, drawing on HR Wallingford's previous work at the site.

The discharges are intermittent, so the average concentration of effluent at the edge of the mixing zone is very much less than the concentration during the discharge periods. This report presents a method for assessing compliance against the Environmental Quality Standard (EQS) Annual Average (AA) concentration and Maximum Allowable Concentration (MAC) by establishing a dilution factor at the edge of the mixing zone (100 m from the discharge tower) that can be used to assess each discharge's contribution to the EQS AA and MAC.

Results for FED effluent and NOx Scrubber Liquor

The FED effluent and NOx Scrubber Liquor have similar hydrodynamic properties and will be discharged in batches of 20 m^3 over 30 minutes during the discharge window. The table below summarises the dilutions predicted for discharge from HW+1 to HW+1.5.

Summary FED effluent and NOx Scrubber Liquor dilutions at 100 m from outfall

discharge	average instantaneous dilution	long-term average (compare EQS AA)	minimum (compare EQS MAC)
daily	1000	48,000	240
17 days	1000	800,000	240
28 days	1000	1,300,000	240

It should be noted that the dilution values given above at 100 m from the discharge point refer to the dilution at the core of the discharge plume. They apply, therefore, to a region a few tens of metres across and up to two metres thick, close to the estuary bed. The depth-average dilution would be significantly higher.

Results for AE

AE will be discharged in batches of 28 m^3, through the same structure as FED, but using a different discharge period of 45 minutes (and on different tides). The AE has a different density from FED. A reference discharge period starting at HW+1 and running to HW+1.75 gives the dilutions summarised below.

Summary AE dilutions at 100 m from outfall

discharge	average instantaneous dilution	long-term average (compare EQS AA)	minimum (compare EQS MAC)
AE daily	700	22,400	250

Discharge period

The results presented in this report, together with those in report EBR4908-RT010, suggest that the optimum time for discharge is just after HW+1 (that is, using a discharge period that starts one hour after high water).

This preferred discharge period offers a compromise between a good initial dilution and good flushing of effluent out of the estuary:

- Earlier in the ebb tide, the initial dilutions are lower; later in the tide they are higher.
- The flushing is very good for any time within 2 hours of HW.
- For an individual discharge up to 3 hours after HW, up to twice as much effluent may return to the estuary as for the same discharge during the preferred discharge period; that is to say, more of the material discharged on one ebb tide might return on the following flood. After several months, any individual later release is likely to have a negligible impact on the total amount of effluent retained.

For FED and NOx Scrubber Liquor, the preferred discharge period is the very end of the present consented discharge window. We suggest that Magnox may request a revision to the consented discharge window. Retaining the same length of discharge window (90 minutes) but starting one hour after High Water (that is, HW+1 to HW+2.5) instead of at High Water would allow the preferred discharge period identified in this report to be used under normal conditions, and provide flexibility to accommodate minor operational hitches such as pump trips while achieving similar initial dilution and flushing performance.

For AE, the fundamental conclusion is similar to that for the other effluents: the preferred discharge period starts at HW+1, and we suggest a discharge window from HW+1 to HW+2.5.

Summary

The main aim of this study was to identify the preferred times for discharging FED, NOx scrubber liquor and AE.

The FED and NOx scrubber liquor have similar hydrodynamic properties. A discharge period from HW+1 to HW+1.5 gives good initial dilution for these effluents and good flushing from the estuary. We suggest that this is the preferred discharge period, and that Magnox should request consent to discharge during a window from HW+1 to HW+2.5 when submitting their application for the new dedicated discharge system.

The AE has different properties from the FED and NOx scrubber liquor, but the results shown here lead to a similar conclusion. The best discharge period is from HW+1 to HW+1.75, and we suggest that Magnox should request the same discharge window as for the other effluents – from HW+1 to HW+2.5.

9. References

Bradwell Power Station – FED discharge dispersion. Report EX6399, R4.0, HR Wallingford Ltd, June 2011.

Bradwell Power Station – Effluent discharge arrangements: Initial dilution. Report EBR4908-RT009-R04-00, HR Wallingford Ltd, March 2014.

Bradwell Power Station – FED discharge arrangements: Far-field dispersion. Report EBR4908-RT010-R04-00, HR Wallingford Ltd, March 2014.

Bradwell Power Station – Annual average concentration of FED constituents. Report EBR4908-RT011-R02-00, HR Wallingford Ltd, July 2014.