



**OTC-28803-MS**

## **Hebron Platform: Innovative Design and Efficient Execution**

Widianto, ExxonMobil Development Company; Justin Chichester and Adel Younan, ExxonMobil Production Company; Jameel Khalifa, ExxonMobil Development Company; Krishna Komperla, WorleyParsons; Knut Bidne, Kvaerner

Copyright 2018, Offshore Technology Conference

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 30 April–3 May 2018.

This paper was selected for presentation by an OTC program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Offshore Technology Conference and are subject to correction by the author(s). The material does not necessarily reflect any position of the Offshore Technology Conference, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Offshore Technology Conference is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of OTC copyright.

---

### **Abstract**

The Hebron platform was successfully installed on the Grand Banks (Offshore Newfoundland and Labrador) in June 2017 with first oil produced in November 2017. It consists of a single shaft concrete Gravity Based Structure (GBS) supporting an integrated drilling and production topsides. The design of the platform was challenged by sub-arctic and extreme metocean conditions which required innovative design and layout approaches for many elements considered routine for typical platforms. This paper highlights the underlying innovative technologies, analytical and design methods as well as the capital-efficient execution strategies employed.

### **Introduction**

The Hebron Project is located in the Jeanne d'Arc Basin, ~350 kilometers offshore Newfoundland and Labrador (NL), approximately ~ 6 nm north of the Terra Nova Field and ~10 nm southeast of the Hibernia development. The Hebron Platform ([Figure 1](#)) is comprised of a concrete Gravity Based Structure (GBS) and topsides installed in 93 meters water depth. Produced crude oil is stored in the platform's storage cells and pumped to shuttle tankers via an Offshore Loading System (OLS).

Concrete GBS's are proven concepts for arctic and sub-arctic regions in which robustness to ice loading (including iceberg impact) is a key design requirement. Considering their cost differential compared to other concepts, such as steel jackets and subsea solutions tied to floating production facilities, it is imperative to optimize all aspects of design and execution. In this paper, key Hebron design challenges are presented, and innovative design solutions as well as capital efficient execution strategies are illustrated for both the concrete GBS and steel topsides structure.

Additional information on Hebron Project are provided in [Cornaglia \(2018\)](#), [Parker et al. \(2018\)](#), [Edwards et al. \(2018\)](#), [Haddock \(2018\)](#), [Perry et al. \(2018\)](#), and [Ryan et al. \(2018\)](#).

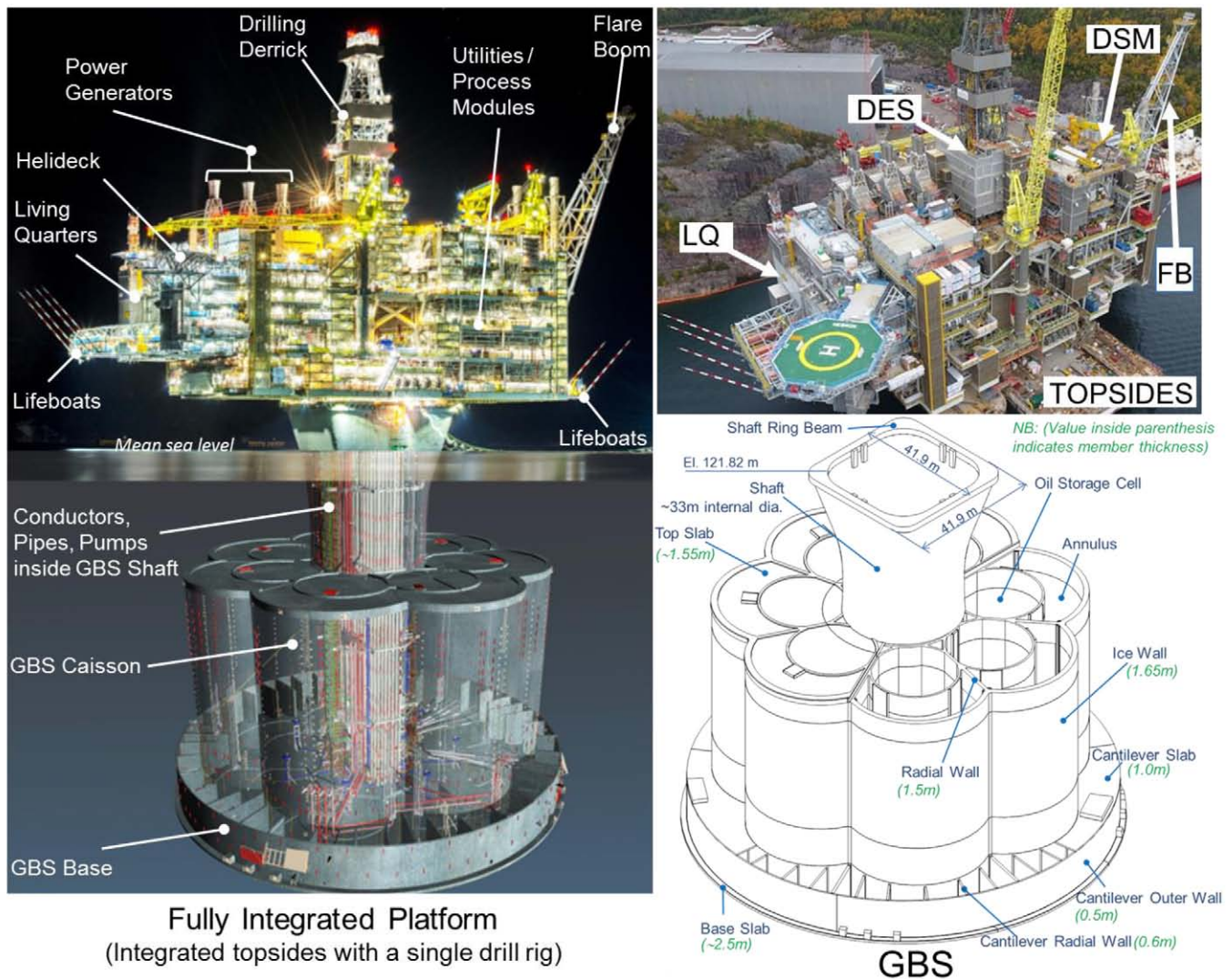


Figure 1—Hebron Platform

### Facility Descriptions

Hebron topsides are designed for full field development requirements including: drilling, production of crude oil, storage and export, gas management, water injection, and the management of produced water with a production life of 30 or more years. The GBS shaft hosts 52 well slots supporting water injection, production, and gas injection. The topsides facilities (operating weight 65,000 tonnes) include the following major modules (Figure 2):

- Utilities and Process Module (UPM),
- Derrick Equipment Set (DES),
- Drilling Support Module (DSM),
- Ancillaries (Flare Boom (FB), East & West Life Boat Stations), and
- Living Quarters (LQ), which is designed to accommodate 220 personnel during steady-state operations.

