Report of

Initial Research of Candidate Systems and Technologies

for

SKIN-TO-SKIN REPLENISHMENT

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Preface

This report of "Initial Research of Candidate Systems and Technologies" discusses the groundwork laid, and the course set for the team's further research into the feasibility of using a skin-to-skin connected replenishment concept. This report combines the findings of what was originally proposed to be three separate reports, namely:

- "Report of Initial Candidate Research",
- "Documentation of Ship Control Concepts to be Simulated", and
- "Report of Promising Cargo Transfer Concepts Selected for Further Study"

1.0 Summary

The overall objectives of the skin-to-skin transfer study for U.S. Navy applications are as follows:

- To establish the over-all feasibility of the skin-to-skin transfer concept between two ships, at sea.
- To assess the concept's potential for operating in a seaway, with motions and loads imposed on the cargo transfer system itself and on the load items being transferred, and with relative motion occurring between the two ships.
- To identify specific technical requirements of the systems involved, the primary emphasis being on the cargo transfer system, but also with regard to the requirements for mooring and fendering gear.

This report presents the findings of research done to determine what technologies show potential for use in achieving skin-to-skin connected replenishment in sea states up to 5. Methods of skin-to-skin connected replenishment that are in use for fuel transfer operations are reviewed. An assessment of the relative merits of systems and technologies, primarily those associated with mooring, fendering and containerized cargo transfer is presented. An assessment of technologies associated with reducing ship motions including ship stabilization and wave reduction technologies is made. This report concludes with a selection of notional ships and specific systems that will be the subject of more detailed analysis and simulation of the skin-to-skin connected replenishment operation.

2.0 Notional Ship Configurations

The selection of a particular pair of ships, or at the very least representative types of ships to be considered, represents an important first step in the task, and one which may influence the outcome. It is, of course, apparent that the over-all feasibility, potential development, and system requirements for skin-to-skin transfer depend to a great extent on the seakeeping behavior of the two ships involved. Apart from the purely dynamic aspects of the match-up, however, the selection of ship types also involves other arguments: the intended naval applications of the concept, and implications for the concept of operations.

2.1 Transfer Ship Selection

Among the candidates for the transfer ship (that is, the ship which is envisioned to incorporate the large items of developmental cargo-transfer system) were the following:

a. Existing Sealift Ships – New skin-to-skin cargo-transfer gear, mooring, and fendering arrangements could be installed on one of the existing MSC sealift classes, LMSR, prepositioning force ships, or LOTS ships. The new gear would either supplement existing gear or replace one or more of the conventional existing cranes. This alternative, based on an existing ship, would be able to provide a near-term proof-of-concept opportunity for components of the cargo-transfer gear. However, arrangements and ship-size constraints would not give full scope to the potential of skin-to-skin transfer as a means of applying ISO-oriented (commercial, modular) cargo access and stowage. (For example, the current assets are all of PANAMAX dimensions or smaller, and for most of the newer ships the arrangements, ramps, and deck heights emphasize RO/RO cargo rather than single or multi-tier ISO size module stowage.)

b. Existing Logistics Support Ships – New skin-to-skin cargo-transfer gear, mooring, and fendering arrangements could be installed on an existing or projected fleet logistic support ship, such as a T-AFS, AE, T-AKE, or T-AKE variant. Like the sealift and prepositioning ships, the fleet logistic train is composed mainly of ships less than PANAMAX size. Further, the deck arrangements and gear are specialized for internal transfer and stowage of pallet-sized items, and munitions, including missile canisters, rather than ISO containers. Topside arrangements are rather specialized, as well, for CONREP and VERTREP logistic operations. Consequently, this alternative would inevitably displace a significant portion of the ship's conventional UNREP plant. The corresponding impact on fleet logistic operations was judged problematic.

c. Notional SeaBase Ship – This option would incorporate skin-to-skin transfer capabilities, and shipboard arrangements to fully exploit the capability of transferring heavier loads, including ISO containers, on a notional "SeaBase" or Maritime Prepositioning Force (Future) ship, [MPF(F)]. This option opens the opportunity of using a post-PANAMAX size ship, with corresponding advantages of scale. It also offers the opportunity of demonstrating a variety of logistic applications. These include not only ISO container-based modularized cargo, *per se*, but also the deployment, transfer, and assembly on shipboard of a variety of ISO-compatible, module-based mission facilities. The disadvantage, of course, is that the platform would have to be acquired new, or converted from a large commercial vessel, most likely a post-PAN containership. Several notional large MPF(F) or SeaBase concepts, up to 93,000 tons have been presented in recent studies, Reference 1.

