CoRWM

Committee on Radioactive Waste Management

CoRWM PAPER

# GDF HIGH LEVEL COST REVIEW

October 2022

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HS2 – Chiltern Tunnel
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# 1 Executive Summary

1.1 The Committee on Radioactive Waste Management (CoRWM) has undertaken a high-level review and assessment of the potential construction and operational costs for a geological disposal facility (GDF). This process has involved the use of extensive underground construction, project management, and nuclear waste regulation experience to provide an order of magnitude estimate which is based on a number of key assumptions as set out in the paper.

1.2 This exercise has allowed a comparison of our cost estimates with those recently published by Nuclear Waste Services (NWS) for the full potential inventory.

1.3 There is a £1.6 billion differential between the NWS and CoRWM lower range estimates (without any additional contingency being included) and a significant differential at the higher range in the order of £16.7 billion.

1.4 CoRWM acknowledges that NDA/NWS have produced cost estimates that recognise uncertainties due to GDF location and inventory, and that they have used guidance issued by HM Treasury on how to appraise policies, programmes and projects. The CoRWM model relies on expert judgement and current experience of modern tunnelling techniques and their impact on costs and schedules. CoRWM also anticipates further advances in tunnelling techniques in the period before construction commences.

1.5 The magnitude of the difference between the NDA/NWS and CoRWM upper bound estimates suggests the need for further discussion to understand the sensitivity of the assessments to the most significant assumptions.

# 2 Foreword

2.1 This CoRWM paper has been produced in order to encourage debate on the issues relating to the estimated cost envelope for the construction and operation of a GDF in the UK.

2.2 CoRWM has undertaken a high-level review and assessment of the potential construction and operational costs for a GDF, using 2021 costings of modern and well proven methods of underground construction, equipment and operations.

2.3 These high-level assessments have been benchmarked against current UK and international infrastructure projects currently under construction, with relevant references and illustrations included where appropriate.

2.4 This estimate has used a series of key assumptions to arrive at the order of magnitude assessment. These have been defined and are set out in the document.

2.5 In February 2022 NWS published its GDF Annual Report (2020-2021)[1], which included updated cost information ). The 'How much will a GDF cost?' section (pages 24 to 29) includes this updated cost data, as set out in Table 1 of this report.

2.6 It should be noted that the figures published by NWS are all costs set to 2017/2018 monetary value. For reference, the retail price index (RPI) uplift from Jan 2018 to January 2021 was 6.7%.

2.7 The Annual Report also included reference to the cost of 'design and early construction' to develop a GDF ready to receive waste, which 'could be in the range of £4 billion to £12 billion' (2017/2018 monetary value).

2.8 These updated forecasts from NWS follow on from the previously published estimate from NDA in 2012 for a GDF ready to receive waste, which was 'in the region of £12 billion'.

2.9 CoRWM has assessed the NWS updated cost information and has provided commentary when considered appropriate within this report.

[1] https://www.gov.uk/government/publications/gdf-annual-report-2020-2021

| Inventory | Cost Estimates | Lower Technical Complexity | Higher Technical Complexity |
|---|---|---|---|
| Legacy waste (includes waste already accumulated and waste from current fleet of nuclear power stations) | Baseline minimum cost estimate | £12.1bn | £18bn |
| | Upper estimate including risk, optimism bias and uncertainty | £20.3bn | £32.2bn |
| Full potential inventory (includes legacy waste, waste from new nuclear and nuclear materials that could be categorised as waste in the future, such as unreprocessed spent fuel) | Baseline minimum cost estimate | £20.3bn | £30.5bn |
| | Upper estimate including risk, optimism bias and uncertainty | £33.1bn | £53.3bn (upper bound) |

Table 1: Breakdown of the baseline costs issued by NWS in 2022

2.10 CoRWM is mindful of the NWS cost envelope ranges.

2.11 This report has been prepared so as to promote consideration of and debate on the issue of the significant cost related aspects associated with the delivery of a GDF, acknowledging that this will be a complex and long-term underground construction project and operational radioactive waste disposal facility.

# 3 Methodology

3.1 There are a number of key variables involved in terms of specific methodology, which include:

- Ground category (hard rock, low strength sedimentary rock, evaporite)
- Total volume of material to be accommodated
- Operational lifespan prior to closure
- Pre-operational underground research laboratory
- Access method(s)
- GDF location (onshore vs inshore)
- Land availability and waste disposal
- Gallery sizes
- Human interface and remote operation capabilities

3.2 CoRWM has used the experience of committee members and historical work by the committee to inform the review presented here. This includes extensive relevant underground construction, project management and nuclear waste regulation expertise.

3.3 The review has broken the GDF down into a series of specific and discrete work package elements, including the fixed and permanent infrastructure necessary to facilitate access to the repository zone itself, together with the disposal vaults and tunnels required for waste disposal.

3.4 Separately, an assessment of annual operational costs has been undertaken to consider the likely long-term operational period overall cost during the emplacement of waste packages.

# 4 Assumptions

4.1 The basic assumptions used for this assessment are set out below and explained in the specific sections that follow:

- A maximum limit on GDF depth of 1,000m
- A low to medium strength sedimentary strata case is adopted. This is considered to be the most onerous and highest technical complexity case in terms of cost and construction assessment
- No significant underground aquifers or zones of high-water pressures to be traversed below the surface
- No soil or other very soft/flowing materials to be traversed below the surface (e.g. silt/sand)
- Main mined 'infrastructure' to include;
    - three vertical shafts (workforce & materials, rock and ventilation)
    - one decline tunnel for waste package transportation
    - large vault tunnels for Intermediate Level Waste (ILW) disposal
    - small vertical/sub-vertical shafts for High Level Waste (HLW) disposal

4.2 A concept GDF design has been developed to support this cost review, and to demonstrate the practical application of the proposed tunnelling methods and construction philosophy. Various diagrammatic layouts for this conceptual GDF are included within Appendix B.

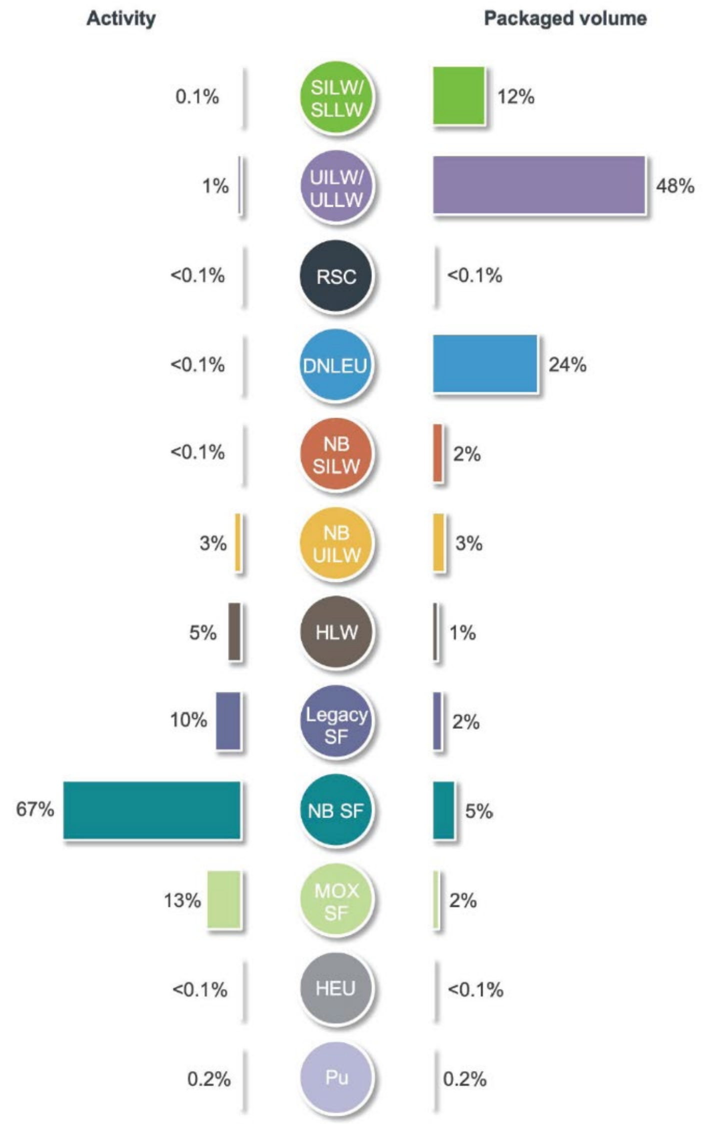
4.3 Together with the concept design, a high-level construction programme has also been prepared to identify potential time periods for specific construction methods, sections and activities.

4.4 This high-level programme shows that the construction elements of the GDF could be completed within a 20-year period (excluding any waste package emplacement).

4.5 The concept design divides the GDF into four separate 'sectors', specifically Phase 1 ILW and HLW zones and Phase 2 ILW and HLW zones. Additional sectors could be incorporated to provide greater construction and operational emplacement flexibility over the life of the GDF operations, or to allow for inventory increases for further nuclear new build waste arisings which may not be accounted for within the current inventory forecasts.

4.6 These costs can be utilised on a pro-rata basis for a different design geometry, tunnel lengths, volume requirements and package sizes. This generic design is provided purely to demonstrate the capability of modern tunnelling equipment to meet the overarching volumetric disposal requirement.

