DEVONPORT ROYAL DOCKYARD NUCLEAR SAFETY UPGRADE

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SUMMARY

Since the 17th century, Devonport Royal Dockyard has undergone several major extensions and upgrades to suit the requirements and technology of the time. The current upgrading of Devonport Royal Dockyard (UK) will result in a modern facility for the refit and refuel of the UK Royal Navy fleet of nuclear powered submarines. This is a major project involving the construction of process buildings, fuel transfer system and general upgrade of the existing dockyard. The D154 project is an extremely challenging project involving several disciplines and short time scales. A major component of the upgrade is the strengthening of the existing docks which are critical to the nuclear safety of the submarines undergoing refit. The critical nature of nuclear safety and the complexity of some of the major structures and plant has required extensive use of dynamic non-linear finite element analysis. In the case of the civil structures, conservative hand calculations supported with rigorous FE analysis has resulted in robust designs capable of resisting a Design Basis Earthquake with a 10,000yr return period as well as dropped load and ship impact. These analyses included structural gaps, frictional contact and Mohr Coulomb soil behaviour. An Alliance of six major companies was established in order to minimise overall cost and programme risk. Cost and programme control are rigorously applied although an Alliance provides the ability to arrange work or budget transfers to ensure that work is undertaken by the most appropriate party. This may be entirely different from that envisaged at contract award. The highly technical nature and degree of external review of such a project together with short time scales requires careful planning and management. The creation of an alliance forms a suitable environment to achieve this.

INTRODUCTION

In 1686 Samuel Pepys was charged with the recovery of the British navy. Devonport Royal Dockyard was subsequently commissioned in 1690. Major additions to the naval base over the centuries include the Keyham steam yard, 1846-53, coinciding with the first use of steam powered vessels circa 1850 and preceding the Crimean War in 1853, and the large No. 5 Basin and associated dry docks (8-12 Docks) 1896-1907. The dockyard was also extended after World War II. In 1969 the UK Ministry of Defence (MoD) decided to provide a complex at Devonport for refitting and refuelling nuclear powered submarines due to the increased number of such vessels. The submarine refit complex (SRC) consisted of two new docks (14 and 15 Dock) 147m long by 21m wide either side of a new promontory which housed the support facilities and was situated in the north west corner of No. 5 Basin. Since the construction of that facility, refuelling practice has involved removal of nuclear equipment by the large 80t capacity refuelling crane, through hatches in the submarine, to the nuclear workshops and core ponds. The height of these lifts increases the expense and difficulty of the refuelling operation.

In the early 1990's the MoD again reviewed its dockyard capability and capacity to support and refit its fleet of nuclear submarines. After a lengthy competitive process between the two main dockyards, Rosyth on the East coast of Scotland and Devonport at Plymouth in the south of England, it was decided that the latter would be upgraded and maintained as the sole nuclear licensed site capable of maintaining and refitting the UK Royal Navy's nuclear submarine fleet. After this landmark decision, extensive negotiations between MoD and Devonport Management Ltd. (DML) led to the formal award of a contract worth £350M known as the D154 project. Primarily this allows for the provision of a new facility created from 9 Dock for the new larger

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Vanguard Class submarines and upgrading of existing facilities (14 and 15 Dock) for smaller existing classes of submarine. The project also includes the provision of a number of process buildings, fuel transfer system and general upgrade of the existing dockyard and electrical services. An aerial view of No. 5 Basin at Figure 1. The SRC is situated in the north west corner (5). The upgraded SRC is shown in Figure 2.