2.2 Customer Ship Selection

Several alternative types of "client" ships were considered: skin-to-skin transfer offers a different range of potential applications for each type. The primary criterion for this initial analysis is to focus on an operationally useful pairing that present challenging technical requirements, but do not unnecessarily complicate the evolution. The technical elements included: (1) significant crane outreach; (2) desire to illustrate the feasibility of transferring 53,000 pound ISO container compatible modules, (3) ability to meet larger fender loads (and energies due to relative motions) associated with larger client ships. The following types were considered:

a. Air Capable Amphibious Force Ships – This option considers transfer to an amphibious force ship, such as an LHD, LHA, or future LHA replacement. Transferred items would include vehicles, ISO container modules (for subsequent transfer ashore on LCAC, as vehicle loads, or via helicopter lift) and non-ISO container cargo. However, this alternative presents a significant complication for skin-to-skin transfer because of the overhangs of the flight deck, sponsons, and deck-edge elevators. These protrusions make fendering arrangements considerably more difficult.

b. Other Logistics Support Ships – This option would consider transfer of similar amphibious force materials to an LPD or LSD type. Although fendering would become much more conventional for these hull configurations, the types would not present the most critical demands for crane reach or fender performance.

c. Small Combatant Ships – This option considers the transfer of palletized stores and munitions, and possibly even missile canisters (given the development of an assumed ability to strike down at sea) to a destroyer-sized surface combatant or to smaller surface ships or craft. Although skin-to-skin transfer might be useful for some logistic purposes (including missile transfer and retrograde of empty missile canisters), it was judged that these kinds of transfers would be adequately served by more conventional UNREP means, although possibly with modified gear. There was judged to be little need for combatants to make use of skin-to-skin ISO-module-sized transfers. Finally, the crane reach and gross fender capabilities required are the least challenging of all alternatives. Topside shaping of the new generation of surface combatants, as exemplified by the recent DD(X) configurations, might require some specialized fendering and mooring arrangements, however.

d. Commercial Container Ships – Transfer of ISO containers from a commercial ship, including especially a PANAMAX cellular containership. Retrograde of ISO containers to the merchant ship would also be undertaken. This was judged to be a challenging, but realistic, client ship. Crane outreach and fender performance issues are at a premium because of the large size of the client. Importantly, transfer at sea from inter-theater transports including commercial (gearless) ships, and then to amphibious or LOTS assets, is at the heart of the SeaBase concept. Finally, the ability to handle several tiers of containers off hatches, or even by accessing lower in the stacks, is a design challenge for the cargo-handling crane.

After considering the arguments presented above, the decision was made to investigate first the pairing of a large, notional, MPF(F) ship with a PANAMAX-sized commercial containership. The chosen hull form is the 90,960 tonne MPF 2010 described in Reference 1 with parameters summarized below in Table 1. The chosen containership is the SL-7 type. The SL-7 is not typical of new-generation commercial container liners. It is a twin-screw design of fine form, and of high performance, while most new ships of PANAMAX dimensions are fuller, several knots slower in design speed, and in most cases single screw. The SL-7 represents a challenging hull-form from the linear-seakeeping standpoint, due to the low prismatic coefficient. Furthermore, detailed SL-7 hull form data was readily available, as all existing examples having been converted to T-AKRs.

Following are the primary hull-form characteristics for the ships chosen for further study and simulation. Lines Plans for each ship are presented in Appendix A.