4.7 A key aspect of this assessment is clarification of the volumes of current and future waste arisings. Figure 1 shows a comparison of the volume associated with each waste group and fraction of the activity (as at 2200).




| Acronym | Definition |
|---|---|
| SILW | Legacy Shielded Intermediate Level Waste |
| UILW | Legacy Unshielded Intermediate Level Waste |
| RSC | Robust Shielded Containers |
| DNLEU | Depleted, natural and low-enriched uranium |
| NBSILW | New Build Shielded Intermediate Level Waste |
| NBUILW | New Build Unshielded Intermediate Level Waste |
| HLW | High Level Waste |
| Legacy SF | Legacy Spent Fuel |
| NB SF | New Build Spent Fuel |
| MOX SF | Mixed Oxide Spent Fuel |
| HEU | Highly Enriched Uranium |
| Pu | Plutonium |

Figure 1: Comparison of the proportions of activity (at 2200) and volume of each waste group (extracted from the RWM GDF Inventory Main Report, May 2021)

4.8 The volumes of UK waste and materials that could potentially be disposed of in a GDF now, and projected to arise over the next 100 years, are set out in Table 2 (data derived from the NDA Inventory reported total packaged volumes).

| Waste Group | GDF Inventory Waste Group | No disposal units | Packaged Volume ($m^3$) | Activity at 2200 (TBq) |
|---|---|---|---|---|
| ILW | Legacy Shielded Intermediate Level (SILW) / Shielded Lower Level Waste (SLLW) | 5,050 | 92,600 | 19,400 |
| ILW | Legacy Unshielded Intermediate Level Waste (UILW) / Unshielded Lower Level Waste (ULLW) | 126,000 | 372,000 | 398,000 |
| ILW | Robust Shielded Containers (RSC) | 949 | 2,610 | 3,180 |
| U | Depleted Natural and Low Enriched Uranium (DNLEU) | 8,380 | 184,000 | 9,800 |
| ILW | NB (New Build) SILW | 10,100 | 18,900 | 154 |
| ILW | NB UILW | 8,230 | 22,100 | 793,000 |
| HLW | HLW | 2,550 | 9,880 | 1,460,000 |
| SF | Legacy SF | 4,160 | 17,000 | 2,780,000 |
| SF | NB SF | 8,940 | 39,400 | 19,000,000 |
| SF | MOX (Mixed Oxide) SF | 2,710 | 11,900 | 3,700,000 |
| U | HEU (High Enriched Uranium) | 780 | 2,470 | 53.7 |
| Pu | Pu | 196 | 620 | 43,700 |
| | Total | 178,045 | 773,480 | 28,207,288 |

Table 2: Number of disposal units, packaged volume and activity in each waste group (acronyms are defined in Figure 1)

4.9 The total volume of ILW is produced by combining the legacy and new build volumes. The HLW lifetime total is 9,880$m^3$ and the ILW lifetime total is 508,210$m^3$. These numbers can also be expressed as disposal units, as 2,550 HLW units and 150,329 ILW units.

4.10 The concept GDF and this cost review has been prepared on the basis that all of this HLW and ILW will be disposed of within the GDF. However, this excludes those categories which are not currently classified as waste (SF, U and Pu). Without any future reprocessing or other treatment, these additional materials would require an approximate 50% increase in equivalent ILW volume and capacity (a further 255,390$m^3$ or 25,166 disposal units).

4.11 This review estimate does not include pre-construction costs, including site selection, assessment, stakeholder engagement, planning or other related preparatory resources and costs. However, for the purposes of assessing whole life cost estimates, a high-level figure has been developed which aggregates to ~£2.5 billion, assessed as below.

4.12 Pre-construction consists of two main stages:

1. Siting process and site evaluation (£0.5 billion)
2. Site assessments and characterisation (£2 billion)

4.13 Likewise, this review does not consider detailed annual operational costs for the delivery organisation for the GDF (formerly Radioactive Waste Management (RWM)). On the basis of £50m per annum to the point of GDF construction (~28 years), this would be ~£1.4 billion.

4.14 As a result, the pre-construction costs are anticipated to be in the order of £4 billion.

4.15 The surface footprint of a GDF site would be modest, at around 1 square kilometre (~247 acres). Current land purchase costs for rural greenfield and brownfield land are in the range of £30,000 to £70,000 per acre in the areas of the UK currently being considered for host communities. Therefore, a likely purchase cost would be in the order of tens of millions. As such, land purchase is not considered to be a substantial cost element.

4.16 Appropriate infrastructure to support a GDF may not be in place at a specific selected site, for example a rail connection to the UK mainline network and relevant utilities (power, water, sewage, roads). UK rail standard costs are in the order of £3 million to £6 million per km of new single track freight line. Thus, a 20km connection would be ~£120 million.

4.17 An overall allowance of £500m for the infrastructure, land and associated services would appear to be adequate for this level of study.

4.18 Similarly, local initiatives, including financial contributions, community funds and equivalent schemes are considered to be included within the pre-construction and operational cost allowances.

4.19 The concept also includes an underground research laboratory (URL) to be integrated into the pre-construction phase, using two vertical shafts and initial underground access roadways which would be required to develop Phase 1 ILW and Phase 1 HLW zones.

4.20 Appendix C to this report includes a technical note prepared by CoRWM which sets out considerations in relation to what is currently considered to be the practical distance that a tunnel could be driven from onshore to inshore (in the case of an inshore GDF located beneath the sea).

4.21 The concept proposes that upon completion of Phase 1 there would be waste package isolation and full segregation from the Phase 2 construction of the next ILW and HLW zones. This is shown in the schematic in Figure 2.

4.22 The construction does not need to be delivered as a start to end critical path. Discrete elements could be delivered over a specific timetable as required for waste emplacement or other overarching drivers, such as the ability to emplace packages whilst undertaking construction activities. However, a piecemeal approach to construction activities will inevitably increase costs due to the complexities of stopping and starting construction works.

4.23 CoRWM has therefore concluded that, for reasons of risk reduction, cost effectiveness and isolation of construction, all excavation works are likely to be undertaken consecutively and not over disparate time periods. The cost estimate follows this logic.

# Concept GDF
# Phases of construction and operation

TBM design
Suitable for both onshore and onshore/offshore sites

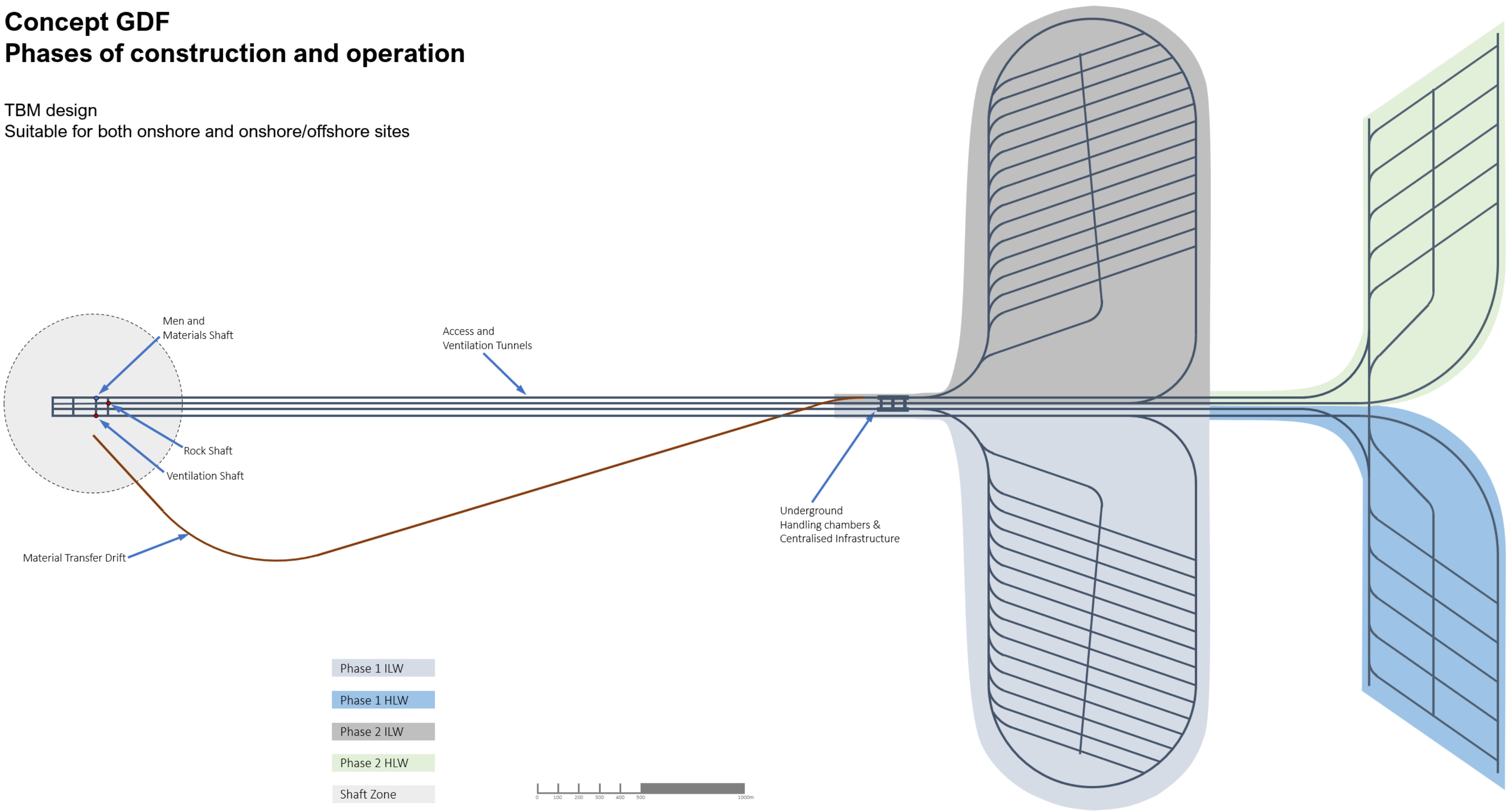



Figure 2: Concept GDF Construction and Emplacement Phases

# 5 Vertical Shaft Construction

5.1 CoRWM confirms that the concept design employs three shafts should be constructed to provide long-term and rapid underground access for people and materials in to and out of the GDF, together with the dedicated ventilation facilities needed for both the construction and operational phases of the GDF.

5.2 In the UK, it is a legal requirement for there to be at least two means of entry and egress from underground facilities, together with separate fresh air intake and exhaust air return routes.

5.3 Based upon current best practice and available technology, it is recommended that the shafts be sunk using state-of-the-art and well proven mechanical shaft boring roadheader (SBR) machines. These machines have revolutionised modern shaft-sinking performance, with much higher levels of safety compared to conventional drill and blast shaft sinking, together with higher advance rates.

5.4 Such shafts are currently being sunk at rates of more than 100 metres per month in good ground conditions. Recent examples include Canada and Belarus.

5.5 The SBR was developed for the mechanized sinking of blind shafts in soft to medium-hard rock (up to 130MPa). This allows for the construction of shaft diameters in the range of 7m to 12m.

5.6 The SBR is equipped with a roadheader boom and a rotating cutting drum. The boom is telescopic and allows for the excavation of the entire shaft cross-section with a depth of one metre in a single cycle. The SBR is suspended from steel ropes and is connected to winches on the surface. As the SBR descends the permanent concrete shaft lining is installed in sections from an upper working deck. A pneumatic conveying system lifts all excavated materials from the shaft floor onto the sinking stage, where sinking buckets are filled from a hopper and then hoisted to the surface and emptied.

5.7 Each SBR machine would cost circa £20m to purchase and commission.

5.8 The GDF shafts should be between 8m to 10m internal finished diameter to accommodate equipment, skips, conveyances and ventilation airflow quantities.

5.9 The approximate construction cost per metre of shaft would be around £60,000/m excavated and lined, at an average of 3m sink rate per day.