Figure 1 Aerial View of 5 Basin and Surrounds

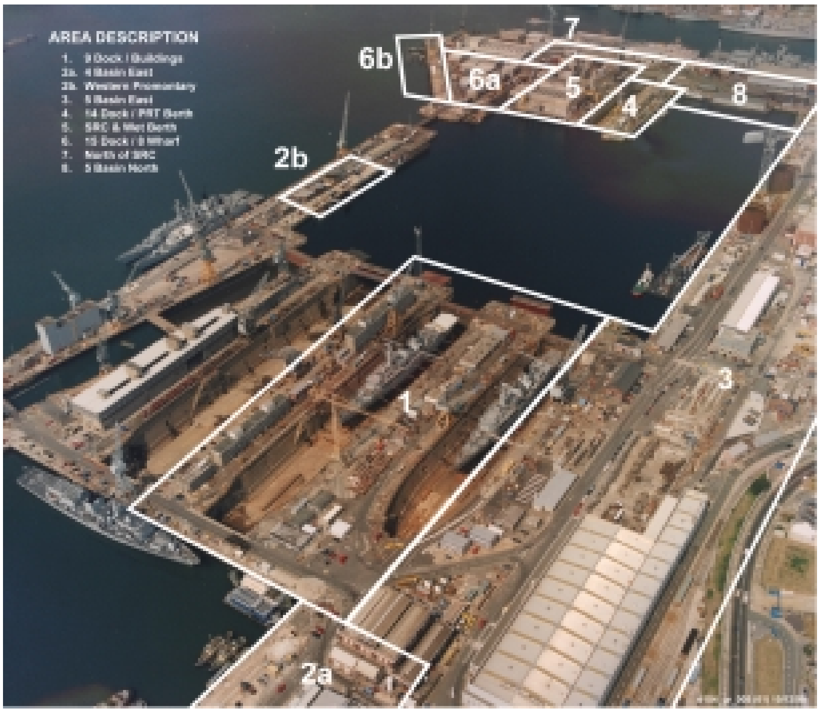
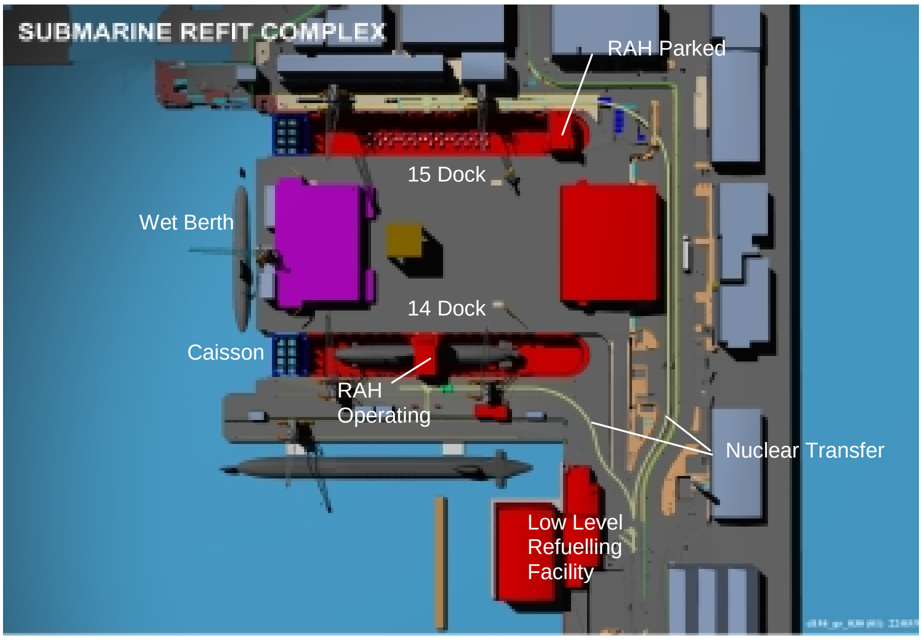
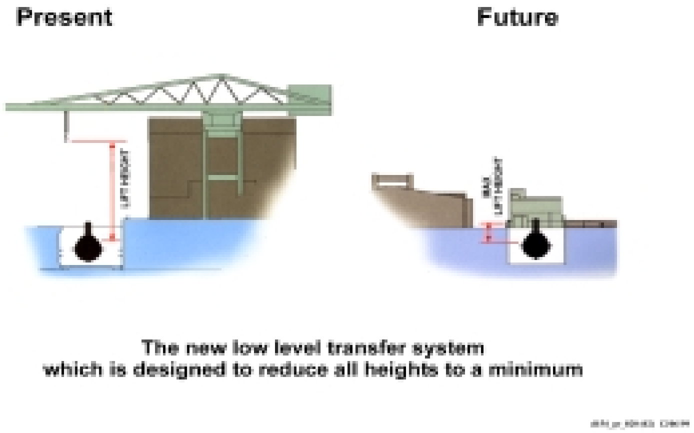