Table 1 – Ship Characteristics

	MPF-F	SL-7
LOA (m)	315.20	288.35
LWL (m)	305.35	274.60
BWL (m)	40.84	32.16
D (m)	35.40	19.51
T (m)	10.50	9.16
V (m^3)	88400	43133
Δ (tonnes)	90690	44250
Waterplane Area (m^2)	10093	5731
Wetted Surface Area (m^2)	14489	8832
LCB (%LWL/FP)	49.5	52.7
C_b	0.675	0.533
C_x	0.967	0.946
C_p	0.682	0.551
C_{wp}	0.809	0.649
Design Speed (kts)	25	30

3.0 Review of Current Commercial Tanker Lightering Operational Methods

A "Commercial Lightering Operational Assessment Study" was prepared by team member Seaward International for this study and is presented as Appendix B. Seaward gathered data from printed sources, such as "Ship to Ship Transfer Guide (Petroleum)" by the International Chamber of Shipping Oil Companies International Marine Forum (OCIMF), Reference 2, as well as soliciting tanker operator input and arranging for a trip to witness an at-sea, skin-to-skin fuel oil transfer. The "Commercial Lightering Operational Assessment Study" presents a comprehensive review and assessment of the current technology used for skin-to-skin operations in relation to the requirements laid forth by ONR for this research. The "Ship to Ship Transfer Guide (Petroleum)", Reference 2, is the general manual which current tanker lighterage operators use as a guideline for their operations. For sketches and more detailed descriptions of the maneuvers described here, please refer to those documents.

The current method of this lightering operation starts when the larger ship holds a constant speed and course, while the smaller ship moves from astern to take a position where messenger lines are used from approximately 50 meters to bring across the special mooring lines with a nylon "grommet", a paired loop of springier nylon line. This line with grommet is designed to have a specific given amount of stretch. The lines are put on a bit on the larger ship, and the smaller ship mooring winches itself to the larger ship's side. The small ship then slows and stops its engines, to be towed by the larger ship. They normally perform the maneuver 5-10 degrees from the primary wind and wave direction, with the larger ship always to windward to create a lee for the smaller ship to roll less. Normally, the operation takes place at one to two knots., especially during uncoupling, in order to reduce Bernoulli effect of suction. The relative freeboard and draft of the ships must also be taken into consideration, as it may change during the course of the operation.

There are also other options for general operational methods. Currently, there are some groups, primarily in the Gulf of Mexico (with smaller, shorter period waves), who will maneuver underway until the ships are moored, then have the larger ship drop anchor and then they transfer fuel at that time. The operation may be conducted heading away from the wind, as it increases the relative period, and also lowers the relative wind. However, this is not recommended by the "Ship to Ship Transfer Guide (Petroleum)", Reference 2, and is not the normal mode of operations.

Normally, the fender configuration consists of primary fenders, hung from davits, floating at the waterline and smaller secondary fenders fore and aft to protect bow and stern plating during approach and unmooring.

Chevron-Texaco has had success with 75' long multiple coil grommets of 2.5" diameter nylon line being used as the primary mooring lines. They have used Polyethylene (HMPE) synthetic fiber line, marketed as Spectra or Dyneema, to connect from the grommet to near the chock, then use 9' of 1.5" wire rope at the chock. On the other side of the grommet, they also use 1.5" wire rope for the mooring winch end. The Spectra is used because its specific gravity allows it to float.

One end of each mooring line is led through a chock and onto a bitt, sometimes connected to that by a quick-release hook. Chevron-Texaco operations use steam-operated mooring winches with brakes rated to 56 tons. The mooring winches are normally brought snug, but with little force on, at the start of the operation. The mooring winches have load monitors, and when a swell comes by the ships, reports indicate that the change in load is 15-20 tons.

There are some limitations of the current system. The OCIMF guidelines that are currently used for this type of operation allow it to begin anytime the winds are less than 30 knots, and the combined sea and swells are less than 10 feet. Once coupled, the operation can continue in up to 12-14 foot seas, but must break apart as soon as possible if the winds top 45 knots or the combined seas reach 16 feet, *sea state 6*.

Operators were asked what improvements could be made to current methods. Their recommendations for a purpose built lighterage vessel include: a longer parallel midbody, a deeper and more full-bodied hull to minimize roll motions, bow thrusters, larger rudder and greater angle of movement, and a CP propeller. Other recommendations included the use of the grommetted lines for primary mooring, with synthetic floating lines in other locations, quick-release hooks for the mooring lines, the use of davits for ease of use of fenders, and the use of closed Panama-style chocks.