5.10 Additional costs would include main permanent and secondary temporary winders, headgear and permanent structures, as well as site management costs and contractor/consultant fees.

5.11 Extracted cost estimates produced by Sirius Minerals for the deep shafts (two shafts each ~1,500m deep) at their Woodsmith Mine in North Yorkshire (now owned and being developed by Anglo American) have been cross-referenced.

5.12 It is estimated that the capital expenditure would be approx. £150m for each of the three deep shafts (max 1,000m deep) including the permanent fit-out and equipment.

5.13 The permanent winders for the three equipped shafts would be for the winding of rock to surface in one shaft, for the winding of people and materials in the second shaft and for emergency purposes in the third shaft. The costs for the winders would be circa £60m and 2x £40m respectively. Total £140m.

5.14 Thus, the three completed and operational shafts would be estimated to cost £590m.

# 6 Access Tunnel Decline

6.1 A decline is an angled tunnel driven from surface downhill at a steady (and usually) continuous gradient.

6.2 The decline would be used to transport radioactive waste packages from surface into the GDF for emplacement.

6.3 Modern tunnel drives regularly utilise Tunnel Boring Machines (TBMs) to construct both long distance and large diameter tunnels at a wide range of tunnel sizes for transportation and utilities projects.

6.4 Depending upon the geology to be driven through, a specific type of TBM design would be selected. These designs have been developed by TBM manufactures over the last decades to be able to construct tunnels in a vast range of geological conditions, from weak soils and sands all the way through to massive granitic hard rocks. Specialist and hybrid designs can cater for saturated ground, high water pressures, and variable ground conditions.

6.5 For example, in medium strength rock the optimum choice would normally be a double shield machine, unless there is a need to traverse through water bearing strata, in which case a hybrid mix-shield or earth pressure balance machine (EPBM) may be selected.

6.6 CoRWM would suggest that a finished internal tunnel diameter of 8.0m would be adequate for the proposed purpose and usage requirements.

6.7 CoRWM envisages that the tunnels should be fully lined as they are excavated, using segments[2], installed within the machine as the drivage proceeds; this would result in an external cut diameter of ~9.1m diameter and an indicative 500mm thick lining (which would be varied based upon specific depth and design criteria).

6.8 This segmental lining would be installed as a single pass permanent lining solution (e.g.no need to install a secondary internal concrete lining) incorporating hydrophilic gaskets, bolts and pocket details.

[2] In current practice segments are made of cementitious concrete, but lower carbon substitutes may be used when the GDF is built to meet Net Zero commitments, for which a contingency has been included.

6.9 The annulus between the excavation and installed liner would be filled with cementitious grout.

6.10 Segments would typically be manufactured on or near site within a dedicated segment casting and stockyard factory facility. Appendix D includes a series of relevant photographs.

6.11 Multipurpose service vehicles are normally used to transport concrete segments and grout into the tunnel to support the TBM operations, as well as moving other materials and workers into and out of the tunnel.

6.12 At a gradient of 1 in 10 (6 degrees) the tunnel would be a maximum length of 10,000m to reach a depth of 1,000m below surface. The tunnel can be driven with curves (of radius not less than 500m for the TBM to negotiate) so it is possible to drive the tunnel from a portal constructed adjacent to the shaft site and arrive in close proximity to the main GDF disposal zone or shaft central zone if required.

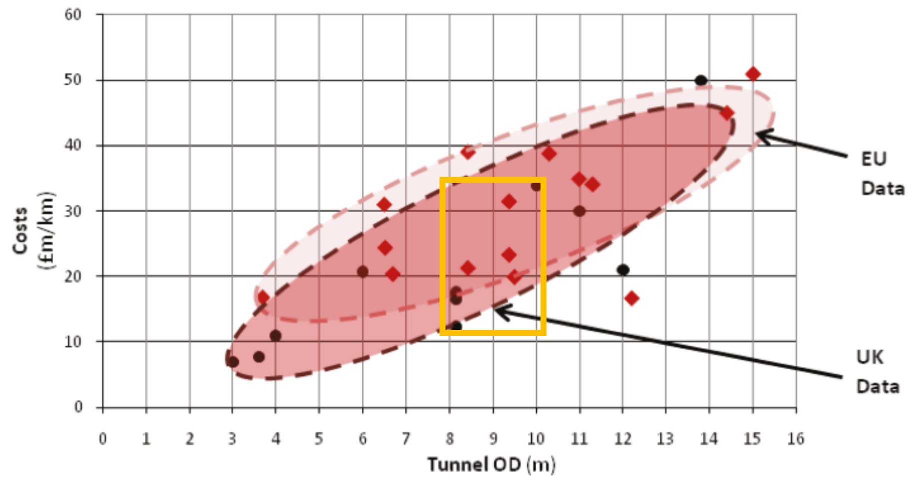
6.13 A modern, state of the art TBM would cost circa £30m to purchase, with the additional back-up equipment, conveyor, pipes, ventilation and transportation adding a further £20m.

6.14 Including the concrete lining, tunnel construction costs would be in the order of £30,000 per metre of finished tunnel, thus a total cost (including equipment, lining, labour and management fees etc) of around £450m.

6.15 Typical tunnel advance rate would be around 150m per week.

6.16 Including portal construction, TBM launch, and the weekly average advance of 150m, the construction time period would be in the order of 120 weeks (refer to the high-level programme at Appendix A).

6.17 Figure 3 sets out a range of completed tunnelling costs in the UK (and EU) for different tunnel diameters. The yellow box covers the applicable range for the GDF tunnel sizes. These figures include all costs associated with the tunnel construction, including portals, shafts, equipment, labour and management.




Source: Infrastructure UK Cost Questionnaires and British Tunnelling Society

Figure 3: Tunnelling costs per km vs tunnel diameter (UK Infrastructure)

6.18 Once the shafts have been sunk a series of interconnecting 'central zone' tunnels need to be constructed away from the shafts and to connect with the TBM decline connection point.

6.19 Dedicated chambers for the arrival, handling and dispatch of waste packages will be required.

6.20 The core underground infrastructure includes these large chambers (~15m wide and 9m high), potentially constructed using the Sprayed Concrete Lining (SCL) method, with roadheader type tunnelling machines and remote shotcrete spraying boom machines. This central infrastructure of two main chambers with associated crossover tunnels, workshops and personnel access tunnels would take around 3 years to construct.

6.21 The central zone infrastructure has been estimated to cost around £400m to construct and fit-out the main galleries (reference to a typical Crossrail main central London deep station package cost of between £412m to £659m).

6.22 Surface facilities, offices, reception buildings, package handling etc. has been assessed to be in the order of £200m. Ventilation equipment would be ~£50m.

6.23 For the Fixed Infrastructure, the estimate would be as set out in Table 3 below:

| Work Package | Estimated Cost |
|---|---|
| 3x Vertical Shafts, fitout and winders | £590m |
| Drift Access Tunnel | £450m |
| Central galleries | £400m |
| Surface Facilities and Ventilation | £250m |
| Total | £1,690m |

Table 3: Summary of Access Shafts and Tunnel Costs

# 7 ILW Access and Chambers

7.1 The UK ILW inventory is currently ~247,000 cubic metres, with a 100-year forecast for ILW to increase up to 508,210 cubic metres (in packaged form).

7.2 To provide a practical reference point, this quantity of ILW would fill the Royal Albert Hall around five times (the Hall is estimated to have a volume of between 85,000 and 99,000m$^3$) or fill the equivalent of 200 Olympic size swimming pools (2,500m$^3$, 50m x 25m x 2m).

7.3 A series of main access roadways (this concept includes for four in total) will need to be driven away from the GDF shaft bottom central zone to locate the disposal chambers a safe distance apart and within the target geological horizon and location.

7.4 Once again, it is proposed that these main long-life roadways are constructed using TBMs.

7.5 Assuming that these tunnels would be constructed in low to medium strength rock, ground support using pre-cast concrete segments would be deemed the most appropriate for long term support and safety requirements.

7.6 These tunnels should also be 8.0m diameter (for simplicity in segment manufacture) and would cost approx. £25,000 per m of tunnel complete.

7.7 The GDF has been split into two distinct phases, with phase one being constructed first and commencing emplacement of waste packages whilst phase two could be constructed separately after the first has been completed.

7.8 This split approach is one of the main requirements for the four parallel roadways from the central zone. This would require three TBMs to be erected underground in sprayed concrete lined (SCL) assembly and launch chambers.

7.9 Underground assembly chambers, each up to 100m long (12m wide and 10m high) would be constructed using roadheaders and sprayed concrete lining techniques. Each chamber and machine assembly would cost circa £50m.

7.10 The equipment costs for the access drives would be £20m x 4 (TBMs, conveyors and associated equipment).

7.11 The first tunnel drive for intake access roadways to the ILW chamber zone would be 9.8km long, completing a large loop with the TBM arriving back at the central zone into a reception chamber for disassembly.

7.12 Drivage costs and management fees for this main loop would be ~£318m.

7.13 A second tunnel drive is required for one of the two main ventilation roadways which also extends to the HLW chamber zone. This drive would also require an assembly chamber (£50m) and would be 6.0km long. The TBM would be buried at the end of the drive, with back-up equipment recovered where appropriate.

7.14 Drivage costs and management fees for this ventilation drive would be ~£204m.

7.15 A third main tunnel drive is required for the HLW access roadways. This TBM would be assembled and launched at the first 90 degree turn of the initial intake tunnel drive, with an assembly chamber constructed for the installation of the TBM head unit (circa £20m).

7.16 The third tunnel drive would be 8.0km long, with the TBM being buried and abandoned at the end of the drive.

7.17 Drivage costs and management fees for this HLW access drive would be ~ £264m.

7.18 A fourth tunnel drive, for a further ventilation drive, is required for the operational ventilation requirements. This drive would also require an assembly chamber (£50m) and would be 3.0km long. This TBM may be recovered where appropriate.

7.19 Drivage costs and management fees for this ventilation drive would be ~ £114m.

7.20 It is envisaged that large cross section ILW chambers (e.g. rectangular profiles with large width and height dimensions) will <u>not</u> be constructed in the sedimentary case, due to long term geotechnical stability issues and complications related to rock mechanics and package emplacement.

7.21 As an alternative, it is assumed that a modified TBM solution is used, with circular tunnels constructed with the same design of pre-cast segmental concrete linings, which would also act as the permanent liner.

7.22 If so desired, for long term multi-barrier engineering considerations, a secondary cast in-situ concrete liner could be installed within the outer segmental tunnel liner during tunnel drivage. A standard slip-form travelling shutter arrangement would be utilised.