Figure 2: Upgraded Submarine Refit Complex



The safety of the existing refuelling method is significantly improved by the upgrade of the civil structures and plant in conjunction with the development of a new low level refuelling system. The main improvement is the elimination of the nuclear lift crane used for withdrawal and transfer of nuclear fuel elements. Not only does the crane itself pose a risk, because of its limited lateral load resistance, but more importantly the height of the lifts is reduced to an absolute minimum. This is shown schematically at Figure 3. In addition all fuel movement around the dockyard is at ground level.

Figure 3: Schematic of Fuel Handling

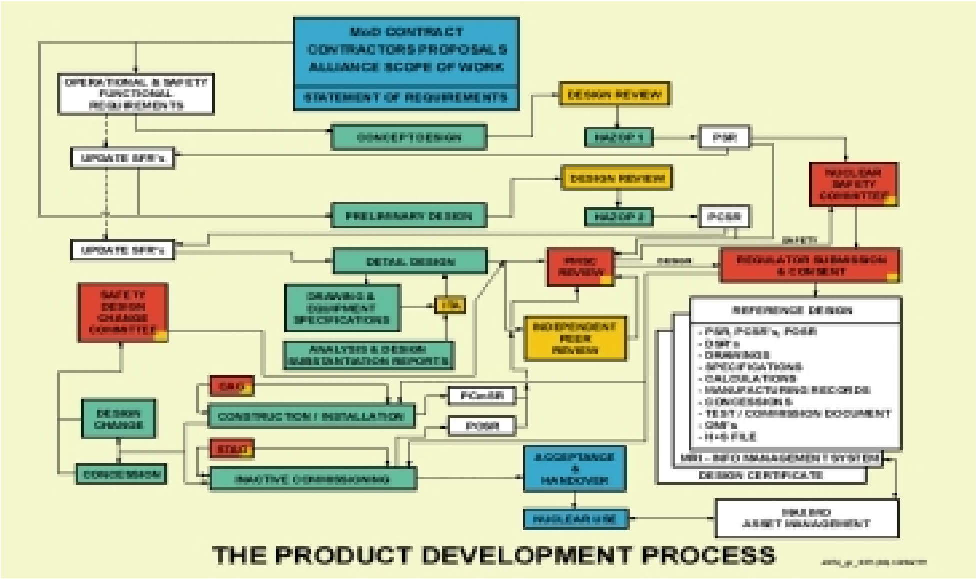


DESIGN PROCESS

Product Development

A schematic representation of the product development for the D154 project is shown at Figure 4. This follows the process from initial production of the specification (Contractor's Proposals) through design and construction/manufacture. At all stages the status of the safety case and supporting design are fully documented in safety reports (SR) and design substantiation reports (DSR). The purpose of the DSR is to confirm that all relevant safety functional requirements (SFR's) have been satisfied and to demonstrate how this has been achieved. The general process and committee review is one which has been developed by MoD and the Nuclear Installations Inspectorate of the UK Health and Safety Executive (NII) to satisfy the requirements of safety cases for nuclear establishments.

Figure 4: Product Development



The design process is safety led, that is the design requirements are derived from the developing safety case. Ongoing design review and independent technical assessment take place in parallel with the design process. A key feature is the use of the HAZOP process. This is a systematic brainstorming process which interrogates the design at the conceptual and detailed stages. This process identifies initiating fault events and SFR's. The two most severe initiating events are dropped load and a seismic event, the latter of which is the predominant design load for the civil structures. Earthquake and dropped load drive the design of the various cranes and lifting devices. Earthquake is an initiating event which may cause a dropped load.