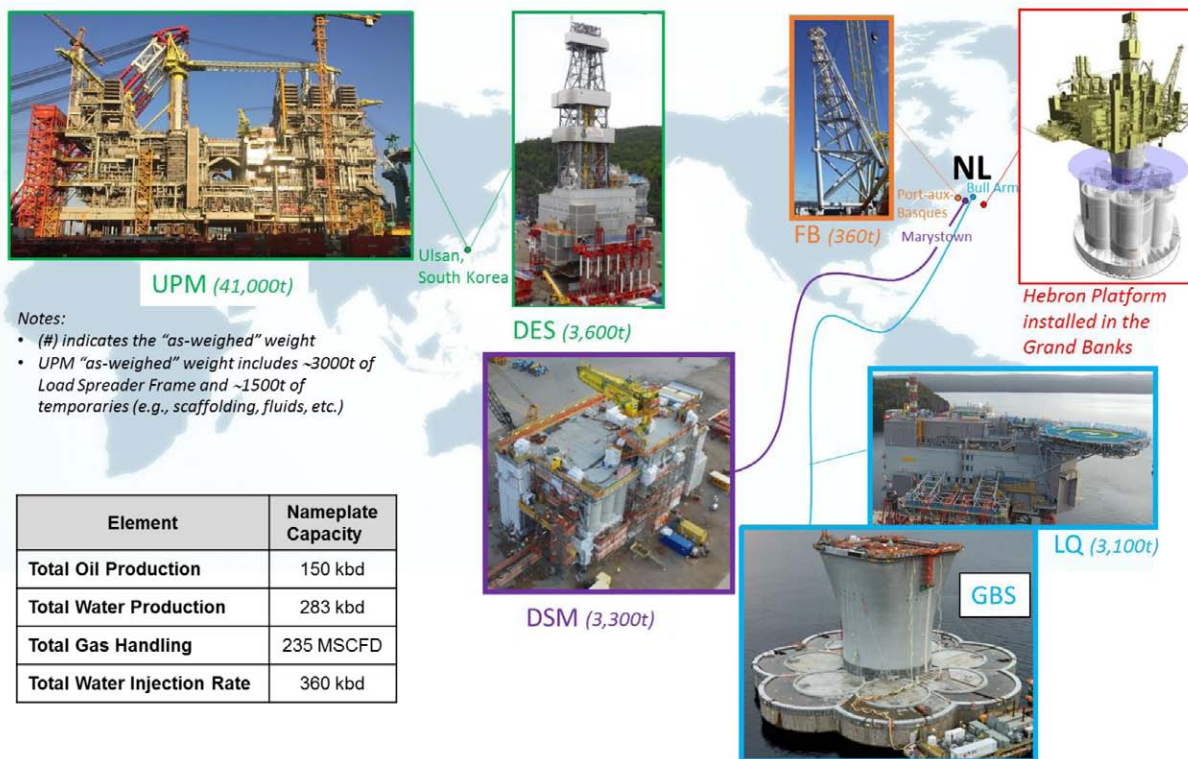


Figure 2—Hebron Platform Construction Locations for Major Steel Modules and GBS

Figure 2 displays the construction locations for the GBS and all major modules.

The total height of the platform with GBS is about ~235 meters, topsides length is ~183 meters and the width is ~75 meters. The GBS concept includes a single shaft supporting the topsides and encompasses all wells in the initial development. It is designed to withstand sea ice, icebergs, meteorological and oceanographic conditions at the offshore Hebron site. The GBS is designed for an in-service life of 50 or more years to support future developments.

The facility uses a single Offshore Loading System (OLS) which consists of a looped seafloor pipe and two separate subsea loading systems designed for an offloading rate of 6700 m<sup>3</sup>/h (~50,000 bbl/hr). The two bases, North and South, remove crude oil product from the offshore facility to an awaiting shuttle tanker. The OLS includes two main offshore pipes with a 610 mm (24-inch) outer diameter, each running approximately 2 km from subsea flanges at the base of the GBS to two separate Single Anchor Loading (SAL) bases. The two SAL bases are connected by a 610 mm (24-inch) outer diameter interconnecting offshore pipe approximately 1.85 km long to form a looped piggable pipe. The pipe loop arrangement allows for pigging operations to remediate the build-up of wax and to allow for flushing of the loading system. The loop can be warmed prior to offloading by circulating warm oil. Flushing can be performed from the platform to the shuttle tanker, and vice versa for flushing of OLS hose system, if required. The launcher and receiver were also designed to accommodate intelligent pigs for pipe inspection purposes.

### Construction Overview

The GBS was constructed from the base to the top at Bull Arm, approximately 150km Northwest of St. John's, NL, Canada. The lower portion of the GBS up to elevation ~27m was constructed in a dry-dock created by building a bund wall and dewatering the site behind it. Subsequently, the dock was flooded, bund wall removed, and GBS base (weighing approximately 180,000 tonnes) was towed approximately 3km to a deep water site. The floating GBS was held in place with nine mooring lines while the remaining



construction was completed. All walls were constructed using the slipforming technique. More detailed information on the GBS construction and key quantities is presented in [Widiyanto et al. \(2016\)](#).

The topsides structure was fabricated in modules at various locations in NL and South Korea. Two of the topsides modules, UPM and DES, were fabricated in South Korea using "block/pancake" construction methods (i.e., the deck was fabricated, as much as practical, on a level-by-level basis and lifted over pre-installed columns and/or vertical bracing members), as shown in [Figure 3](#). After the UPM and DES fabrication was completed, the modules were separately loaded-out to Heavy Transport Vessels to be transported to Bull Arm NL. All the other topsides modules were integrated to the main UPM module at the finger pier in Bull Arm and the completed topsides structure was mated with the GBS while floating at the deep water site. The mated platform was then towed offshore and installed at the final offshore location.

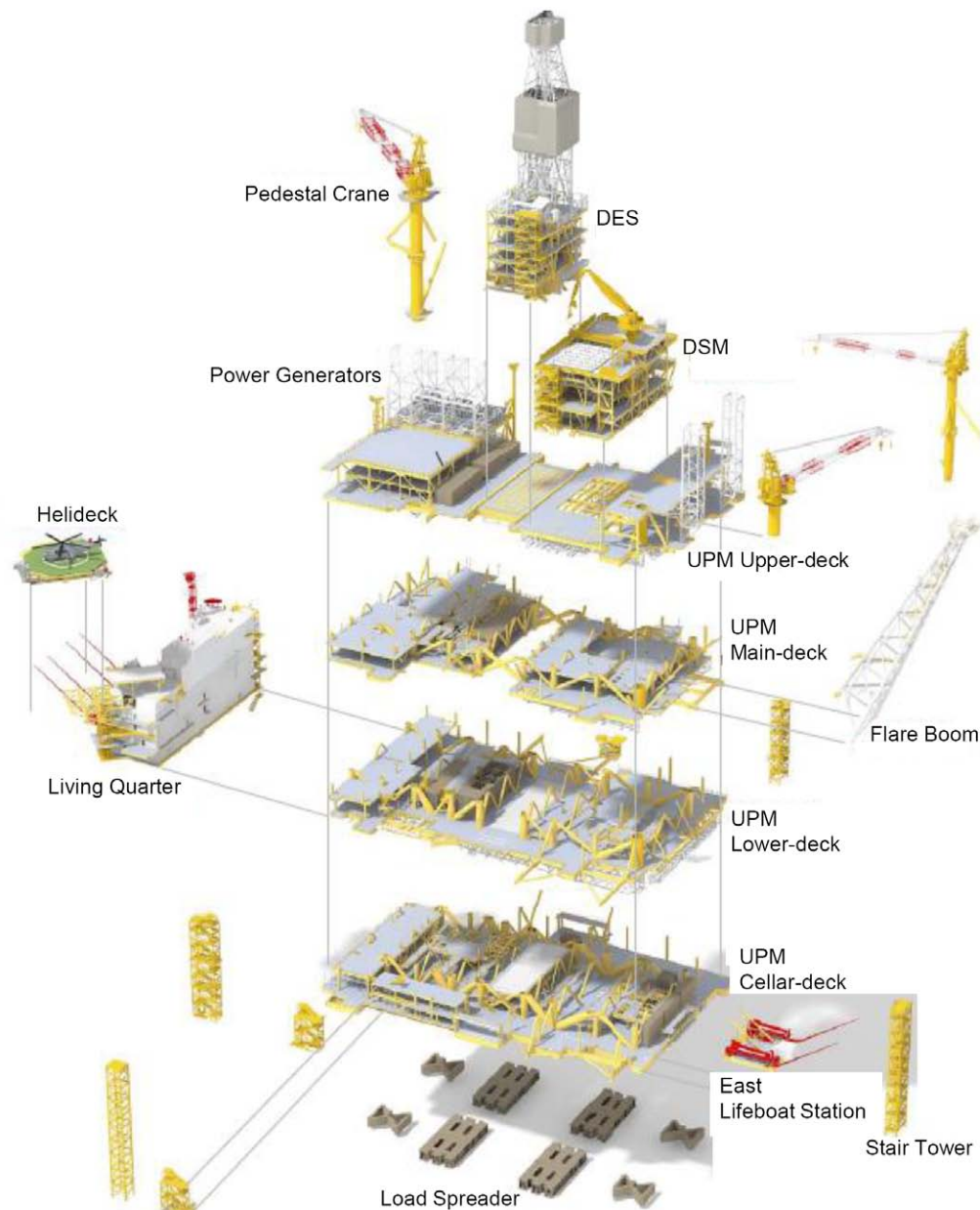


Figure 3—Hebron Topsides Block Division for Construction

## Key Challenges

Some of the key design and execution challenges are discussed in this section.