7.23 It is proposed for this review that each ILW disposal ‘chamber’ would be a maximum of 1,000m long with a minimum 9.0m internal diameter (Cross Sectional Area of tunnel for disposal and backfilling ~52m$^2$).

7.24 At the end of each chamber drive, the specialist TBM would be designed so that the main cutting head would be disconnected and the TBM shield hydraulically collapsed, thus allowing the whole unit to be rapidly withdrawn back through the constructed chamber and then readied to drive another ‘chamber’ from the ILW main access roadway.

7.25 A concrete invert would be installed to provide a flat and stable floor slab for package emplacement activities.

7.26 At a construction cost estimate of £35,000 per metre, a 1km chamber would cost £35m excluding the TBM. One TBM (~£30m) could drive around 20 chambers within a normal working ‘lifespan’, thus an equivalent equipment cost of £1.5m per chamber.

7.27 A total cost of £40m per 1km chamber has been applied (to include TBM assembly, concrete invert installation and associated permanent equipment costs).

7.28 Each of the phases of ILW chambers would construct 14 chambers with total length of 13,030m; equivalent to 677,560m$^3$ total disposal volume space.

7.29 The chambers would be as follows: 8No @ 980m long and 6No @ 970m down to 700m long.

7.30 The two phases would therefore provide 1.36 million cubic metres of void space. At a modest maximum fill ratio of less than 40% (to provide sufficient void space for backfilling of standard package sizes), this would provide more than 540,000 cubic metres of ILW package space.

7.31 Two grouting galleries would also be driven using roadheaders and sprayed concrete linings, at £15,000 per m, total length for the pair 3,600m; total cost = £54m.

7.32 An alternative approach compared with the circular TBM and concrete lined tunnels proposed above would be to construct larger, more traditional profiled chambers using conventional roadheader type cutting machines, with sprayed concrete temporary and cast concrete permanent liners. However, this approach is less likely due to a number of significant risk, cost and time-related factors, including ground support, operational conditions and safety related considerations.

7.33 The ILW chambers would cost £520m including equipment and fit-out ready for package emplacement. Thus, for the ILW Facilities, the estimate would be as set out in Table 4 below:

| Work Package | Estimated Cost |
|---|---|
| TBM Assembly Chambers | £150m |
| 4x TBMs | £80m |
| Main Loop Tunnel Drive (1) | £318m |
| Ventilation Drive (2) | £204m |
| HLW Access Drive (3) | £264m |
| 2nd Ventilation Drive (4) | £114m |
| Grouting Gallery Tunnels | £54m |
| Total Main Drives | £1,130m |
| ILW Chambers | £520m |
| ILW Chambers Total | £1,650m |

Table 4: Summary of ILW Chamber and Tunnelling Costs

7.34 The total for main drives and ILW chambers is therefore £1,650m (£1.65 billion).

# 8 Heat Generating HLW Canister Access and Chambers

8.1 The UK HLW inventory will have a total package volume projected to be 9,880m$^3$.

8.2 To provide a practical reference point, this HLW volume would be equivalent to 100 Routemaster (London double decker) buses (90m$^3$, 8.4m x 4.4m x 2.44m) or approximately 4 Olympic sized swimming pools (4 x 2,500m$^3$).

8.3 Currently there are 3,040 2D02/C packages (High Level Liquid Waste) and 3,061 2F01/C (Vitrified High-Level Waste) packages in the UK inventory. The 2F01/C packages consist of a stainless-steel container, 430mm in diameter and 1340mm high, and contain 400kg of glass, bulk density 2.65t/m$^3$. It is assumed in the Inventory that the 2D02/C packages will be conditioned and packaged in the same way as other HLW streams.

8.4 The final disposal schedule within the 2021 inventory (Table 2) identifies a total of 2,550 disposal units for HLW.

8.5 Cylindrical flasks of vitrified waste need to be disposed of in a distributed manner to ensure adequate spacing for heat dissipation into the surrounding rock mass.

8.6 An optimum approach could be to drive HLW tunnels away from main access roadways and then to drill (working from the far end retreating backwards) large diameter vertical or inclined blind ‘shafts’ into the floor of the tunnel for subsequent installation of flasks and suitable barrier material (e.g. bentonite/cement/grout).

8.7 Various NWS (and prior NIREX) studies have proposed a range of similar dimensions for deposition holes. This review assumes they will be 1.75m diameter, with the 0.9m diameter disposal container (steel container containing the HLW package) surrounded by pre-formed bentonite rings and plugs with concrete base and floor slabs. The maximum depth required for a single container would be 7.55m.

8.8 A specific mechanised modern technique developed for specialist mining applications over the last few years has been the blind ‘box-hole’ borer. These innovative machines are used in underground mines to drill vertical or inclined blind ‘shafts’ within tunnel galleries.

8.9 A box-hole borer can drill vertical and inclined holes up to 1.8m diameter and as deep as 70m. These machines can work in the majority of rock conditions. Example photographs are included within Appendix D.

8.10 For vertical downholes the boring machine would be modified to collect rock cuttings from the bottom of the hole during drilling using either a large vacuum suction unit (as per the shaft boring roadheader) or using recirculating drilling mud (as per standard borehole drilling). The complete borer units are ~£5m each.

8.11 The operational cost to drill each shaft is not substantial; with an estimate of £10,000 per metre of shaft bored (based upon labour, supplies and equipment).

8.12 As a result, a 7.5m deep shaft would cost ~£75,000; whilst a 50m deep shaft would cost £500,000.

8.13 With the correct inter-package spacings, a number of containers could be 'stacked' (with suitable packers/spacers and isolation materials between each container) in deeper shafts, e.g. at a spacing of 15m per cannister in a 70m deep shaft a total of 5 canisters could be remotely deposited into each hole.

8.14 For 2,550 canisters this would require more than 510 shafts to be drilled. This would total £270m for all of the shafts drilled using a number of separate borer machines (five assumed).

8.15 If inclined shafts (angled down from the horizontal at 30 to 40 degrees) were drilled at 20m centres on either side of the tunnel, then this would require ~4.2km of tunnels (for example 6 tunnels each ~700m long driven using roadheaders and sprayed concrete linings).

8.16 The generic TBM design for this review currently includes 7,400m of HLW tunnels for shaft drilling.

8.17 These tunnels would be typically 6m wide, 4.5m high and cost approx. £15,000 per metre of tunnel complete.

8.18 Two grouting gallery tunnel drives would be approx. 2,000m long; total cost £30m.

8.19 The equipment costs would be ~£15m per roadheader and SCL equipment setup.

8.20 Drivage costs and management fees would therefore be ~£111m.

8.21 Thus, for the HLW Facilities, the estimate would be as set out in Table 5 below:

| Work Package | Estimated Cost |
|---|---|
| HLW Shaft Drilling | £270m |
| Tunnel Drives | £111m |
| Grouting Gallery Tunnels | £30m |
| HLW Chambers Total | £411m |

Table 5: Summary of ILW Chamber and Tunnelling Costs

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# 9 Summary Construction Cost Breakdown

9.1 Table 6 sets out the combination of fixed infrastructure and variable disposal excavations rounded to the nearest £50m. These costs do not account for the operation of the GDF in terms of transportation and emplacement of radioactive waste flasks, canisters or containers. Specialist remote handling equipment, containment doors and lifting machinery will be required for these tasks.

9.2 By specifically dividing up zones within the GDF for construction of chambers and separate emplacement of packages, construction activities could be performed with semi-automated existing equipment, with emplacement being undertaken remotely using robotic and remote operated equipment.

9.3 It is estimated that the specialist transportation and handling equipment for the movement and emplacement of radioactive waste packages into the GDF would cost not more than £1.5 billion based upon existing systems and equipment available to safely operate in an underground environment.

9.4 These units may include:

- Automated transport units with captive rail guides and electronic guidance systems for decline and underground transportation of waste packages (modified MSVs) (£100m)
- Automated and remote operated mobile handling and emplacement stacking machines (£200m)
- Automated and remote operated mobile travelling units for the handling and lowering of HLW waste containers into bored shafts (£200m)
- Package transfer and handling equipment (£500m)
- Civil engineering barriers, grouting, bulkheads etc (£500m)

9.5 At the point of GDF closure, reinstatement should address complete backfilling of all tunnels, shafts, chambers and drifts.

9.6 All of the galleries could be grouted (thereby permanently sealing the waste within the GDF using cementitious material) to suit the overall programme or when there is no longer any requirement for retrievability, and as approved by the regulators and licence conditions

9.7 On the basis of the overall lengths of openings remaining at the point of closure, up to 3 million cubic metres of cementitious grout/backfill would be required. At £200/cubic metre, this would be £600m for materials, plus the necessary pipelines, pumps, bulkheads, monitoring and other equipment. An allowance of £700m would be prudent over a minimum ten-year closure period.

| Type | Detail | £m |
|---|---|---|
| Fixed | | |
| | Shafts | 600 |
| | Drift | 450 |
| | U/G central tunnels | 400 |
| | Surface infrastructure | 250 |
| Sub-Total | | 1,700 |
| | | |
| Variable | | |
| | Access roadways | 1150 |
| | ILW disposal chambers | 550 |
| | HLW tunnels | 200 |
| | HLW shafts | 300 |
| | Equipment | 1,500 |
| Sub-Total | | 3,700 |
| | | |
| Total | | 5,400 |
| Contingency | 20% | 1,080 |
| Grand Total | | 6,480 |

Table 6: Schedule of GDF Construction Costs

9.8 The total estimated construction costs for a maximum 1,000m deep GDF, with three shafts, decline material transport tunnel, central infrastructure and suitable access tunnels, chambers and disposal shafts for the full UK inventory of ILW and HLW is indicated to be between £6 billion to £7 billion in 2021 costs.

9.9 Contingency levels of 20% to 50% would typically apply to high level cost estimates where there is a concept design only. In this case, realistic industry rates and current equipment prices have been utilised to reduce the cost risk envelope.

9.10 Using the base total, with a 100% contingency, would result in a construction delivery cost of £10.8 billion.

9.11 To compare, the whole of Crossrail has been forecast (2022) to cost £18.9 billion. The Crossrail Act was given royal assent in July 2008 and provided for the construction of an overground and underground railway running east-west beneath central London. The Crossrail scheme scope included:

- 10 new stations (9 underground)
- Complex and large underground stations constructed using SCL techniques for the five main central London stations – each twin 234m long platform length and 12m diameter
- 42km of tunnels with 8 No 7.1m diameter TBMs (average progress rate was 38 m/day)
- 4.5 million tonnes of excavated material transported by river/sea
- 31 upgraded overground stations
- All signalling, control systems and overhead equipment
- 65 new trains (each 200m long) and depot facilities
- Operational testing, commissioning and handover of fully operational railway to TfL

9.12 The Crossrail Governance and Organisation also provides insight for the delivery of a complex railway project (see figure 4).