Safety Functional Requirements

LEVEL 1	LEVEL 2
1.1 NSRP remains undamaged whilst in dock 1.2 To provide suitable protection to PCD/ACRC Facility 1.3 To provide suitable protection to overside services plant 1.4 To ensure that all loads remain undamaged and stable	2.1 Accidental flooding will not occur (including slow flood) 2.2 Accidental dewatering will not occur 2.3 Maintain submarine in a stable condition 2.4 Prevent accidental impacts on submarine

Table 1 – Typical safety Functional Requirements

In fact the detailed design is substantiated against SFR's at levels 3 and 4. However, the design requirements for the dock structures can be seen from the level 1 and 2 SFR's. Seismically qualified dock structures are necessary to satisfy 2.3 and 2.4. In order to satisfy 2.1 and 2.2 the structure must remain substantially intact after a seismic event.

Safety/Seismic Categories

To differentiate between the levels of duties placed on components they are given a safety category and a seismic category ranging from 1 to 4. Safety Category 1 signifies a direct impact on nuclear safety whilst 4 indicates no effect. Seismic categorisation gives a measure of the amount of damage tolerable during seismic loading. Categories range from S1, requiring no permanent deflection, to S5 where total collapse is acceptable. All Dock structures are Safety Category 1, Seismic Category S3 which permits some permanent deflection.

Features Of Design

Nuclear facilities in the UK are designed in accordance with the NII Safety Assessment Principles which, in common with modern standards, require designs to demonstrate redundancy, diversity, segregation and defence in depth solutions. These features are most applicable to plant and process design which are not considered in this paper. It is however worth noting a number of features of the design which are of interest.

General Risk Mitigation

The design philosophy adopted generally is to avoid the hazard if possible. In the case of dropped load this is made possible by the design of the crane. This alone is unlikely to provide sufficient reliability, therefore it is necessary to introduce hazard mitigation or containment. In the case of a dropped load this generally involves catching the load via provision of load follower or impact protection. The last resort in all cases being a 'consequences' argument. The seismic hazard can only be dealt with by mitigation or containment. For the civil structures this means designing the structures to resist the applied loads.

Low Level Refuelling

Current UK practice involves lifting fuel into and out of the submarine using large cranes. This increases the difficulty and cost of seismically qualifying the various refuelling components. The D154 project set out to minimise this risk by use of Reactor Access Houses (RAH) which are supported by the dock structures and which incorporate integral high integrity cranes. At the same time the docking level of the submarine is arranged to be just below cope level. These two factors minimise the lift heights as indicated schematically in Figure 3. In addition to this all fuel movement around the dockyard is at ground level.

Choice of Cranes

The use of goliath cranes is commonplace in dockyards, however, their use presents an unnecessary dropped load risk. This type of crane places a large part of the crane body directly over the submarine. In addition the crab is a significant weight at high level. Portal cranes with low centres of gravity were therefore chosen. Thus the significant weight of the crane is remote from the submarine. Only the lightweight jib and payload are ever over the vessel. Whilst the cranes are seismically qualified, the choice of crane reduces risks and helps directly towards achieving the required safety targets.

UPGRADE OF CIVIL STRUCTURES

The general scheme for strengthening the dock structures is the construction of a completely new liner, including a new floor, inside the existing docks. Reuse of the existing steel caissons (dock gates) was precluded by their condition and strengthening requirements for seismic loading. The existing sealing arrangement was also unsatisfactory for reverse hydrostatic pressure. New steel gates were not favoured due to lack of robustness compared with concrete caissons.

Loadcases

The civil structures are designed for normal, extreme and accidental loading. Normal loads include operational and 50year return period environmental loads. The operating basis earthquake (OBE) is defined as 0.03g peak horizontal ground acceleration (phga) at rock head. Extreme loads include environmental loads with a return period of 10,000 years. The most significant being the design basis earthquake (DBE). The DBE is defined as 0.25g phga. Both the OBE and DBE are consistent with the UK hard site spectrum. A safe margin assessment (SMA) to 0.35g phga is carried out to guard against cliff edge effects. The margin assessment draws on conservatisms within the design and reduces partial material load factors.

Dock Closure

Replacement caissons were designed for all three docks. These structures are massive rectangular cellular reinforced concrete gravity structures. They are floated into placed and sunk in position. Portable pumps are used for deballasting and trimming.