### Iceberg Impact Load

The International Ice Patrol's website archive of icebergs drifting south of latitude 48° N dating back to 1900's shows annual iceberg counts ranging from zero to more than 2,000. These icebergs drift into the area where the Hebron platform is installed, and therefore it was essential to design the platform for iceberg impact.

Iceberg impact was considered at two return periods: 100-year and 10,000-year. The load generated at the first return period is an Extreme Level Ice Event (ELIE) while the second is considered an Abnormal-Level Ice Event (ALIE), a very rare event per ISO 19906. It should be noted that a 10,000-year event corresponds to an annual probability of exceedance of  $10^{-4}$ .

The development of iceberg impact loads for the Hebron GBS was based on state-of-the art probabilistic analysis that satisfies ISO requirements. In addition, a range of expert opinions representing Type II uncertainty was covered using a logic tree analysis. This uncertainty analysis ensures stability of the design recipe as it protects it against future change of opinions.

The 10,000-year iceberg impact load on the caisson/ice wall (which is governed by the iceberg impact) is 486 MN. More detailed information on the development of iceberg impact load for Hebron GBS is presented in [Widianto et al. \(2013\)](#).

### Single Shaft

The conceptual design of Hebron platform started with the topsides weight that was significantly less than the current operating weight of 65,000 tonnes. Therefore, a single shaft that offered benefits such as smaller caisson size (hence attracting less ice and wave loading), lighter GBS (attractive for floating stability), and less concrete volume was selected. Despite those benefits, the implementation of a single-shaft concept for Hebron presented technical and execution challenges:

- The single concrete shaft results in fewer and more closely spaced topsides support points with higher loads per support and a longer cantilevered topsides structure. This results in higher forces on topsides members and nodes which drives:
  - Higher strength grout/concrete and denser reinforcement, which presented a significant constructability challenge.
  - Large topsides baseplates which presented a challenge to ensure that the grout would completely fill the entire space underneath the baseplates.
  - Larger member/node sizes and thicker plate thicknesses, beyond applicable limits of current empirical existing code/standards formulas.
- The combination of a large diameter single-shaft, the relative shallow water depth over the caisson roof elevation, and large design wave height resulted in large wave slamming loads on the GBS shaft and on the underside of topsides, as discussed in the following section.
- All drilling, process, and piping interfaces with the oil storage cells and outside environment, needed to be located in a congested wet shaft (i.e., shaft filled with sea water) resulting in constructability complexity.

A single shaft concept prevents the more traditional separation of utility and process components into separate GBS compartments. As such, close attention was paid to loss prevention challenges including the design of a submersible firewater pump arrangement within robust protective caissons, ventilation of the shaft to meet regulatory requirements, risk mitigation of potential dropped objects during drilling operations, and strategically placed blast and firewalls on the topsides.

## Wave Impact

The combination of GBS geometry, overall water depth, and metocean conditions resulted in large wave impacts on the GBS shaft and underside of the topsides structure, and local upward accelerations on the topsides structural steel and some equipment.

Figure 4 shows a schematic of the wave-structure interaction and snapshots from wave model tests. The wave-structure interaction consists of the following (see the numbers shown in Figure 4 for illustration):

- Wave impact on the GBS shaft
  1. The shallow water depth above the caisson causes a shoaling effect resulting in large waves that break and accelerate the crest forward.
  2. The accelerated crest causes a high wave impact load on GBS shaft. Wave model tests revealed that these wave impact loads were higher than those based on current industry standard
- Wave run-up
  3. The wave front runs up the shaft, impacting the underside of the topsides
- Rooster-tail: topsides
  4. Due to the large shaft diameter, the wave front splits around both sides of the shaft and collides at the back of the shaft (5), creating an upward jet (rooster-tail) that impacts the underside of the topsides

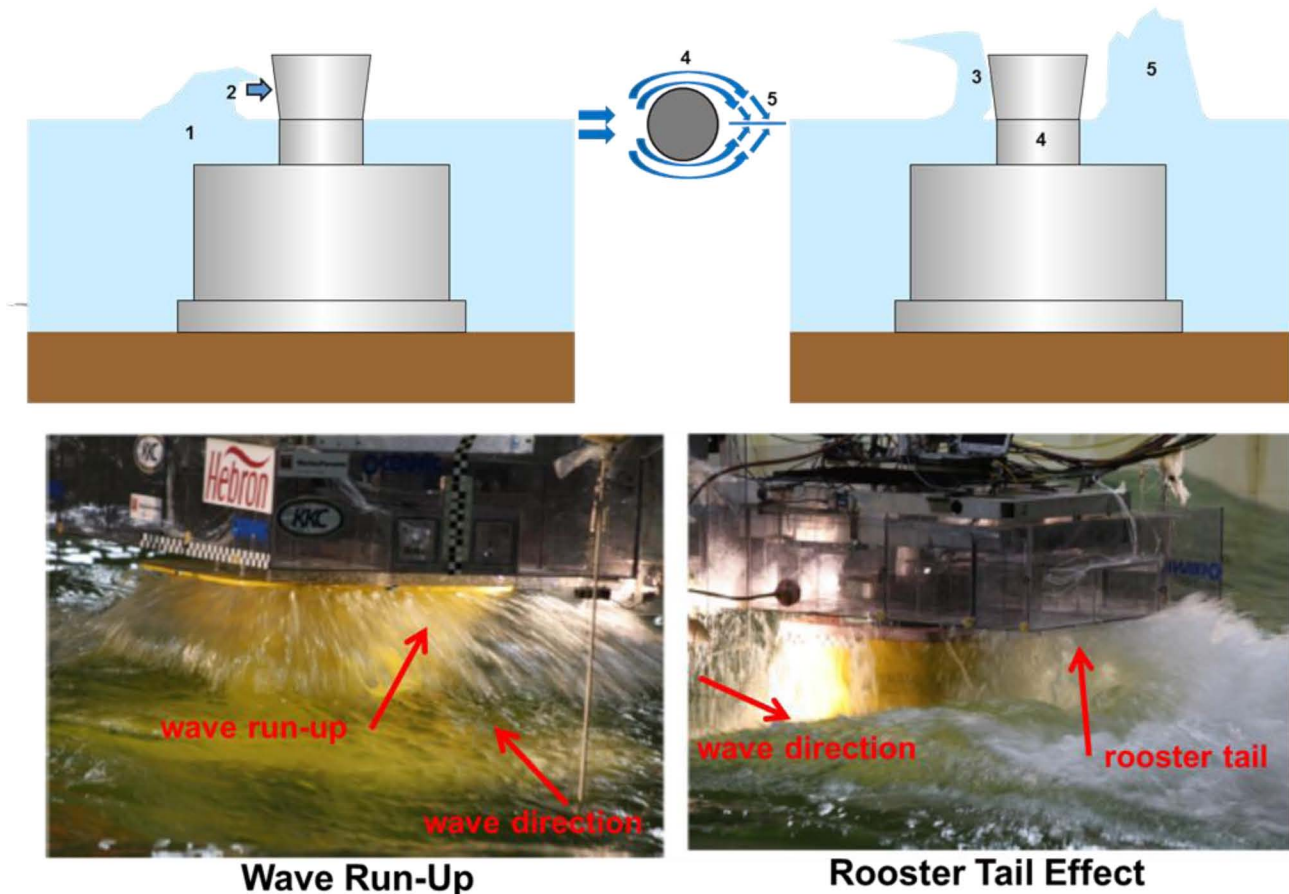


Figure 4—Hebron Platform Wave-Structure Interaction



More detailed information on wave model tests and the analysis approach to define the wave impact loads are presented in Oberlies et al. (2014).

The magnitude of the wave impact load is significant, up to about 2.2MPa pressure on the GBS shaft. This resulted in a design load of 108 MN within a 50m<sup>2</sup> area placed everywhere along the circumference at the shaft just above the waterline.

In order to resist the impact load from the wave run-up and the "Rooster-tail", the underside of the topsides' cellar deck was shielded with wave slamming steel (Figure 5) consisting of 10-mm/12-mm thick plate stiffened by inverted T-stiffeners. This differentiates Hebron topsides from other topsides structures. Maintenance platform lugs were installed on the wave impact steel to facilitate periodic inspection.