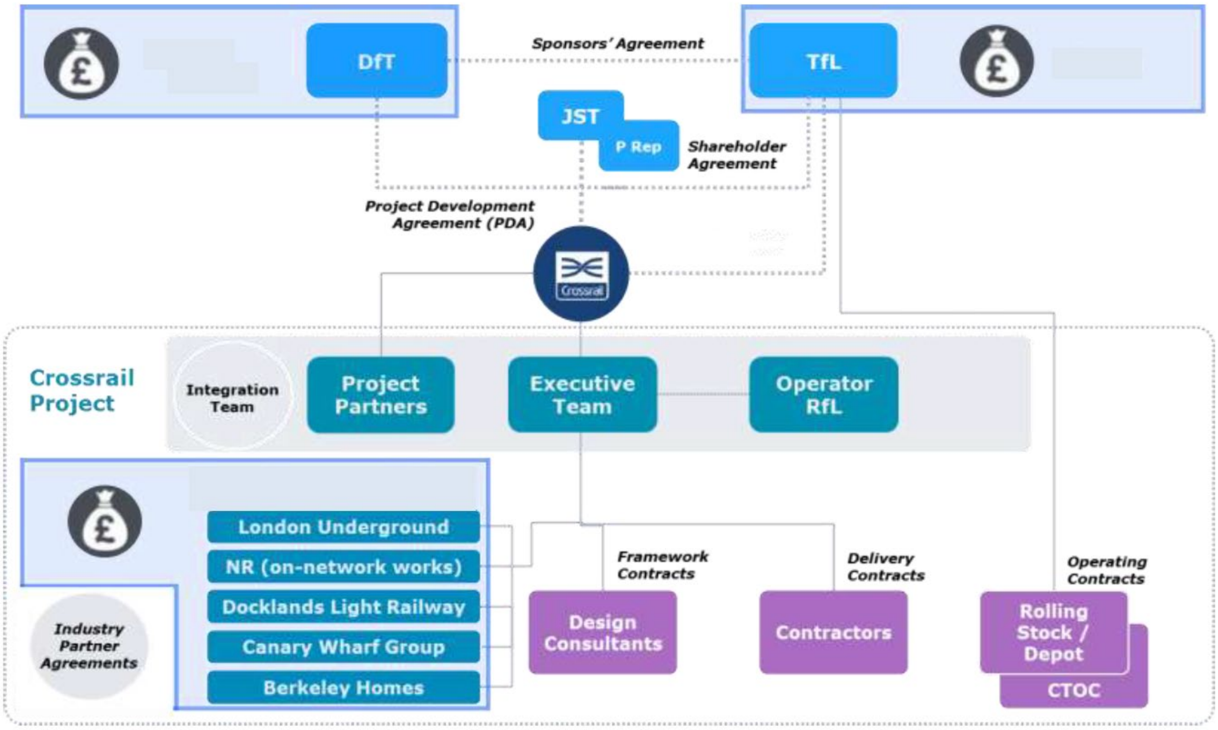



Figure 4: Crossrail Governance, Organisation and Funding Sources

9.13 High Speed Two (HS2) is currently under construction, with the Phase One element (London to Birmingham) currently forecast to cost £44.6 billion. To provide a comparison, this includes the delivery of a fully operational high-speed railway, with the route-works including:

- 140 miles of dedicated track
- 103km (64miles) of tunnels (all twin bore) - Euston 7.2km; Northolt 13.5km; Chiltern 16km; Long Itchington Wood 1.6km; Bromford 5.6km
- 4 stations
- £2 billion rolling stock
- Over 500 bridging structures
- Over 50 viaducts measuring about 15km in length (including the UK's longest viaduct 3.4km long over the Colne Valley
- Over 70 cuttings over 72km in total
- Over 110 embankments about 61km long

# 10 Summary Operational Cost Breakdown

10.1 Given that the GDF is likely to be operational for a very long period of time until ultimate closure (at least 100 years), a high-level assessment of baseline annual operating costs has been undertaken.

10.2 Key operational costs will include:

- Management and Employees
- Equipment purchases and maintenance
- Plant and materials
- Power supply
- Monitoring
- Security.

10.3 Core cost assumptions are set out in Table 7 below (rounded to nearest £1m):

| Cost Centre | Quantity | Rate | Total |
|---|---|---|---|
| Employees | 250 No | £55,000<br>(each all in cost) | £13.75m |
| Management | 40 No | £80,000<br>(each all in cost) | £3.2m |
| Power Consumption | 10MW<br>365d/24hr | £0.14 per kWh | £13m |
| Fixed Costs | Sum | 1 No per annum | £10m |
| Materials and Consumables | Monthly | £1m per month | £12m |
| Equipment, Plant operations and maintenance | Sum | 1 No per annum | £10m |
| Monitoring, systems, IT | Sum | 1 No per annum | £12m |
| Security | Sum | 1 No per annum | £6m |
| Contingency | | 20% | £16m |
| **Total** | | | **£96m** |

Table 7: Schedule of Annual GDF Operational Costs

10.4 Based upon headline assumptions, annual operating costs for the GDF would be ~£96m per year, including a 20% contingency allowance.

10.5 For 100 years of operation this would equate to £9.6 billion (without applying any discount rate).

10.6 To compare, the approved Lower Level Waste Repository (LLWR Plan) 2018-2023 sets out all of the operation and closure costs for the period 2018 to 2135 (117 years) which totalled £5 billion (an annual average of £42.7m).

# 11 Total Cost Estimate for GDF Lifespan

11.1 Table 8 sets out the sum of the cost estimates, developed within this paper, for the whole life cost of a GDF to accommodate all of the current and forecast UK ILW and HLW inventory identified as suitable for disposal within a GDF.

11.2 CoRWM's High Level Assessment suggests that the overall cost envelope for a GDF would be around £22 billion for construction, operation and closure (incorporating a contingency of 20%).

| Phase | Cost (no contingency) | Cost (20% contingency) |
|---|---:|---:|
| Pre-Construction | £4.0 billion | £4.8 billion |
| Land and Infrastructure | £0.5 billion | £0.6 billion |
| Construction | £5.5 billion | £6.6 billion |
| Operation | £8.0 billion | £9.6 billion |
| Closure | £0.7 billion | £0.8 billion |
| **Total** | **£18.7 billion** | **£22.4 billion** |

Table 8: Summary GDF cost estimate totals

11.3 For simplicity, it can be considered that each 10% of contingency adds £0.6 billion to the construction costs and £0.8 billion to the 100-year lifespan operational costs and closure.

11.4 Thus, even with a high degree of uncertainty applied (to counter any optimism bias) a 100% contingency would increase the costs to £12 billion (construction) and £16 billion (operation). The total upper range with 100% contingency for construction and operation would be £28 billion.

11.5 Applying a 100% contingency to the whole programme cost assessment of £18.7 billion results in a total maximum of £37.4 billion.

11.6 Using the current inventory (see 3.8) of HLW lifetime total 9,880$m^3$ and 2,550 No packages and ILW lifetime total 508,210$m^3$ and 150,329 No packages, one method of considering disposal costs is to assess the cost per cubic metre of packaged waste and cost per package.

11.7 Adopting an initial consideration that 75% of the costs are attributable to ILW disposal and 25% to HLW (in terms of the construction cost proportions within this review), noting that HLW represents less than 2% of the ILW/HLW inventory in both volume (1.9%) and number of packages (1.7%).

11.8 These unit rates are set out in Table 9 and Table 10 below.

| Inventory | Per cubic metre (no contingency) | Per cubic metre (20% contingency) |
|---|---|---|
| ILW | £28k | £33k |
| HLW | £473k | £568k |

Table 9: Volumetric unit rate disposal costs

| Inventory | Per package (no contingency) | Per package (20% contingency) |
|---|---|---|
| ILW | £93k | £112k |
| HLW | £1.8m | £2.2m |

Table 10: Package unit rate disposal costs

11.9 The addition of currently non-waste material, in particular new-build nuclear waste in ILW form, would add an additional 25,166 disposal units. This would, using the unit rates above, add a further £2.4bn to the overall costs (no contingency), or £2.8bn with 20% contingency.

# 12 Discussion

12.1 Modern tunnelling and underground construction methods have evolved to be extremely well proven, reliable, and cost effective, with high levels of productivity, automation and intrinsic safety.

12.2 It is considered unlikely that there would be high risks associated with the construction costs of a GDF based upon the application of well proven technology and construction methods. This has been demonstrated to be the case on a series of major UK infrastructure schemes involving underground construction, including High Speed 1, High Speed 2, Thames Tideway and Crossrail (noting that Crossrail witnessed significant delays due to the complex rail environment integration and associated cost over-runs).

12.3 Utilising modern tunnelling methods significantly reduces the impacts of the host geology, given that with the adoption of TBMs and segmental linings the ground exposure risk is completely eliminated (no open tunnel face), thus producing a much safer tunnelling environment. This approach also significantly reduces the sensitivity of the GDF costs being impacted by geological and technical factors, thereby considerably reducing the risks associated with the concept of "higher technical complexity".

12.4 Operation of the GDF, in terms of waste package emplacement, must be fully automated to completely isolate personnel from the emplacement chambers and disposal processes. Through careful design of the surface facilities, and the integrated package transfer and handling process, fully automated transport, transfer, handling and emplacement is well within the scope of modern and existing equipment, instrumentation, monitoring, visual and remote sensing capabilities.

12.5 In CoRWM's view, the GDF design process must focus upon ensuring the removal of as much complex engineering from the underground environment as possible, with the over-arching principle being to simplify construction, operation and safety case aspects so as to deliver a successful and cost effective GDF for the UK.

12.6 CoRWM considers a critical de-risking approach must be adopted to avoid any further complication of the underground design and construction/operational activities, which is already complex and challenging in an underground setting.

12.7 This paper sets out at a high-level, yet practical, GDF programme with an initial delivery timescale of ~10 years from commencement of on-site construction to the earliest possible available chamber for waste package emplacement.

| | Published Figures (2017/2018 Monetary Value) | | 2021 Monetary Value | |
|---|---|---|---|---|
| Cost Envelope | Lower | Higher | Lower | Higher |
| NWS | £20.3bn | £53.3bn | £21.7bn | £56.9bn |
| CoRWM | | | £20.1bn | £40.2bn |
| Variance | | | £1.6bn | £16.7bn |

Table 11: Comparison of Cost Envelopes (Full Inventory)

12.8 Table 11 presents the latest published NWS cost envelope and the 2021 equivalent figures together with the CoRWM lower and upper range estimates.