The Seaward report assesses the use of current methods for naval applications. They note an increased importance and priority for reliability, and note the need for safety. They recommend foam-filled fenders because they will continue to function even when punctured. They also suggest the use of aircraft tires in a tire and chain net, because that will be more durable than the commercially used truck tires. They again recommend fender davits, and here they note that the minimum fender spacing should be no more than 30% of the length of the smallest vessel to come alongside. For this reason, they suggest the use of several sets of different sizes of fenders, one for containerships, another set for barges and landing craft. Last, for the secondary fenders, they recommend foam filled fenders without tire nets, on one slewing davits with slide-boards for storage.

4.0 Fendering Methods

The "Fendering" function in this evolution is performed by three components: lines, mooring winches, and fenders. Use of fenders, mooring winches and mooring lines during commercial tanker lightering operations is described in Appendix B. A comprehensive assessment of fendering technology is presented in Appendix C.

4.1 Lines

Four types of lines were reviewed. Three are homogenous Nylon, Synthetic Fiber (Spectra, etc) or Wire cables. The fourth is a composite line, which is currently being used in tanker skin-to-skin cargo transfer. These are wire cables with a flexible "grommet" of nylon rope in the center in order to add a certain amount of stretch.

The commercial oil tanker lightering operations use these grommets in two sizes: 50 feet and 75 feet (this is the length of the loop, the actual rope is twice as long). The grommets have a breaking strength of approximately 260,000 pounds and have diameter of approximately 3-inches. The stretch characteristics for present grommets are that the rope will stretch 10% at 50% of the breaking strength and will stretch to 19% just before breaking. The first grommets were a double braided nylon rope and could only be used for ten lightering operations before needing replacement. The grommets used today are a wire lay nylon rope and are used for 160 operations.

The flexibility provided by the grommets is considered an important function in the overall mooring approach. It provides a low inertia energy absorber, capable of reacting quickly and keeping mooring tensions within safe levels. The function of the flexible grommets is analogous to that of a pneumatic rubber tire on a vehicle. The tire has little mass and can react before the wheel and suspension system can.

4.2 Mooring Winches

Four mooring winch variations were considered in this study. There are mooring winches that are locked and left in that position 100% of the time, allowing the rope to be the sole dynamic part of the mooring winch - line system. There are mooring winches which are locked, but reset at times during the evolution by crew in order that the tension in the lines not become too great. These are currently used in tanker operations. Also considered are constant tension mooring winches, which keep a constant force in the line at all times. Last, there are computer controlled mooring winches, which are able to take into account the ship motions, and set the tension accordingly. These might be capable of actively dampening ship motions.

Either the locked mooring winches or the constant tension mooring winches appear to be the best choices for this study. This decision stems primarily from safety considerations, and secondarily a consideration of the current level of technology. Determining which of the two is better will be considered as an optimization problem during the study.

The mooring winches which are locked 100% would allow for reduced manning during the evolution; however, they are unquestionably a safety concern from the point of view that it does not allow the rope tension to be monitored. If the ships move too far apart, there is no control to release tension before breakage. This could become a hazard.

Any mooring winch system which is kept highly tensioned is subject to the same safety concerns as above. Being that the line would be near is maximum working strength much of the time, it would wear quickly. A line near its maximum strength is also more susceptible to shock loads and breakage than otherwise. Especially in the two locked mooring winch systems, this could be quite hazardous.

4.3 Fenders

Four different fender types are considered. There are air-pneumatic fenders, which come in three types, low pressure 'soft' fenders, high-pressure 'hard' fenders, and 'dynamic' variable pressure fenders. The fourth type is foam filled 'solid' fenders. For this study, the differences in these fender types, which will be explained below, do not point to an immediately clear answer as to which ought to be used for the problem of mooring two ships to each other in the open ocean. Therefore, in the course of this study, all types of fenders will be examined by computer model and an optimization study will be run to determine which fender type is best suited for this application. A comprehensive assessment of fendering technology is presented in Appendix C.

4.4 Mooring Winch, Fender, and Line Systems

This study can only be completed when all three elements of this system are combined to bring two ships together at sea. It is most important then to know what the combination of factors from each of the separate elements is that will best allow this evolution to take place. The choices from each element were previously narrowed down individually. Now then, a set of systems must be chosen to actually test. Three systems will be initially chosen. After these have been thoroughly tested, more systems may be added to the simulation program, if there is time available.