Figure 5—Wave Slamming Steel Underside of the Cellar Deck

### Crude Processing

Hebron's crude has a design API gravity of ~19° for its largest formation and required a combination of unique topsides facility elements to economically produce. The facility includes provisions for gas injection, gas lift, and water injection for reservoir pressure maintenance and artificial lift. Processing of oil below 22° API gravity traditionally requires large tanks or vessels with extended residence times to separate the

oil and water. ExxonMobil's onshore heavy oil facility in Chad utilizes ~20 acres of tankage and facilities to separate and process the same nameplate capacity as Hebron (~150kbd) which is accomplished in ~4 acres.

### Worldwide Construction

As described in the previous section, the construction of platform modules was performed in various locations worldwide. After being fabricated in South Korea and various steel fabrication yards in NL, all topsides modules were transported to be integrated at the finger pier in Bull Arm NL. The upper right picture in Figure 1 shows the completed topsides (after integration of all modules).

Structurally, the topsides experienced multiple construction/transportation/temporary phases with various loading and support conditions different from those associated with the operation phase (Figure 6). Since these temporary phases governed the design of many parts of the structure, various loads and support conditions during temporary phases were analyzed. "Locked-in" stresses were also accounted for in the design.

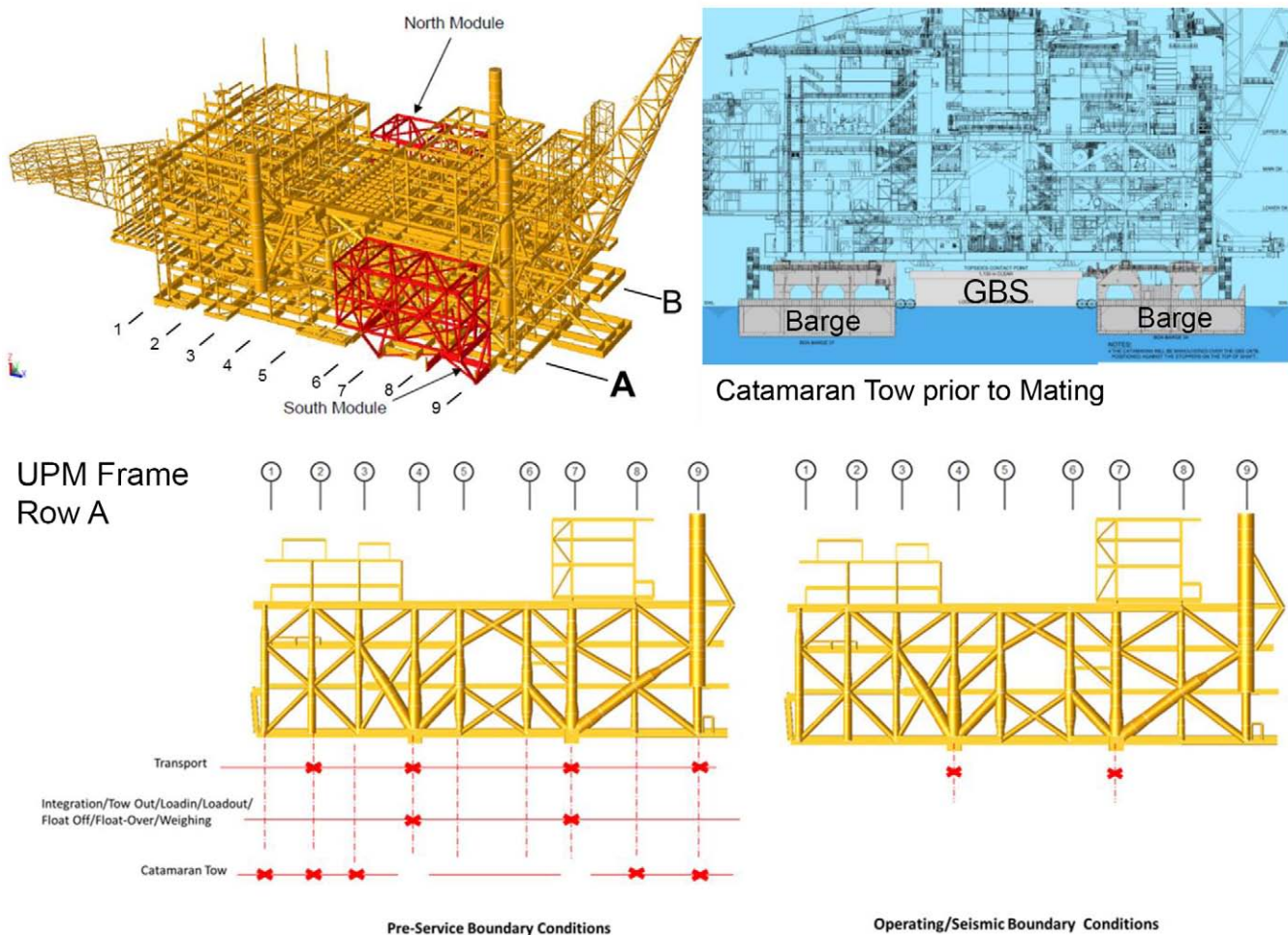


Figure 6—Structural Analysis Model and Various Support Conditions

Focus on large module dimensional control is critical for any integrated platform fabricated in multiple geographic locations. In order to ensure that all modules fit together during fabrication and integration without clashes, a comprehensive dimensional control survey program by an independent third party was critical. While each fabricator was required to perform standard dimensional control, key integration and operational dimensions were assessed by the same third party using state-of-the-art survey equipment, combined with detailed 3D modeling, and structural analysis (to estimate structural deformations during



various phases and adjust the survey results as necessary). This philosophy allowed Hebron to integrate all modules at Bull Arm NL with no major clashes and ahead of schedule.

Effective management of interfaces among various Contractors (e.g., topsides and GBS Engineering, Procurement, Construction/Fabricators, Load-out, Load-in, Integration Contractor, Heavy Transport Vessels Contractor, Marine Operations Contractor, etc.) was crucial in order to ensure smooth execution. In addition, effective weight control and weight management were one of the key enablers for successful integration.

## Capital Efficient Design Considerations

Capital efficiency and project viability do not always emerge from a single decision, but from a series of elegant solutions working together driving value into design. These solutions must work to overcome the project's key challenges. This section presents several capital-efficient considerations implemented in the design of Hebron platform, which do not compromise the general code requirements. Optimization was a joint effort among various parties to search for capital-efficient solutions.

### Facility Optimization

Through the use of Vessel Internal Electrostatic Coalescer (VIEC) in the main separator and the Compact Electrostatic Coalescer (CEC) in the second stage of separation, Hebron is able to reduce residence times and process the full name plate capacity on an equivalent of 20% of onshore facilities spacing.

In addition to the above project enabling technologies, it is a combination of many technological advancements working together that drives design efficiency while considering many of Hebron Platform unique considerations, specifically: an open platform architecture, strategic placement of fire and blast walls, cutting edge submersible and line shaft pumps, space and weight savings heat exchangers, and passive exhaust coolers on the main power generation trains.

***Open Platform Architecture and Strategic Placement of Blast and Fire Walls.*** Recognizing the platform is located in sub-arctic climate with less extreme temperatures than other true arctic environments, the topsides was designed with open architecture and strategically placed blast walls that maximizes natural ventilation while providing fire and blast protection for key safety critical components. The blast walls were placed to segregate the LQ / utilities from the wellbay, wellbay from the processing section, processing section from the east end lifeboats, and the DSM from the gas compression area.

***Cutting Edge Submersible and Line Shaft Pumps.*** The Hebron platform single shaft configuration drives all necessary firewater, seawater, and crude oil booster pumps to be placed in the same GBS shaft as the wellbay. As a result, a pump system that is mounted and retrievable from the topsides (without entering the GBS shaft for maintenance or operation) is required. This, coupled with the required air gap height of 30.4 m between the topsides and the Mean Sea Level (MSL), drove the project to employ submersible seawater pumps which are among the longest in industry (46.8 m) and the longest in industry line shaft crude booster pumps (47.4 m) which lift crude from the GBS storage cells to topsides for offloading to shuttle tanker. The primary driver for the long length is the required air gap height between the topsides and sea level to accommodate North Atlantic environmental conditions (e.g., large waves and icebergs with high sail height). These pumps were specifically designed to work with the Hebron platform height and to minimize the "on deck" footprint while still performing the intended functions.