12.9 Note that the £12.1 billion in Table 1 (setting out the NWS ranges) is only for legacy waste. All of the work undertaken by CoRWM has been for both the legacy and future waste arisings, as per the current inventory (excluding nuclear materials and spent fuel that may be disposed of in a GDF if no further use is found for them)

12.10 As a result, there is a £1.6 billion variance between the minimum range estimates (without any additional contingency being included).

12.11 However, there is a significant variance at the maximum range of £16.7 billion.

12.12 The 'upper bound' high range estimate as proposed by NWS seems high given that the scope of works (e.g. the volume required for the GDF inventory), extent of construction, period of operation, and overall scale of the scheme can be estimated with a good degree of confidence.

# 13 Appendix A: High Level Construction Programme

GDF Construction Programme

| Activity | Duration (weeks) |
|---|---|
| **Site Establishment** | |
| Site Setup | 50 |
| Erect offices and welfare facilities | 35 |
| Construct segment factory | 30 |
| Shaft Collar & Foundations | 25 |
| Fore-shaft construction | 45 |
| Tunnel Portal construction | 30 |
| Rail siding construction | 120 |
| Surface Handling Facility Construction | 156 |
| Rock Handling Facility | 35 |
| Landscaping & rock management | 650 |
| **Equipment** | |
| Order SBR x3 | 0 |
| Order Drift TBM | 0 |
| Order U/G TBM's x4 | 0 |
| Order winders | 0 |
| Delivery of SBR's | 56 |
| Delivery of drift TBM | 52 |
| Delivery of U/G TBM's | 52 |
| Delivery of winders | 52 |
| Segment Production | 366 |
| **U/G Construction** | |
| Shaft 1 Erection & Commissioning (winder, headgear etc) | 38 |
| Shaft 2 Erection & Commissioning (winder, headgear etc) | 38 |
| Shaft 3 Erection & Commissioning (winder, headgear etc) | 38 |
| Shaft 1 Sinking (1000m) | 85 |
| Shaft 2 Sinking (1000m) | 85 |
| Shaft 3 Sinking (1000m) | 85 |
| Erect Drift TBM | 40 |
| Launch & Drive TBM Decline | 80 |
| TBM u/g launch chambers | 80 |
| Install drive 1 TBM | 45 |
| Install drive 2 TBM | 45 |
| Install drive 3 TBM | 45 |
| Launch TBM drive 1 (9.8km) | 70 |
| Launch TBM drive 2 (4.4km) | 35 |
| Launch TBM drive 2 (3.2km) | 26 |
| Central Zone Construction (Chambers etc) | 140 |
| Phase 1 ILW Construction (14km) | 100 |
| HLW Roadway TBM Launch Chamber | 30 |
| HLW Access Roadway TBM drive 3 (7.2km) | 50 |
| Phase 1 HLW Chamber Construction | 60 |
| Phase 1 HLW Shaft Drilling (400 No) | 80 |
| Phase 2 ILW Construction (14km) | 100 |
| Phase 2 HLW Chamber Construction | 60 |
| **Waste Disposal** | |
| Phase 1 ILW Available for package emplacement | 0 |
| Phase 1 HLW Available for package emplacement | 0 |

# 14 Appendix B: Concept GDF Design

*See separate pdf document for large size drawings showing stages of construction and operation*

# 15 Appendix C: Access Tunnel Length Constraints

## Introduction

15.1 Historically, the generic GDF designs all focussed upon an onshore facility, where the access shafts and tunnel/s (Access Zone 1) were on land with the actual GDF vaults (Disposal Zone 2) in close proximity to the access shafts (within one or two km's maximum). This approach was within proven tunnelling distances using existing methodology.

15.2 The introduction of an inshore GDF option, where the access shafts and tunnel/s are on land, but with the actual GDF vaults remotely located under the sea-bed, results in a likely requirement for significantly longer underground access tunnels between Zone 1 and Zone 2.

15.3 Figure C1 shows a simplistic graphical representation of the two different settings, with distance markers in km's from the onshore access location to the potential inshore GDF vaults.

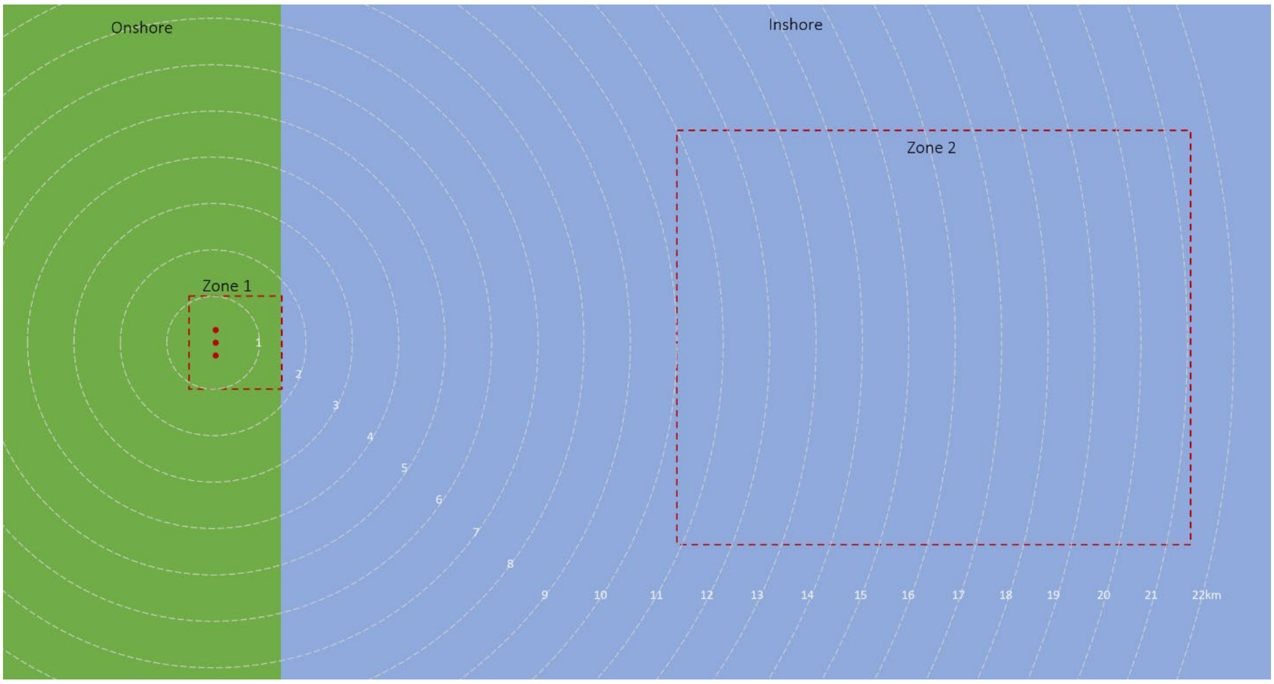



Figure C1: Potential proximity of GDF vaults to access shafts

15.4 This technical note considers the realistic distances that can be tunnelled based upon state-of-the art (but proven) technology and real case histories. It further explores limitations on the ultimate distance between the two zones and sets out some initial recommendations.

## Historical Reference Projects

15.5 Tunnelling and underground construction has a long and varied history, with all major ancient civilisations having developed their own methods of sub-surface excavation.

15.6 Gunpowder was first used to blast tunnels out of rock in France in 1681, with dynamite arriving in the mid-19$^{th}$ century, together with the development of drills powered by steam and compressed air.

15.7 The world's first tunnel to pass beneath a river was the Thames Tunnel, pioneered by Marc Brunel, which was 1,200 feet long and constructed between 1820 and 1841. This tunnel was pioneering in many ways, not least the use of the first 'shield' tunnelling technique.

15.8 Today, tunnelling technology has evolved and matured to a point where a range of technologically advanced, self-contained tunnel boring machines have been successfully deployed around the world.

15.9 There are thousands of examples of successfully (and not so successfully) completed tunnelling projects, using the wide range of techniques. TBMs have been very well proven, as long as they are correctly specified and the ground conditions are thoroughly explored and defined to match the machine type and design.

15.10 A wide range of infrastructure tunnels can be identified which extend to more than 20 kilometres in total length, but these are in all cases constructed using more than one tunnelling machine, and typically driven from both ends to meet (e.g. the Channel Tunnel was constructed from both the UK and France).

15.11 The Channel Tunnel key statistics are:

- It is 50,450m (31.3 miles) long in total (third longest railway tunnel in the world)
- the underwater section (still claimed to be the longest undersea tunnel in the world) is 37,900m (23.5 miles)
- at its lowest point, it is 75 metres (250ft) deep below the sea bed and 115m (380ft) below sea level

- there are three parallel tunnels, two single track running tunnels at 7.6m internal diameter (ID) and a third service tunnel at 4.8m (16ft) ID
- it was constructed using pre-cast concrete segmental linings with waterproof gaskets.

15.12 Crossrail, the latest high-capacity East-West London railway, has twin running tunnels, each with an internal diameter of 6.2m over a distance of 21km (13miles), again driven by a combination of TBMs from different start and end points along the route alignment.

## Current Capability and Limitations

15.13 Modern tunnel drives regularly utilise Tunnel Boring Machines (TBMs) to construction both long distance and large diameter tunnels at a wide range of tunnel sizes for transportation and utilities.

15.14 The Channel Tunnel demonstrated that one TBM can drive at least 18km in a single drive. Subsequently, this has been surpassed and improved upon in a number of cases and tunnel diameters.

15.15 The longest single TBM drive currently exceeds 25.4km at 4.8m ID.

15.16 Modern TBMs can be designed to excavate through any combination and type of geological and hydrogeological formations, ranging from saturated sand through to extremely hard rock.

15.17 Other techniques still employed in specific circumstances include:

- Drill and Blast tunnelling (typically fractured and hard rock, unlined, dry conditions)
- Roadheader boom type tunnelling machines (softer rock, temporary linings, dry conditions)
- Hand tunnelling (soft ground such as London clay)

15.18 TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the tunnel and makes them suitable to use in heavily urbanized areas. Drilling and blasting however remains the preferred method when working through heavily fractured and sheared rock layers.

15.19 The major disadvantage of the TBM approach is the significant capital costs. TBMs are expensive to construct and can be difficult to transport. However, the longer the tunnel, the less the relative cost of tunnel boring machines versus drill and blast methods. This is because tunnelling with TBMs is much more efficient and results in shortened completion times, assuming they operate successfully.