The three notional systems the simulation will begin with are the 'Solid' foam-filled fenders, Composite lines, and Locked (not 100%) mooring winches, the 'Solid' foam-filled fenders, Composite lines, and Constant-Tension mooring winches, and the 'Soft' low-pressure air fenders, Composite lines, and Constant-Tension mooring winches. The reasons for these selections will be explained below individually.

The 'Solid' foam-filled fenders, Composite lines, and Locked (not 100%) mooring winches are currently used in tanker operations of this nature. It is natural then, to test these as a baseline against which to compare the other results.

The 'Solid' foam-filled fenders, Composite lines, and Constant-Tension mooring winches are a natural selection, because the C-T mooring winches will do the same job as the locked mooring winches, but to a higher degree. They will require less manning during the operation because they are automatic.

The 'Soft' low-pressure air fenders, Composite lines, and Constant-Tension mooring winches will be the third part of the initial simulation test matrix.

5.0 Surfactant Technologies

The use of surfactants is only feasible in the case of the ships transferring cargo in a stationary position. Even so, the amount of material needed to create an effective surfactant block against developed waves is very large. Surfactants have been explored for resistance reduction, but the literature on their use for wave damping is sparse. Surfactants reduce the tendency of waves to break, having their greatest effect on the short-period waves that have little effect on large ships motions. Longer swells, which do cause ship motions, will be reduced little by surfactants. Also, surfactant layers do not last long, and are not highly effective in general. We have not to this point been able to find any significant information regarding the use or design of surfactants capable of damping large period waves. Also, use of surfactants in peacetime may require an environmental impact study. The ecological effect of large quantities of surfactants may be a problem sufficient to create opposition to surfactant use. It is currently our view that further significant research should not be considered for this study.

6.0 Motion Damping or Wave Damping Technologies

6.1 Floating Breakwater Dock

A floating breakwater might work in the cases that we would transfer material in a stationary or a drifting position. However, a breakwater of enough size to significantly reduce the energy of the waves in an open seaway would be such a large weight and volume taken up on the deck of (or towed by) the Prepositioning ship that it would seriously limit that ship's effectiveness. A floating breakwater would probably be so large it would have to be towed to the operations area – like the “Mulberry” floating harbors used after D-Day in WW II. Moreover, to deploy such a system takes an inordinate amount of time, space, and a low sea state to begin the task.

6.2 Fin Stabilizers

Hydrodynamic pitch stabilization fins can be passive or active. The primary difference between active and passive is that an active system can have some effect on pitch period, while passive systems will not. Passive fins used for pitch control are usually passive and placed at bow and stern to increase pitch damping. The added pitch damping will reduce the ship’s pitch motion amplitudes little effect on pitch period. The MPF and SL-7 system being examined for this study, exhibit low pitch motions. The interest is in synchronizing their pitch periods to reduce the relative motions induced by asynchronous pitch, so *active* pitch stabilization fins would be needed rather than passive fins. A calculation of active pitch control fins that could develop sufficient force to change the pitch period and amplitude of the MPF so that is matched to the SL-7 showed that the fins would need to be very large. A rough calculation suggests a size of 28 m (span and chord for a square planform fin with a 25% flap on the trailing edge), and a power consumption of about 6400 kW. These dimensions and power demands are obviously far too large to be practical.

Active fins used for roll stabilization are usually installed amidships. These function by developing lift forces and roll moment to counteract the ships roll moment Using electric or hydraulic actuators, the fin angle to the flow is adjusted to reduce roll motions. While fin stabilizers can reduce roll motions up to 80% at favorable speeds of 15 to 20 knots, at the operational speeds we are envisioning, they will be practically ineffective. As a dynamic lift device, of course, a fin's side force is proportional to the square of the flow speed.

6.3 Flume System

The Flume system consists of one or more tanks, partially filled with water, where the sloshing of the water is either controlled actively by air pressure or other means, or passively by the geometry of the tank. The water is always on the high side as the ship rolls. This reduces the ship's roll motions. Flume tanks are not quite as effective as fins, but they work at any ship speed. While the tanks and plumbing take up substantial space in the ship, they are relatively low-tech components and not expensive, except when considering the loss of ship volume. Active flume systems require a very large input of energy to become more effective than passive ones, up to 10% of the propulsion power in some cases according to Reference 3.