The caisson seals are critical to the design since rapid ingress of water could, if uncontrolled, lead to destabilisation of the docked down submarine. Because the caissons are gravity structures with no positive fixing, allowing greater operational flexibility, it was essential that the seals function over a large displacement range. The seals chosen have a nominal stroke of 250mm and are precompressed a minimum of 110mm at installation. This relaxed the need for tight control over the caisson during installation and meant that the relative movement of the caisson during a seismic event became less critical to the design. At DBE, the caisson was designed for zero base friction through to horizontal fixity. A coefficient of friction of zero may be considered overly conservative for concrete to concrete surfaces; literature suggests that a lower bound value might be 0.3. However, concern over silt ingress and uncertainty of the hydrodynamic effects during seismic excitation lead to the adoption of zero as the lower bound. Analysis showed that the peak relative displacement of the caisson was approximately 65mm and that the minimum seal precompression was maintained for DBE.

An elastomeric ‘stopblock’ is mounted on a sill upstand which also supports the horizontal section of seal across the bottom of the dock. The primary purpose of the stopblock is the prevent over compression of the seals during installation. Depending on the friction between the caisson and the sill, the stopblock also acts as a thrust block. The stiffness of the stopblock is such that it has a pronounced strong isolating effect at very low levels of friction.

In addition to preventing ingress of water into the dock during refit, the caissons were also required to maintain the dock full during floating trials post refit when subject to the OBE. To prevent excessive sliding of the caisson away from the dock during such a situation, a shear key between the caisson and dock sill was incorporated. The shear key was configured to allow reversal of the caisson and installation of a temporary seal to facilitate maintenance of the main seals.

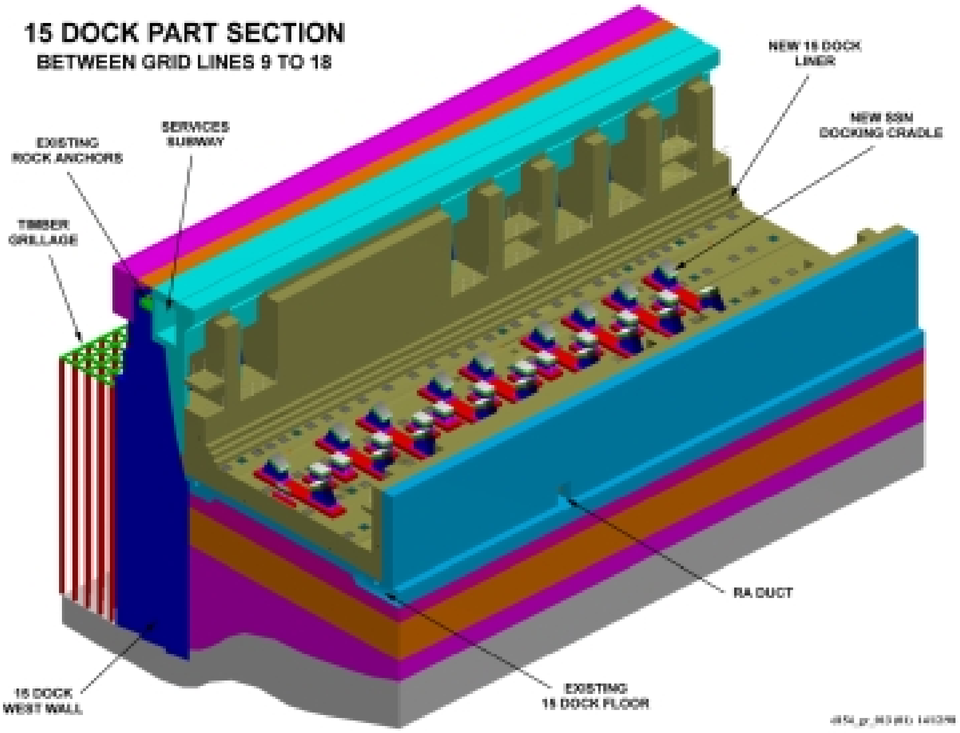
The potential for sliding and rocking of the caisson required non-linear analysis to establish the displacement demand imposed on the seal and the forces/displacements acting on the stopblock. Secondary response spectra where also required for safety related plant mounted on the caisson. The safety related plant included generators and free flood mains providing cooling water to the submarine.