15.20 TBMs can operate in a range of tunnel diameters from one metre up to the largest (to date) of 17.6m (Bertha was used to construct a 2.7km long road tunnel) and have replaced more conventional tunnelling methods in a significant majority of cases where longer distances and longer life tunnels are required.

15.21 State of the art TBM design has progressed significantly since the Channel Tunnel was constructed, with the ability to drive a single TBM at least 20km with the correct design and operation.

15.22 In the case of an inshore GDF, where the distance between Zone 1 and Zone 2 is anticipated to be at least 2,000m, it is anticipated that the TBM method will be the preferred method, particularly where Zone 2 could be 10km or more from the shoreline.

15.23 Depending upon the geology to be driven through, a specific type of TBM design would be selected. These designs have been developed by TBM manufacturers over the last decades to be able to construct tunnels in a vast range of geological conditions, from weak soils and sands all the way through to massive granitic hard rocks. Specialist and hybrid designs can cater for saturated ground, high water pressures, and variable ground conditions.

15.24 For example, in medium strength rock the optimum choice would normally be a double shield machine, unless there is a need to traverse through water bearing strata, in which case a hybrid mix-shield or earth pressure balance machine may be selected.

15.25 Tunnel size is typically influenced by a number of factors, including:

- End use requirements in terms of function
- Required cross-sectional area or minimum clearance envelope
- Ventilation airflow quantity and air velocity constraints
- Ground conditions and tunnel lining requirements
- Services and other installed equipment/facilities

15.26 TBM tunnels are usually lined immediately within the tunnelling machine shield, just behind the cutter head. These liners consist of pre-cast concrete segments, installed as a single pass permanent lining solution (e.g.no need to install a secondary internal concrete lining) incorporating hydrophilic gaskets, bolts and pocket details. The annulus between the excavation and installed liner would be filled with cementitious grout.

15.27 Segments would typically be manufactured on site within a dedicated segment casting and stockyard factory facility or transported to site from a remote production facility. Where tunnels are in excess of a few km's in length, it is usual practice for the segment manufacturing facility to be based at the tunnelling site itself to reduce transportation impacts and costs.

15.28 Either multipurpose service vehicles or rail locomotives could be used to transport concrete segments and grout into the tunnel, to support the TBM operations, as well as moving other materials and workforce into and out of the tunnel. In longer drives small gauge railways are usually specified for speed and efficiency using battery locomotives.

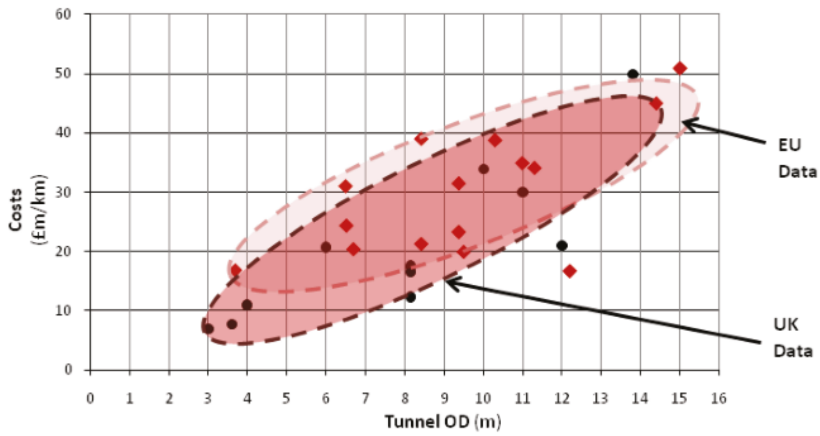
15.29 Other services consist of a substantial electrical supply to the TBM, a conveyor for spoil removal, pipes for services (water etc), lighting and walkway.

15.30 TBM tunnels can be driven incorporating curves (usually of radius not less than 500m) where required and are accurately steered using computer and laser guidance systems.

15.31 Typical tunnel advance rates would be around 150m per week but can be significantly higher than this is specific conditions.

15.32 Dependent upon the depth of the proposed GDF in the specific location, the TBMs could be driven from onshore via a dedicated portal and down grade as declines, or driven horizontally from the bottom of vertical shafts, with the TBMs assembled underground in pre-constructed launch chambers.

15.33 Figure C2 shows typical completed tunnelling costs in the UK for different tunnel diameters. These figures include all costs associated with the tunnel construction, including portals, shafts, equipment, labour and management.




*Source: Infrastructure UK Cost Questionnaires and British Tunnelling Society*

Figure C2: Tunnelling costs per km vs tunnel diameter (UK Infrastructure)

15.34 Figure C2 demonstrates that with increasing tunnel diameter there is an equivalent increase in construction costs. This will also be the case, to a lesser extent, with extended drive lengths (beyond 10km) which would result in cost increases due to additional transportation time, reduced available working time, ventilation requirements/limitations and electrical distribution infrastructure.

15.35 In terms of the main impacts of increasing lengths of the access tunnels (e.g. distance from Zone 1 to Zone 2) the major impacts are:

- Cost increases directly associated with the increasing metres driven
- Ventilation costs (e.g. fan power consumption) will increase over the life of the operational phase of the GDF as a result of the increased airway resistance which will be introduced with increasing tunnel lengths
- Travel times in to and out of Zone 2 will increase significantly with extended distances
- The need for progressively quicker transportation systems to reduce travel times for the workforce (in particular) – with resultant significant cost and safety impacts

15.36 Travel times will have a significant impact upon workforce operational shifts and effective working time in the vault disposal zone. Figure C3 shows the impact of distance and transportation average speed on the travel time to and from Zone 1 to Zone 2 and vice versa.

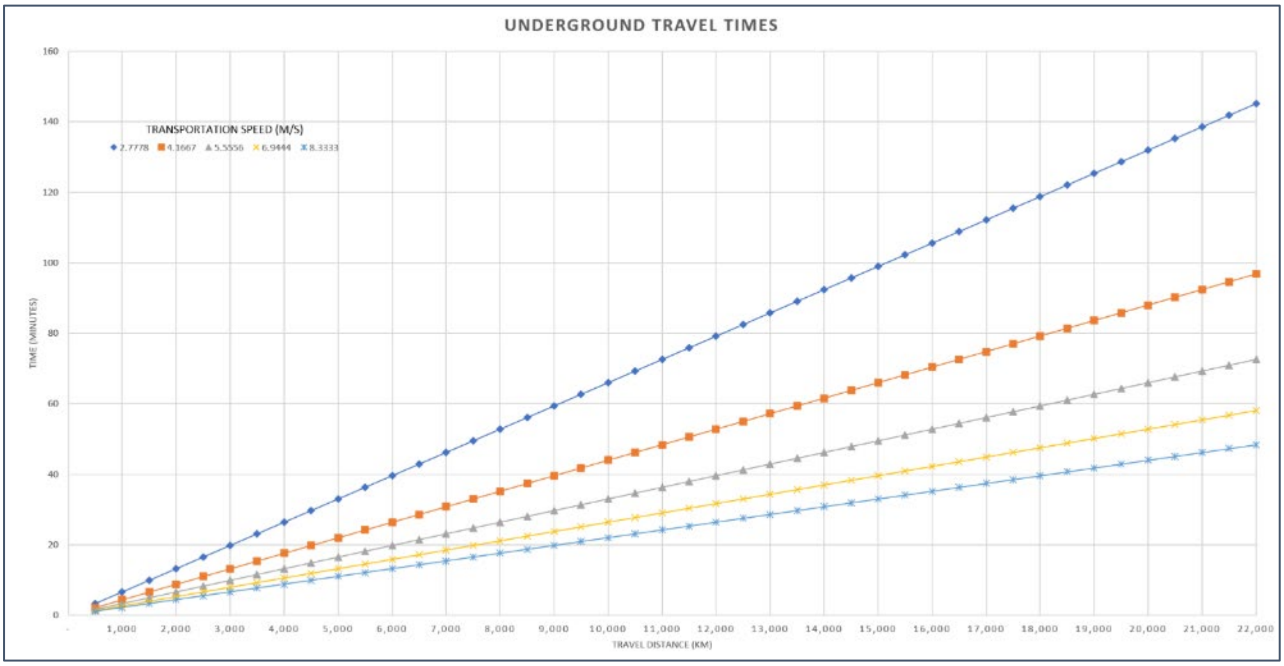



Figure C3: Travel Times vs distance and speed

15.37 The travel times in Figure C3 are 10, 15, 20, 25 and 30km/h respectively, shown as metres per second. High speed dedicated underground rail transportation is practical at each of these speeds, with the correct specification of rail, sleepers, locomotives and rolling stock with suitable standards of installation and operational guidelines. The chart includes a proportion of time for acceleration from the starting departure point and deceleration to the end arrival point.

15.38 This indicates that the journey time for a 18km travel distance would be at least 40 minutes each way for people transportation. Lower transportation speeds significantly increase travel time, which can easily exceed more than 1 hour each way without the correct transportation systems in place.

15.39 Transportation of waste packages would be speed restricted for safety and should not be as critical in terms of time and cost impacts, as long as multiple packages can be moved into the GDF on a regular and consistent basis.

## Commentary

15.40 CoRWM would suggest that the connecting tunnels between Zone 1 (onshore access shafts) and Zone 2 (GDF vaults) are driven using the TBM method, for speed, safety, efficiency and finished tunnel quality and longevity.

15.41 The maximum distance considered to be reasonable and applicable for a single TBM drive would be between 18km to 20km based upon current practice. This is a proven achievable distance for a TBM to drive prior to significant mechanical issues (e.g. longevity of main bearings and drive motors). Modern TBMs allow the changing of cutting tools and wear plates in-situ, so in itself this should not be the limiting factor in terms of machine performance.

15.42 A minimum of two parallel tunnels would be required. This would be essential in terms of legal safety requirements (to ensure a second means of egress in the case of emergency evacuation), to establish a ventilation airflow network and have separate tunnels for different usages (e.g. radioactive waste package transportation vs. materials and manpower movements).

15.43 A series of interconnecting crosscuts (with airtight doors) would be required to ensure safety and access between the parallel access tunnels.

15.44 A finished internal tunnel diameter of at least 6.0m would permit the installation of high-speed transportation systems, potentially one dedicated to the high-speed movement of materials and the workforce to the Zone 2 working area and another to transport waste packages. This would also deliver an operational loading gauge height of around 4.2m.

15.45 A 6.0m diameter tunnel (CSA of 28.3$m^2$) would permit an airflow of more than 100$m^3$/s (cubic metres per second) of air at a low air velocity of 3.5m/s. Such significant volumes of air would ensure suitable environmental conditions within the operational GDF in relation to geothermal temperatures, airborne dust and heat emitted from equipment and other mechanical and electrical activities.