The location and geometry of the tanks can play havoc with the general arrangement of the ship as well. Tanks are most effective when they reach all the way across the ship and are well above the roll center. This takes up scarce, valuable real estate near main deck level amidships.

For an existing 540-ton minehunter, an active anti-roll tank system has 21 tons of liquid plus 7 tons of equipment. It is unlikely the weight/volume of a flume system is linear with ship displacement, but in this example, the device is 5% of the total ship displacement. We expect numbers more like 3% for ships of the size we envision for the simulation.

6.4 Anti-Pitch Tanks

A Chinese system dating to the late 14th century used tanks in the bow and stern of the ship that were allowed to flood and drain at a controlled rate through calibrated holes. Since the ship's pitch period is generally such that there is a delay before the ship rises to a wave, reducing the buoyancy of the bow as the wave climbs up the ship's side forward reduces pitch response. Such tanks could modify the ship's pitch inertia and natural period, resulting in behavior similar to anti-roll tanks of the Flume type.

Calculations indicate that pitch tanks could be effective, but they would have to be relatively large, about 20% of the ship length. The problem of losses introduced by accelerating the incoming water to ship speed and then dumping (wasting) it is hard to solve on a vessel that, unlike 14th century junks, requires an input of mechanical energy for propulsion.

6.5 Moving Weights

In a few designs, moving weights have been arranged to compensate for roll motions. For large ships this usually isn't practical because of the size of weights required (similar order of magnitude to that of a flume system, because the weight is accomplishing the same purpose). Of course, the weight must be supported by the ship's buoyancy, and energy input is required to move the weights. A typical device is a circular track with a railroad-type car running around it at a rotational speed corresponding to the ship's roll period. Back-and-forth tracks have also been used, but they require rapid acceleration of the weight at each end. The French aircraft carrier *Charles de Gaulle* uses such a system.

6.6 Bilge Keels

Bilge keels add damping in roll, reducing roll amplitudes. They are quite effective at all speeds, and above-normal sized bilge keels can be provided at little cost in ship resistance or construction cost. Larger bilge keels are normally more effective.

6.7 Rudder Roll Stabilization

This is a system with upgraded steering gear motors that allows very rapid cycling of the rudder. High frequency rudder motions (too rapid to turn the ship) are used to reduce roll motions. While somewhat less effective than fins, RRS can reduce roll motions substantially at higher speeds. However, at our baseline speed, RRS will be practically ineffective.

6.8 Active Mooring Winches

With computerized feedback controls adjusting winch line tension it is theoretically possible to vary the stiffness of the connection between the two hulls. We are not sure yet whether that has any leverage in reducing motions. The system would rely on a feedback loop that includes the motions of both ships and the tension in all winches, and allows the computer to define a tension for each winch that will best dampen the relative motions. During the early stages of this study, this particular system will not be modeled or simulated. During later stages, once the general ship motions are more fully understood, an investigation of this specific technology should be performed.

6.9 Variable Stiffness Fenders

Dynamic, variable-pressure pneumatic fenders with a compressor continually online and a remote controlled relief valve on each fender could, in principle, vary the fendering pressures between the hulls enough to damp motions. Like active mooring winches, this would again call for a complex control system.
These systems will require a computer, air compressor(s), air lines and valves to each fender, and constant feedback in the form of ship motions input and pressure sensors on each fender.

6.10 Sails

It is well attested in sailing literature that sails, at certain angles to the wind, can have a powerful damping effect on roll. On the other hand, the heel angle resulting from sails might interfere with the interface between the ships. But for a large ship, the heel angle becomes smaller as the ship's roll stiffness increases with size. To take advantage of the roll reduction due to sails, the Romeo course would have to be into the wind, with the relative wind angle from 10 to about 50 degrees off the bow. Sails could also be used in transit to reduce fuel consumption. A significant drawback of using sails is the negative effect that they would have on other ship missions such as aircraft launch and recovery.

6.11 Gyrostabilizers

A gyrostabilizer is a flywheel-like device that can be spun up to a high speed. If the gyro is big enough, it tends to preserve ship attitude (both pitch and roll) and reduce motions. They were quite common on ocean liners prior to WW I, but have since fallen out of use. *Active* gyrostabilizers are mechanically processed to increase the stabilizing moment. These devices are considerably more effective for their weight than the passive variety, and have been used more recently. They must still be physically heavy in order to be effective, and also call for a big input of energy. The mass and energy consumption are major drawbacks that seem to make a gyrostabilizer less attractive.