***Space and Weight Savings through Heat Exchanger Selection.*** All types of heat exchangers for all applications were carefully selected to fully optimize the space, weight, and cost. As a result, the use of more conventional shell & tube exchangers was minimized in favor of more compact plate & frame and printed circuit heat exchangers. In the gas compression trains, all gas cooling systems are printed circuit, allowing for a greatly reduced footprint and overall costs.

**Passive Exhaust Coolers.** During the first few years of operation, the Hebron platform produces more power than is required to harvest energy through the waste heat recovery units. As a result, short term hot exhaust temperatures could limit access to the upper derrick which would infringe on important drilling equipment during prevailing wind conditions. The project identified and employed a passive exhaust plume cooling / dilution system which contains no moving parts and reduces the output exhaust temperature by up to 50%. This allows drilling to proceed unimpeded during unfavorable wind conditions without personnel limitations on the derrick during early field life. Additionally, the design geometry of the coolers allowed for reduced wall thickness when compared to traditional exhaust stacks resulting in a lighter supporting structure.

### **Constructability**

The design of GBS and topsides was done based on comprehensive constructability input from Construction/Fabrication Contractors throughout the design process starting from the conceptual phase. The constructability effort and feedback improved execution certainty and ultimately eliminated potential schedule delays.

**GBS.** Constructability aspects were approached systematically beginning with the concrete mix design development program started prior to Front End Engineering Design (FEED), all continuing to the end of construction in the field. To accomplish this, a team of construction specialists was established at start of FEED. In order to improve constructability, numerous full-scale mock-ups were carried out during the design phase and are described in a later section of this paper.

**Topsides.** Realizing the critical path fabrication schedule, the South Korean fabricator identified key personnel who would be working on fabrication drawings, and these individuals were brought on board early before the start of the detailed design phase. A procedure was established, which enabled the Fabricator's engineers to review the topsides design drawings and make recommendations that were assessed and incorporated where possible into the EPC engineering design and drawings.

Some examples of notable Fabricator recommendations include:

- Preferred steel materials and sections. Using Fabricator "preferred" steel improved procurement and overall fabrication schedule.
- Efficient concentric nodes fabrication methods and procedures
- Weldability and welding clearances
- Fabrication dimensional tolerances
- Constructability input on wave slamming steel fabrication/welding
- Schedule-effective "block/pancake" construction methods. In addition to main deck levels which are normally being constructed in block/pancake approaches, mezzanine decks were also fabricated in parallel with the main decks and then placed on the corbels of the topsides columns. Since mezzanine decks are not integrally built with topsides columns, in-situ welding and wait-times were eliminated, resulting in shorter overall fabrication time.
- Several highly involved topsides nodes and details were re-analyzed and detailed in a manner that is easier and safer to build, due to the fact many of the large diameter nodes and wave slamming steel created enclosed/ hazardous spaces while welding.
- Provisions to share cable tray space between the EPC and Fabricator in particular for fabricator designed cable runs
- Methods to handle 3D model exchange between the EPC designer and Fabricator
- Early methods to handle installation of key equipment

This early Fabricator input in the detailed design phase made it possible to fabricate the topsides primary steel with minimal technical queries and redlining of drawings, which typically impacts the construction schedule in many other projects. In essence, the Fabricator started shop drawing production based on Contractors' engineering drawings that had been fully endorsed by the Fabricator's Construction and Quality departments. Ultimately the UPM module left the Fabrication yard with less than 0.5% nominal carryover work, far less than industry average during heated market conditions.

### Topsides Concentric Nodes Configuration

Compared to eccentric nodes commonly used in other topsides offshore structures, the concentric nodes configuration (with member work points having minimum possible eccentricities as shown in Figure 7) chosen for topsides nodes on the two main longitudinal frames resulted in more open space and optimized the total platform weight. However, this also presented some challenges on both design and fabrication.

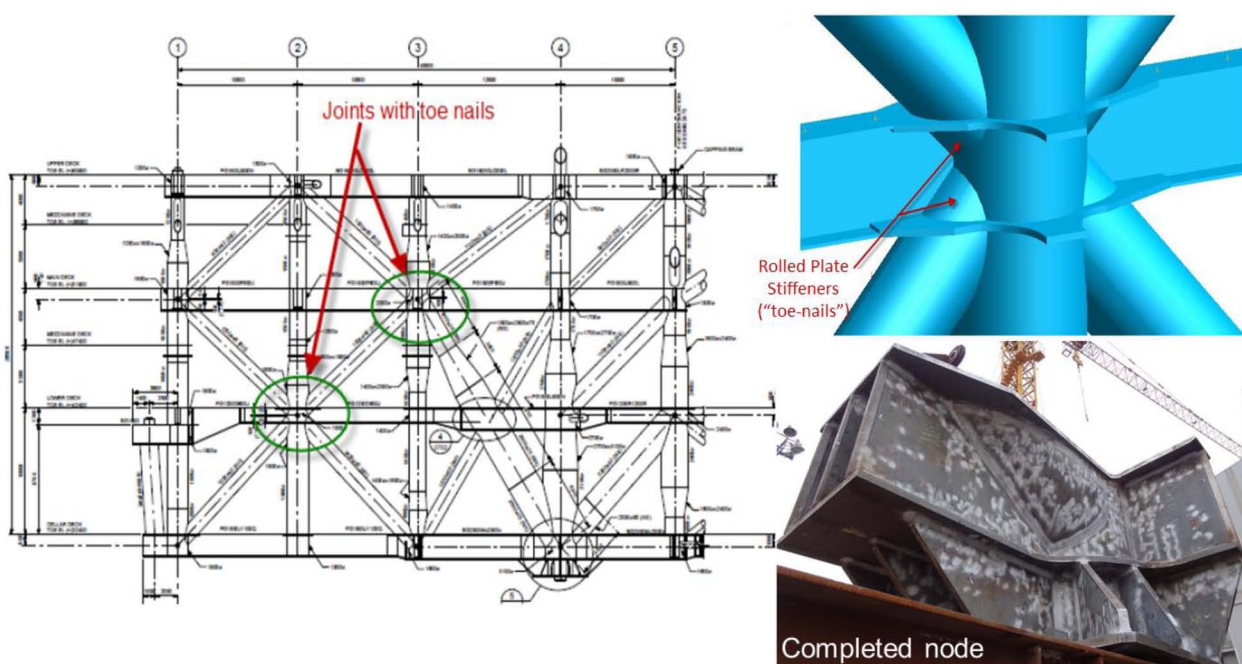


Figure 7—Concentric Node Configuration

- Design Phase challenges:

The geometry configuration of a complex concentric node shown in Figure 7 would not fully align with the existing specified configuration of tubular joints in ISO codes (primary design code of topsides) or API, such as T, K, Y, and X joints. Therefore, these complex nodes were designed in a two-step process that involved the initial design using code provisions, with appropriate interpretations, and finalization of the design using FEA. For complex joints, compliance with stress limit criteria based on linear-elastic FEA would not produce the optimum design due to hot-spot (localized) stresses. Therefore, in order to produce weight-saving designs, a strain based criterion has been applied at the location of hot spot stress regions, using non-linear FEA (to capture stress redistribution) with an appropriate material constitutive relationship that includes strain hardening.

In addition, the design of joints had been performed for the actual combination of joint forces at every node, for every load case, with no overdesign associated with using envelope maximum forces for the members, as normally done to save computational time and effort.

- Fabrication Phase challenges:



Fabrication of complex concentric nodes is challenging, especially during rolling and fitting-up curved stiffeners (phrased as ‘toe nail stiffeners’) at the far side of the flange plates where the tubular members intersect the joints. Due to early Fabricator input implemented in design (such as maximum plate thickness) and Fabricator experience and capability, rolled plated stiffeners up to 90 mm thickness were successfully fabricated, fitted-in and welded in compliance to fabrication specifications.