15.46 CoRWM suggests that the tunnels should be fully lined as they are excavated, using segmental pre-cast segments installed within the machine as the drivage proceeds; this would result in an external cut diameter of ~7.1m diameter for a 500mm thick lining.

15.47 In terms of cost estimates, if each tunnel rate were to be £25m per km, for each access tunnel every additional km would be £25m. Thus, the difference between an access tunnel 10km vs. 20km would be at least £250m per tunnel

15.48 This is a clear demonstration of the potential cost implications of an inshore GDF vs an onshore GDF, particularly if the GDF repository is in the 10km to 20km zone.

Committee on Radioactive Waste Management

# 16 Appendix D: Example Photographs

Example photographs showing relevant equipment, techniques and finished works.


Figure C1: SBR assembled on surface (© Herrenknecht)

Figure C2: SBR during sinking in frozen ground (© Herrenknecht)

Figure C3: Typical modern shaft sinking headframes and winder houses

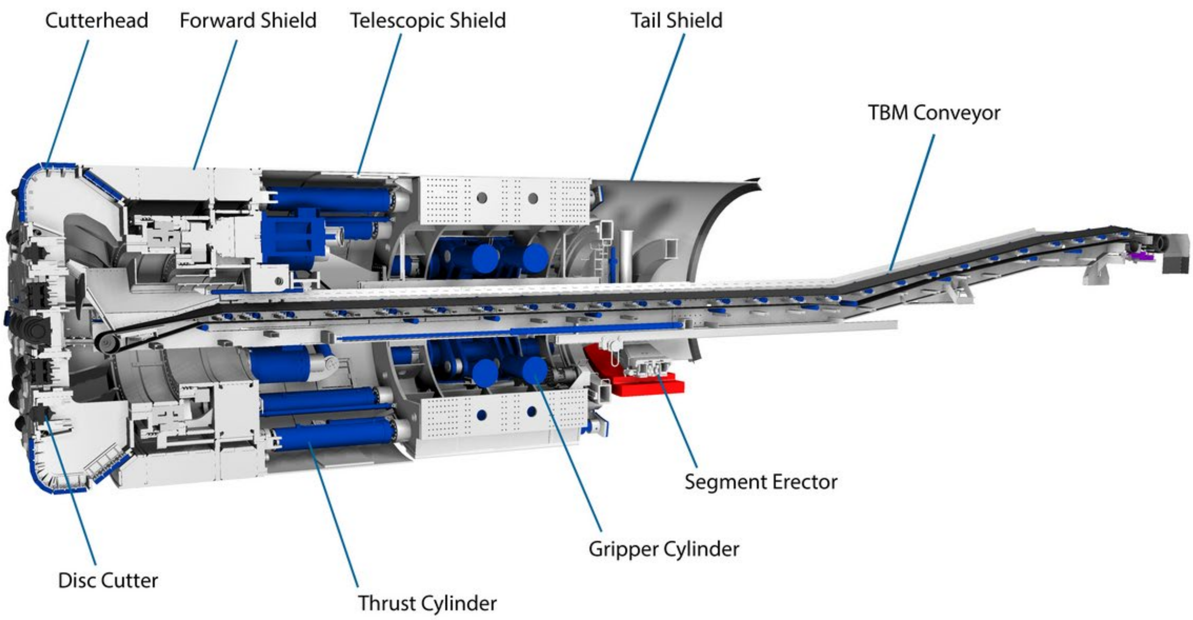



Figure C4: Double shield hard rock TBM cross-section schematic (© Robbins)


Figure C5: ~10m diameter double shield hard rock TBM (© Robbins)

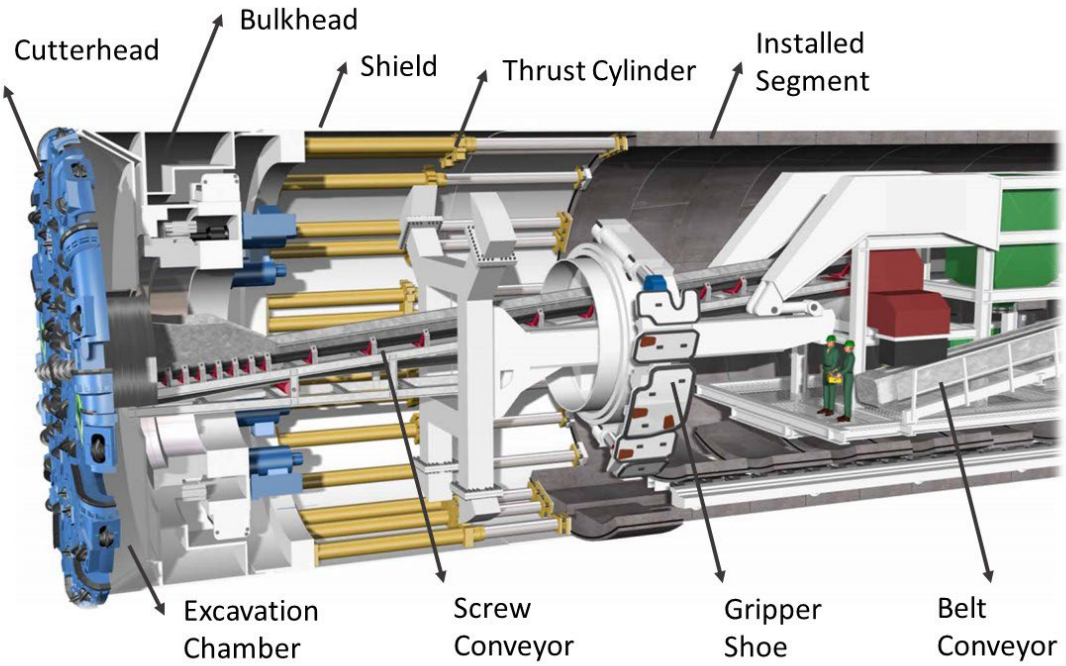



Figure C6: Earth Pressure Balance mixed ground TBM cross-section schematic


Figure C7: ~Crossrail 7.1m diameter Earth Pressure Balance TBM (© Herrenknecht)

Figure C8: Concrete segmental lined tunnel during construction (© Crossrail Ltd)
Note: walkway, cables & pipework (left), ventilation duct (top) and conveyor (upper right)

Figure C9: Finished 7.15m internal diameter segmentally lined permanent tunnel
(© Channel Tunnel Rail Link)

Figure C10: Multi-purpose gantry used for tunnel fit-out (© Crossrail Ltd)

Figure C11: Old Oak Common Segment Factory (© Crossrail Ltd)


Figure C12: Segment factory with casting moulds (© Herrenknecht)


Figure C13: Concrete tunnel segment loading onto an MSV (© TMS)

Figure C14: Dual cab MSV operating on an incline with concrete segments

Figure C15: MSV with captive rail guidance and rack & pinion

Figure C16: MSV transporting segments to TBM underground

Figure C17: Underground TBM assembly chamber (© Thames Tideway)


Figure C18: TBM erection within a SCL assembly chamber

Figure C19: Underground TBM assembly chamber


Figure C20: Robotic boom shotcrete spray machine

Figure C21: 12m diameter SCL tunnel (© Crossrail Ltd)

Figure C22: 12m diameter SCL tunnel (© Crossrail Ltd)

Figure C23: Roadheader tunnelling machine (sprayed concrete lined tunnel)

Figure C24: Roadheader tunnelling machines (sprayed concrete lined tunnel)

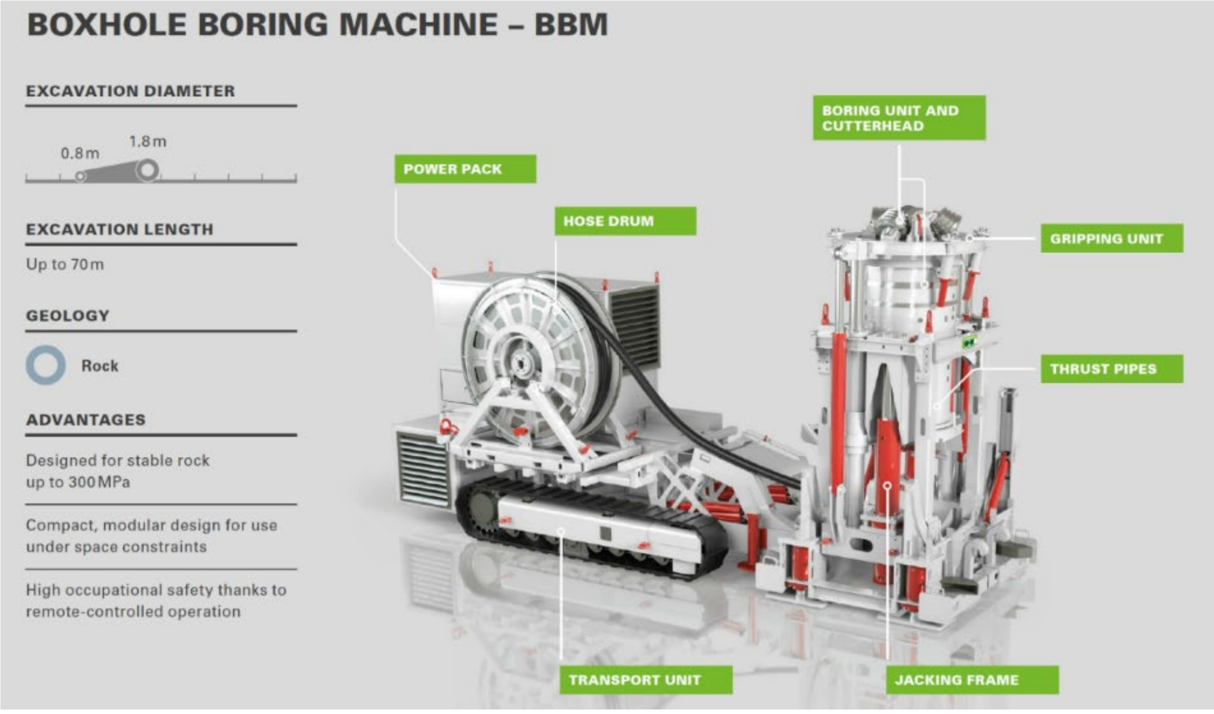



Figure C25: Blind 'boxhole' shaft borer (© Herrenknecht)

Figure C26: Boxhole borer transport unit and boring unit underground

Figure C27: Remote control boring unit
Note: drilling ‘tubes’ are inserted into the borer as the hole progresses

Figure C28: Example of blind drilled ‘shaft’

# 17 References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