Dock Walls

The basin and dock walls constructed circa 1900 are mass concrete up to 30m high with a retaining height of approximately 15m high and a base width of 9m founded on bedrock. The retained materials consist of a layer of very weak alluvium overlain by slate fill from the excavation of the basin itself. In some places a timber grillage was constructed by driving pitch pine timber piles into the alluvium with an overlying timber grillage to act as a relieving platform to support the slate fill during construction. The highly disparate stiffness of the alluvium and slate fill together with the timber grillage result in a potentially complex seismic respsone. Although the dock walls are all fairly similar the following discussion refers explicitly to 15 Dock

The basin walls forming part of 14 and 15 docks where strengthened by the installation of ground anchors in addition to a thin liner and buttresses as part of the SRC construction. A typical section of the 15 dock walls is shown in Figure 5. Although the retaining walls forming 14 and 15 docks are intrinsically robust, reliance was not placed on the long term performance of the ground anchors which were not counted on for strength of the upgraded structure.

Figure 5: Schematic of 15 Dock Wall



A significant feature of the original mass concrete walls is the presence of lift joints and weak mortar layers at day joints. The potential failure of these planes of weakness could result in sliding or overturning of the unstrengthened wall. The addition of the new liner prevents sliding along these planes but does not preclude opening of the joints should the existing wall anchors fail. Tensile failure of these joints not only reduces the flexural strength of the wall but also reduces the stiffness of the wall altering the seismic response. Thus no reliance has been placed on the existing dock walls for strength other than the self weight.

Joint opening also has a pronounced effect on the seismic motion at the top of the wall and hence on plant design. Secondary response spectra at the top of the dock walls are particularly sensitive to joint opening and closing. Joint opening causes a reduction in stiffness when the wall displacement is towards the dock as well as giving rise to high frequency energy on closure.

Analysis

A range of analysis methods were used to determine design actions within the strengthening elements and to derive input motion for safety related plant mounted on the dock floor and walls. To reduce programme risk, due to heavy external review, hand calculations were used to substantiate the strength of the new design with more detailed finite element analysis progressing in parallel to validate the strength calculations and produce secondary response spectra for plant.

The elastic solution was used for calculating the dynamic soil loads on the dock walls in conjunction with the equivalent linear soil structure interaction analysis software. Non-linear dynamic soil structure interaction analysis using the general finite element software LUSAS was used to cross validate the manual calculations and to demonstrate that non-linear soil behaviour and joint opening/closing resulted in less onerous wall loading. The finite element analyses were also used to determine input motion for the design of the RAH, dockside cranes and the submarine cradle.

The dock structures are generally fairly uniform (apart form some variations in bedrock and strata depths) in cross section with the exception of the 15 dock west wall which has a variable extent of retained materials. Two dimensional analyses were performed using plane strain conditions. Three dimensional non-linear dynamic soil structure interaction analysis was not considered practicable at the outset of the project. Various representative sections were analysed using a range of soil properties and input motions. Analysis also included various combinations of linear and non-linear elements within the model.

A non associative Mohr Coulomb soil model was chosen for the analysis. The material model chosen had been widely used in previous SSI studies. The constitutive model provided isotropic hardening. This type of hardening is inappropriate for cyclic loading of soils which tend to exhibit kinematic hardening. Although an elastic – perfectly plastic behaviour was assumed, kinematic hardening can be accommodated by using an overlay of elastic – perfectly plastic elements with progressively increasing yield stiffness. This approach was investigated at an early stage but not considered for the main analyses.

Analysis with a non-linear soil/wall interface and linear wall joint behaviour was considered inappropriate since rapid closure of the joint lead to the input of high frequency energy from the soil ‘slapping’ on the back of the wall. This effect was even apparent when the Mohr Coulomb soil model was used, since the closure forces acted to increase the confining stress in the material an thus enhanced the strength. The soil did not yield as one might first expect. Opening and closing of the wall lift joints also resulted in the input of high frequency energy. The results obtained form such analyses gave reasonable results in terms of displacement and structural actions but produced unrealistic secondary response spectra in the high frequency range. A soft closure interface model was required to give a more realistic representation of the expected behaviour. A substantial number of parametric analyses were undertaken to establish the sensitivity to input motion, soil stiffness, joint failure and wall cross section.