### **Topsides Design Consideration for Iceberg Impact**

Survey of icebergs indicated that a significant percentage of icebergs in the Grand Banks are "Dry-Dock" and "Pinnacle" icebergs, which tend to have high sail heights that could impact an overhanging deck of the topsides structure. Unlike the concrete GBS, it is cost prohibitive to design the topsides structure for iceberg impact load. Design codes (CSA S471-06 and ISO 19906) require the use of an air gap (vertical distance between the underside of topsides structure and the sea level) to achieve  $10^{-5}$  probability of iceberg impacting topsides and permit iceberg management (utilizing supply vessels to tow icebergs away) in determination of iceberg to topsides impact probability.

Since the air gap has complex impacts to drilling and production facility design as well as overall cost, it was important to optimize the air gap distance. The probability of icebergs with high-sail height impacting an overhanging deck of topsides was computed using the Monte Carlo approach with over 1.5 million simulations. In order to meet the code requirement of  $10^{-5}$  annual probability of impact, a 30.4m air gap was selected and the LQ module was raised vertically an additional 10.8m. Iceberg Management with 80% effectiveness was also included, considering that Iceberg Management is a routine activity on Grand Banks for protection of offshore facilities.

### **Non-Linear Finite Element Analysis (NLFEA)**

Internal forces used to design offshore concrete GBSs are typically calculated using linear-elastic finite element analysis. However, during analysis and design of Hebron platform, complex NLFEAs were effectively utilized for the analysis and design of the following:

- Ice walls subjected to 10,000-year return period iceberg impact  
NLFEA captured the redistribution in internal forces due the cracking of concrete under tension, allowing the ice wall to carry more load as membrane compression rather than bending. This is much more efficient since concrete has a greater capacity to resist compression. Nonlinear behavior also reduced the peak forces/moments due to redistribution. Compared to a linear elastic analyses, the use of NLFEA in ice walls design resulted in improved constructability and construction safety, considerable cost and schedule savings: ~3,500t less reinforcement; ~700t reduction in post-tensioning cables; and reduced risk of schedule delays. Detailed analysis and verification of these NLFEA are presented in [Widianto et al. \(2013\)](#).
- GBS Shaft subjected to 100-year and 10,000-year return period wave impact  
The use of NLFEA in the shaft reduced the peak tension in shaft walls due to overall bending thereby reducing the reinforcement by 300t and, more importantly, reducing the number of layers of reinforcement from two layers to only one layer on each face of the shaft cross section, resulting in a more constructible shaft wall. The reduction of the amount of reinforcement in the critical high density wave impact area was about 50% and crucial for a successful slipforming operation of the shaft.

### **Integrated Seismic Soil-Structure-Interaction (SSI)**

The implementation of an integrated seismic SSI proved to be efficient and effective in performing the seismic analysis and design of all components of the Hebron platform through consecutive project phases and various contractor structural models.

The method consists of the following steps (Younan et al. (2015)):

1. Developing a benchmark SSI one-step model for GBS and topsides, which was maintained by an SSI expert company
2. Providing impedance functions and seafloor motions to EPC contractors for use in structural models
3. EPC contractors running structural models with provided impedances and seafloor motions
4. Acceleration response spectra at a number of GBS and topsides locations, computed by contractor models (in various parts of the world), must match those obtained by the benchmark SSI model.

This approach enabled different EPC contractors (GBS and topsides) to perform their own separate SSI analysis using the same foundation properties developed by the geotechnical contractor, resulting in a more efficient design process with different levels of detailing according to the component of interest.

### **Foundation Optimization**

Hebron GBS has a flat, circular base slab with 500 mm deep soil skirts. Several key considerations related to the foundation design optimization for the Hebron GBS are as follows (Tistel et al. (2015)):

- Elimination of scour protection

GBSs located on sand are in some cases subjected to scour, especially around corners and edges of the structure where the seabed current is amplified. The circular shaped foundation for Hebron was favorable when considering scour. Furthermore, a comprehensive scour risk evaluation was carried out for Hebron including assessment of seabed material (grain size), historical current, and experience from nearby GBS to conclude that installing scour protection around the Hebron GBS was not needed. Instead, a comprehensive periodic and after-storm scour inspection plan were implemented.
- Elimination of underbase grouting

A comprehensive assessment (including survey) of seabed bathymetry and soil properties concluded that the platform could be installed directly on the seabed without performing offshore underbase grouting. Finite element analyses were also used to assess local stresses against the base slab and the foundation base slab was designed for local peak stresses caused by the minor unevenness of seabed.
- Optimization of skirt depth

Corrugated steel skirts were used mainly to increase the horizontal sliding resistance by transferring the loads deeper into the soil where it is stronger. From a constructability perspective, shorter skirts are cost effective because they require shallower trenches in the dry-dock construction site (less construction work), minimize the negative impact from skirt length to the draft requirement during tow, and are subjected to smaller stresses during soil penetration at installation. In order to improve roughness and sliding resistance, the GBS foundation base slab was cast directly on a sufficiently coarse aggregate bed in the dry dock.

### **Early Development of Concrete Mix Design**

There are several distinctive characteristics of the Hebron GBS that challenged the design and construction compared to typical buildings and bridges:

- Heavily stressed and reinforced—average reinforcement density of over 300 kg/m<sup>3</sup> compared to 75 to 150 kg/m<sup>3</sup> for typical concrete buildings and bridges.
- Much higher compressive strength (specified compressive strength of 65 MPa)
- Higher slump to deal with congested reinforcement (240mm initial slump and >200mm after 2 hours)

- Lower w/cm ratio (maximum water to cementitious materials ratio) and lower Chloride diffusion coefficient to improve durability
- Resistant to freezing and thawing for the splash zone
- Low heat of hydration to minimize the risk of cracking on thick sections (up to 3.2m at the base slab)

In order to minimize the risk of any schedule delay, the development of concrete mix design was started 2 years prior to the first major casting of the base slab. The mix design process started with identification and prequalification of materials followed by extensive trials with multiple types of cement, aggregates and admixtures to determine the combination that met all the design requirements.

### **Concrete Crack-width Calculation**

Crack-width provisions in various codes and standards are semi-empirical, based on test results of relatively small-scale "beam" type specimens. None of test specimens had multiple layers of transverse reinforcement similar to those used in the Hebron GBS elements. The currently available semi-empirical formulas generally required additional reinforcement beyond those required by the ultimate limit state.

A new method for calculating crack width in thick elements with multiple reinforcement layers was implemented in the design of Hebron GBS. This method accounted for the crack-initiation effect from several layers of transverse reinforcement that is not fixed/welded to the main reinforcement and was validated by a parametric study using NLFEA. The new method did not require any additional reinforcement beyond that needed for the ultimate limit state, which improved constructability.

### **Capital Efficient Execution Considerations**

This section presents several capital-efficient considerations implemented in the construction of Hebron platform, mainly to improve execution certainty (avoiding cost associated with rework/repair) and reduce risk of schedule delay.

### **Topsides Fabrication and Integration**

Topsides consists of a large integrated deck with separate drilling support and derrick equipment modules, LQ module with helideck, flare boom module, and lifeboat structures. The integrated deck contains all process and utility systems, workshops, switchgear, and instrument rooms. Utilizing the integrated deck concept minimizes the inter-module piping, electrical, and instrumentation connections. It also maximizes the amount of checkout and precommissioning that can be accomplished before the module is transported to the final integration location.

Tanks within the UPM were fabricated as separate modules, tested and commissioned at the tank fabricator yard prior to being transported to the main Fabrication yard. Then, the fully-tested and commissioned tanks were installed in synchronization with the "block/pancake" construction of the UPM.

Assembling of the LQ was done inside the module hall at Bull Arm by stacking all levels indoors. After the majority of work was completed indoors, the LQ was moved outdoors for final completion ([Figure 8](#)).