Time history results were provided to the plant designers in addition to SRS in cases where multi point (support) excitation required consideration. This was necessary in the case of the cranes where the motions at the rear and front legs differed significantly in the vertical direction and for the RAH which is supported on both sides of the dock.

CONTRACTUAL AND MANAGMENT

In awarding the contract, MoD were keen to minimise their exposure to risk of cost and programme overruns. They therefore adopted a strategy which appointed DML as a prime contractor. In essence this involves DML assuming overall responsibility of the project from inception to completion. This includes all procurement and management of construction. In this arrangement, MoD (the client) plays a relatively small role which is a marked departure from previous practice whereby MoD or their agents more closely controlled contract management.

The different approach was evident from the earliest stages in that the MoD’s requirements were contained in a simple Cardinal Points specification. This directed that a number of submarine refitting and support facilities should be provided and the dates when they were required by. Critically all elements had to be fit for purpose.

DML’s response to this was to prepare a detailed set of Contractor’s Proposals describing exactly how they intended to meet the client requirements.

Dart Alliance

DML established a team of leading organisations that would give them the ability respond to the invitation to tender. Whilst formally theses were subcontractors to DML, it was always the intention that the project would be run as an Alliance. This is a contracting strategy whereby the advantages of creating a team from industry leading organisations are maximised whilst the associated problems of friction created by working in a contractual environment are minimised. It also creates the opportunity to minimise cost by pooling of contract risk and the ability to take maximum advantage of innovation. This organisation, known as the DART Alliance (Devonport Alliance Redevelopment Team) comprised the following organisations:

DML	hold the main contract from MoD. Provides user and nuclear licensee knowledge
Babtie Group	main civil engineering design
Rolls-Royce	design and procurement of all fuel handling systems
Strachan & Henshaw	design and procurement of Reactor Access Houses and submarine support cradles
Brown & Root	building and infrastructure design
BNFL Engineering Ltd (BEL)	preparation of safety cases and design of LLRF facility

Under the main contract each organisation is a subcontractor to DML and formal sub contracts exist, although in practice the job is run in accordance with the Alliance agreement. This is a legal document which was created simultaneously with the creation of the main D154 contract. This method of working has been applied successfully in the offshore oil industry, and normally involves the client as a part of the Alliance. However as MoD funding is provided by public money they were unable to become a part of the Alliance although they were supportive of the contract being run this way. In most cases, parallel alliance or partnering agreements were established for subcontracts covering other major elements such as construction and major plant manufacture. This allowed a competitive tender process as well as the benefits of an alliance arrangement.

The prime contract fee for the work is a target cost incentive arrangement, whereby any savings below the target cost are split between the client and the prime contractor. Cost overruns are borne by the prime contractor. Within the Alliance division of the savings (or overspend) is based on the relative values of the individual subcontracts.

Work by the various partners is undertaken at a number of facilities around the UK. Whilst collocation of the entire design team would have been advantageous this proved impractical. However collocation of parts of the design team for various parts of the facility, again in various locations across the UK, has occurred successfully. An Alliance Project Team (APT) comprised of staff from all partners has been created and is based in Devonport. This is responsible for overall project management and also acts as the design authority for the design and construction of the facility.

The D154 Project is extremely challenging and brings together a broad spectrum of disciplines all of whom have to be managed to the achievement of success against the cardinal points specification set by MoD. All of this has to be achieved in a short timescale. It was the view of all parties that the creation and operation of an Alliance was a key factor in achieving this aim. It is preferable to channel the efforts normally associated with the negative aspects of contractor/subcontractor relationships to the creation of a mutually supportive, co-operative environment. Alliancing does not, however, represent an easy option. The disciplines of cost and programme control are rigorously applied although within an Alliance it is easier to arrange work or budget transfers to ensure that work is undertaken by the most appropriate party. This may be entirely different from that envisaged at contract award.