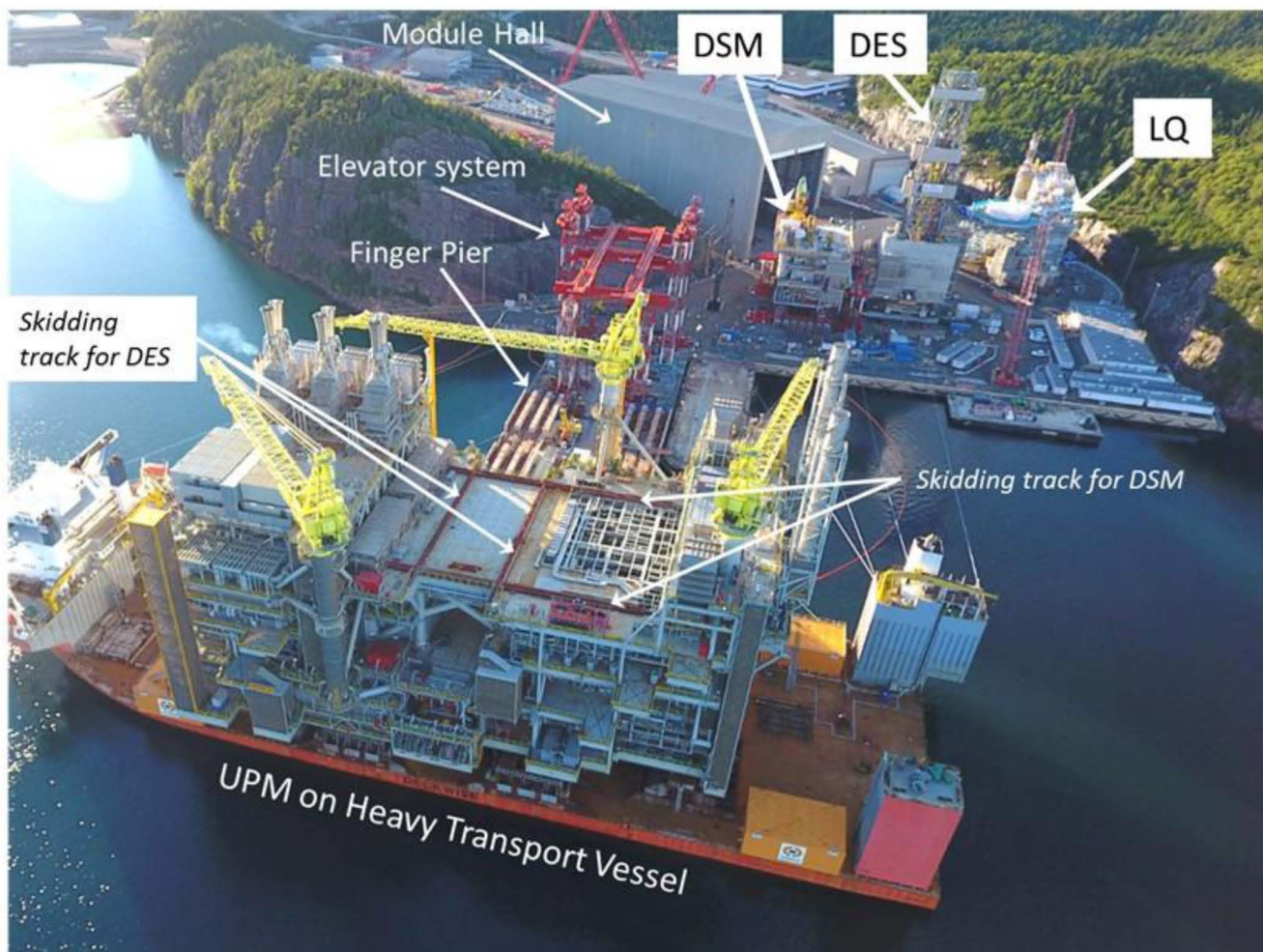


Figure 8—Integration of Topsides Modules at the Bull Arm Finger Pier

### Mechanical Completion and Commissioning

A "zero carryover" philosophy was implemented, meaning that achievement of mechanical completion and commissioning of each module to the fullest extent possible at each location before release to the subsequent phase (i.e., fabrication yard, Bull Arm integration pier, DWS, and final installation site location).

### Comprehensive Dimensional Control Survey

Typical dimensional control in South Korean fabrication yards involves dimensional surveys by Fabrication Contractor's Quality department, at each stage of modular construction to comply with the specified fabrication dimensional tolerances. For Hebron, with the added emphasis to avoid any potential construction delays as a consequence of dimensional misfits among the interface modules and the main UPM, a parallel and independent dimensional control program was developed using the services of specialist Survey Company. A rigorous dimensional control check list was developed and items on the check list were closely monitored for fabrication out-of-tolerances, by both the Fabricators and specialist survey teams working in tandem. All reported out of tolerances were analyzed by Engineering Team and corrective actions were taken during the fabrication phase itself, before sending the modules to Bull Arm.

Key items that were tracked and monitored through these dimensional surveys include: interface connections between UPM and ancillary modules LQ, Flare boom and Life boat stations, capping beams for DES skidding, and DSM support stools. One unique feature of this dimensional control program was embedding the engineering assessment of deflected configuration of the UPM in its various support configurations from South Korean fabrication yard to the integration pier and including those

calculated deflections into the fabrication so that the final deflected configuration would permit problem-free installation of interface modules and smooth skidding of Drilling rig. Meticulous management of dimensional control and corrective actions enforced during various stages of fabrication is one of the key successful enablers for integration of various modules that were fabricated in various locations.

### **Comprehensive Weight Control**

Similar to dimensional control, developing a robust and comprehensive weight control program based on the stages of project execution was essential to maintaining cost and schedule, topsides weight budgets, Not-to-exceed (NTE) weights, and center of gravity (CoG) envelopes for all loading conditions, which were set at the end of FEED. In addition to developing clear budgets for the phases, each module was weighed before transport and the result backed into the weight management program and analytics. The project team then leveraged the actual results to capture additional weight opportunities as the project progressed. Two examples are described below:

- Through strict adherence to weight budgets and increased ability to perform ground up weight estimates, the UPM weighed 2.5% (~1,000 tonnes) below the NTE weight budget at the conclusion of the fabrication phase in South Korea. This result was analyzed with the "as-weighed" results of all modules and provisions were made to allow an opportunity to have drill pipe pre-loaded on the platform before its tow-to-field, reducing critical path schedule by several days and delivering significant value to the project.
- Through tracking CoG by phase, the project was able to move the DES (including the drilling derrick) to a more favorable position for start of drilling offshore. Thus allowing more drilling bulks to be loaded on the platform before tow-to-field and reducing critical path schedule by a few days.

These value capture opportunities were not possible without continued focus and discipline on weight management, control, and analytics.

### **Full UPM Utilization Initiative**

Recognizing the importance locating the Canadian integration workforce as close as possible to work fronts during the critical integration phases of all modules at Bull Arm, most of traditional store rooms, offices, and workshop space in the topsides were outfitted with temporary lunch and break room space for the work force. As a result, during the critical-path integration phases, breaks could be taken on topsides. This allowed reduced transit time by the work force and resulted in more efficient execution.

### **GBS Overall Design and Execution Strategy**

In order to meet the schedule requirement, construction of the GBS had to be started prior to the completion of its detail design. Furthermore, the design of the GBS had to be started prior to the topsides design being completed. This was accomplished as follows:

- Key topsides interfaces affecting GBS design were frozen very early in the design phase. These included: topsides weight and center of gravity, number, size and location of drill slots, risers, utility pipes, etc. A rigorous interface management process was followed to allow both the topsides and GBS teams to align on and agree upon these key interfaces.
- Next, the global analysis and design of the GBS was conducted. This determined the overall geometry of the GBS and allowed the general sizing of the different GBS elements.
- Subsequently, detailed design of the various GBS elements was carried out starting with the foundation, which was the first element to be constructed in the dry-dock. The detailed design determined the reinforcement amounts, embedments, etc. for the element in question.

- The other elements of the GBS were designed to stay ahead of the construction team in the following sequence: caisson walls, piping, structural decks, roof slab, shaft and finally the connection to the topsides

### **Concrete Batch Plants**

Two identical independently operated, fully automatic batching plants were used for concrete production at dry dock and deep water site locations. This 100% redundancy execution strategy was implemented to improve execution certainty during the most demanding concrete pour (continuous slipforming operation more than one month period). Unplanned stop of slipforming operation is very costly (from both cost and schedule perspectives) as it requires preparation of the unplanned cold-joint and higher density of reinforcement.

Concrete from the batch plants was pumped directly from the batching plants, which avoided costs of handling/transporting concrete. Concrete was then discharged using placement booms at the pouring location.

### **Innovative Steel-Panel Bulkheads for Base Slab Construction Joint**

In order to improve the construction schedule for GBS base slab, cost-effective and innovative vertical steel-panel bulkheads with horizontal corrugations were used as formwork between the various sections of base slab (poured in 4 sections). The corrugated vertical steel panels were designed to be left-in place and detailed to ensure leak-tightness. Compared to conventional formwork that would require stripping and surface preparation after concrete is set (very time consuming for thick base slab with many layers of dense reinforcement), the use of left-in place formwork resulted in a shorter construction time.

The corrugated steel-panel was needed because the more commonly used expanded sheet metal could not resist the high in-plane membrane forces and transverse shear forces that the 1.8m and 2.5m high construction joint was subjected to. The steel bulkheads were supported on a concrete strip foundation cast to a height above the bottom reinforcement layers. A steel mesh was used above the bulkheads to allow access to the top layers of reinforcement. Headed studs and steel ribs were welded to the bulkheads to resist in-plane forces and to ensure proper bonding between the bulkhead and the concrete. To ensure water tightness, a two-component low-viscosity epoxy was injected into the joint through hoses installed at several locations over the depth of the bulkhead.

### **Slipforming of All GBS Walls**

Slipforming technique (i.e., formwork panels that continuously move upward using hydraulic pumps and yokes) allows uninterrupted concrete placement, reinforcing bar installation, and minor surface repair. Slipforming allowed walls with high reinforcement density to be placed cost effectively, minimized the construction schedule, and improved leak-tightness as most construction joints were eliminated.

The slipforming of the GBS caisson walls at the deep water construction site is believed to be the second largest slipforming operation in history (behind Gullfaks C GBS), incorporating approximately 15,000t of reinforcing bar and about 50,000 m<sup>3</sup> of concrete over a 34-day period. The formwork used for this deep water site slipforming would stretch over 2 km.

The slipforming of the shaft includes flaring at the top, which is believed to be the largest in the industry. As shown in [Figure 1](#), the GBS shaft is round (~33m internal diameter) at the base and square (~42m wide) at the top. This geometry was optimized to minimize wave load but still provide sufficient space inside the shaft for all the Mechanical Outfitting while maximizing the spacing of the topsides support points.

### **Full-scale Mock-ups**

Full-scale mock-ups ([Figure 9](#)) are small parts of GBS built as a full-scale model using the same procedures, equipment and materials as planned for the actual structure. In addition to regular and early review of design



drawings, full scale mock-ups of several complex elements of the GBS were conducted and lessons-learned were fed back to the design team to make the design more constructible. The mock-ups also allowed the opportunity to train the work force on these complex operations prior to actual construction. A few important mock-ups are listed below:

- Base slab for the up to 3.2 m thick section with multiple reinforcement layers (up to 10 layers per concrete face). Some of the main findings were as follows:
  - Verified that concrete could be placed/vibrated with no honeycombing or voids,
  - No horizontal construction joints required
  - Orthogonal horizontal reinforcement layout for both the top and bottom rebar layers, which are more efficient than the radial layout (from a constructability point of view), was feasible.
- Slipforming of walls with high reinforcement and embedment density: verified that all required reinforcement and embedments could be placed while still allowing the slipform to move at a reasonable rate.
- Topsides-GBS connection: Determined the high-strength grout (80 MPa) that would completely fill the space between the underside of topsides baseplate and the GBS ring-beam; determined the material/finish required on the crushing tubes that would provide the required impact and friction resistance.
- Post-tensioning duct grouting: verified that the grout will completely fill the very long (80m) vertical ducts as well as horizontal ducts.
- Golden welds: verified/established procedure to carry out golden welds to required quality



Figure 9—Various Mock-ups

## Solid Ballast

In order to improve floating stability during tow and improve sliding resistance after platform installation, 222,000 tonnes of solid ballast with a specified density of 3500 kg/m<sup>3</sup> (approximately 10m thickness) was placed at the bottom of the oil storage and annulus cells. Unlike the previous Hibernia platform, all solid ballast was placed (as a slurry mixture comprising iron ore, fly ash, cement, and high-range water-reducing admixtures) at the deep water site using concrete pumps. This avoided extra costs associated with offshore installation of solid ballast.

Since the solid ballast was placed before the completion of platform construction, it was designed to have sufficient stiffness to ensure stability during marine operations (deep submergence test and towing to the field) but still be flexible enough to prevent large lateral pressures on the GBS walls and minimize loads on the piping embedded in the solid ballast.

## Summary and Conclusion

Overall, the Hebron team was able to resolve significant challenges to deliver a cost effective and space-efficient platform. Advanced probabilistic analyses, state-of-the-art wave model tests, and NLFEA provided tools for engineers to safely design cost-effective offshore platforms in sub-arctic and extreme environment, including topsides large concentric truss nodes with geometries outside currently available industry standards. Various applications of innovative design methods, and deployment of space and weight reducing technology enabled efficient construction and commissioning, and reduced overall costs of the project. These methods, along with the capital-efficient execution method implemented in Hebron, are critical in industry to remain competitive in today's price environment.

## Acknowledgment

The authors would like to extend special thanks to the following:

- Co-venturers Chevron Canada, Suncor Energy, Statoil Canada and Nalcor Energy – Oil and Gas for management support and provision of secondees to the Project team.
- Canada – Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) for the regulatory oversight, guidance and approvals required to advance the project.
- The Project team and contractors who worked tirelessly to make this Project a success.
- ExxonMobil Upstream organizations and ExxonMobil Canada Properties for the collaboration and support throughout the Project.

## References

- CAN/CSA-ISO 1996:10 Petroleum and Natural Gas Industries — Arctic offshore structures*. 2010. Canadian Standards Association.
- Cornaglia, V.P. 2018. Geoscience Overview of the Hebron Field. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-29070-MS
- Edwards, S.C, Fuller, D.A., Nahas, M. et al. 2018. Integration of Multi-Site Engineering, Procurement, Fabrication and Commissioning. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-29072-MS
- Haddock, J. 2018. Hebron's Labor Empowerment Strategy – A Legacy of Success. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-28697-MS
- Oberlies, R., Khalifa, J., Huang, J., et al. 2014. Determination of Wave Impact Loads for the Hebron Gravity Based Structure (GBS). Presented at the 33th International Conference on Offshore Mechanics & Arctic Engineering, San Francisco, California, USA, 8-13 June. OMAE2014-23503.
- Parker, G.J., Wolfe K.J., and Sellars, S.L. 2018. Hebron Offshore Development Project Overview. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-28695-MS
- Perry, R.F., Overstake, M.A., Hagen, O. et al. 2018. Successful Management of Major Marine Operations for the Hebron Project. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-28744-MS



- Ryan, M.F., Kourvelas, C.P., Tuttle, D.C. et al. 2018. The Application of Digital Technologies to Improve Collaboration and Support of Remote Offshore Operations. Proc. Offshore Technology Conference, Houston, Texas, 30 April – 4 May, OTC-28821-MS
- Tistel, J., Eiksund, G. R., Hermstad, J., et al. 2015. Gravity Based Structure Foundation Design and Optimization Opportunities. Presented at the Twenty-fifth (2015) International Ocean and Polar Engineering Conference, Kona, Hawaii, USA 21-26 June. ISOPE-I-15-767.
- Widianto, Khalifa, J., Younan, A., et al. 2013. Design of Hebron Gravity Based Structure for Iceberg Impact. Presented at the Twenty-third (2013) International Offshore and Polar Engineering Conference, Anchorage, Alaska, USA, 30 June – 5 July. ISOPE-I-13-036.
- Widianto, Khalifa, J., Taborda, G., et al. 2016. Concrete Gravity-Based Structure: Construction of the Hebron Offshore Oil Platform. *Concrete International, American Concrete Institute*, **38**(6):29–36.
- Younan, A. H., Kaynia, A. M., Loo, M. M., et al. 2015. Seismic Design of Hebron Platform: an integrated soil-structure-interaction approach. Presented at the 34th International Conference on Offshore Mechanics & Arctic Engineering, St. John's, Newfoundland, Canada, 31 May – 5 June. OMAE2015-42134.