7.0 Select Notional Cargo Transfer Systems for Initial Analysis

7.1 Review Known Motion-Compensated Crane Concepts

7.1.1 Rider Block Tagline Crane Concept

The rider block tagline concept was developed as a pendulation control device to be used with conventional luffing boom cranes. The concept fairleads the hoist lines from the boom tip sheaves through a “riding block” pulled inward by taglines. The inward pull of the taglines against the main hoist cables prevents the in/out pendulation. By using two taglines, each pulling at a side angle, side-to-side pendulation is also prevented. The rider block weight is supported from a line from the boom tip. The block is raised and lowered as required to keep the block as close to the load as is practical, since pendulation below the block is not controlled. An additional feature can be added to the basic rider block crane configuration to improve performance. A vertical motion-compensation system would use high horsepower crane hoist winches to adjust the vertical position of the load relative to the customer ship. Alternatively, lower crane hoist winch horsepower could be used if a motion prediction algorithm is developed to time the load pick-up or drop-off.

Provided that the rider block is close to the load (a situation that is not always possible due to physical interference with the taglines), and provided that the crane is equipped with a vertical motion-compensation system, the x,y,and z degrees-of-freedom can be controlled. The pitch, roll, and yaw motions of the load are more difficult to control. A powered rotator located on the container spreader usually controls the yaw. The rotator must work against the hoist ropes to produce a twisting moment. The hoist ropes do not however greatly resist this twisting moment unless they are widely separated. Essentially, this limits the acceleration forces available to compensate for load yaw relative to the customer ship. Load roll and pitch motions could be damped by side-shifting the load below the spreader. A system that uses these side shifting mechanisms in a dynamic control scheme can be envisioned as a way to compensate for load roll and pitch for ship-to-ship relative motion. This control method, however, would be indirect, using the force of gravity by adjusting CG position relative to the x, y, z fixed attachment point to control the load.

7.1.2 AutoLog Crane Concept

The AutoLog large array robot is a SEICOR and Penn State based concept that uses three or four main cables to move a load in the x, y, and z directions in a large array. If four cables are used, one of the cables acts as a redundant load cable that maintains tension, rather than determining position. To obtain the other three degrees of freedom (load roll, pitch, and yaw), a similar load rotator and CG side shifting mechanism approach to that described for the rider block tagline crane concept has been proposed.

Operator Control interfaces, ISO corner fitting image recognition software, motion-compensation sensor selection and analysis, and control algorithms have been developed by Penn State for the AutoLog concept, and proposals for full scale development of a container ship self-unloader have been presented.

7.1.3 Robo Crane Concept

The RoboCrane is a National Institute of Standards and Technology (NIST) developed concept that achieves control of the six degrees of freedom by using six cables arranged in an inverted Stewart platform arrangement. The "Stewart" platform is the commonly used term for motion-simulator platforms that typically use six hydraulic cylinders to control the motion of a simulator. NIST has proposed the concept in a variety of forms and for a variety of applications. Control system technology to coordinate the motions of the six crane hoist winches is well established. NIST has proposed several motion-compensation crane applications, but none have been fully developed to date. The RoboCrane concept offers direct control of all six degrees of freedom, and does not depend on Center of gravity control to achieve the desired motion or position.

7.2 Brainstorm New Crane Concepts

A team of seven JJMA and NIST personnel were assembled to brainstorm crane concepts that had the potential to meet the operational concepts developed as described previously. The team members represented a wide variety of backgrounds and expertise including:

- Conventional shipboard crane design and manufacturing – JJMA's Bill Schulz;
- Ship Handling – Naval ship operation and maintenance – JJMA's Rick Holliday;
- Ship's Structural Analysis – JJMA's Ray Kramer;
- Dynamic Analysis – JJMA's Chris Higgins
- RoboCrane inventor and control system engineer – NIST's Jim Albus;
- Intelligent Systems Division program manager with familiarity with multiple crane applications – Roger Bostelman;
- RoboCrane mechanical engineering – NIST's Adam Jacoff

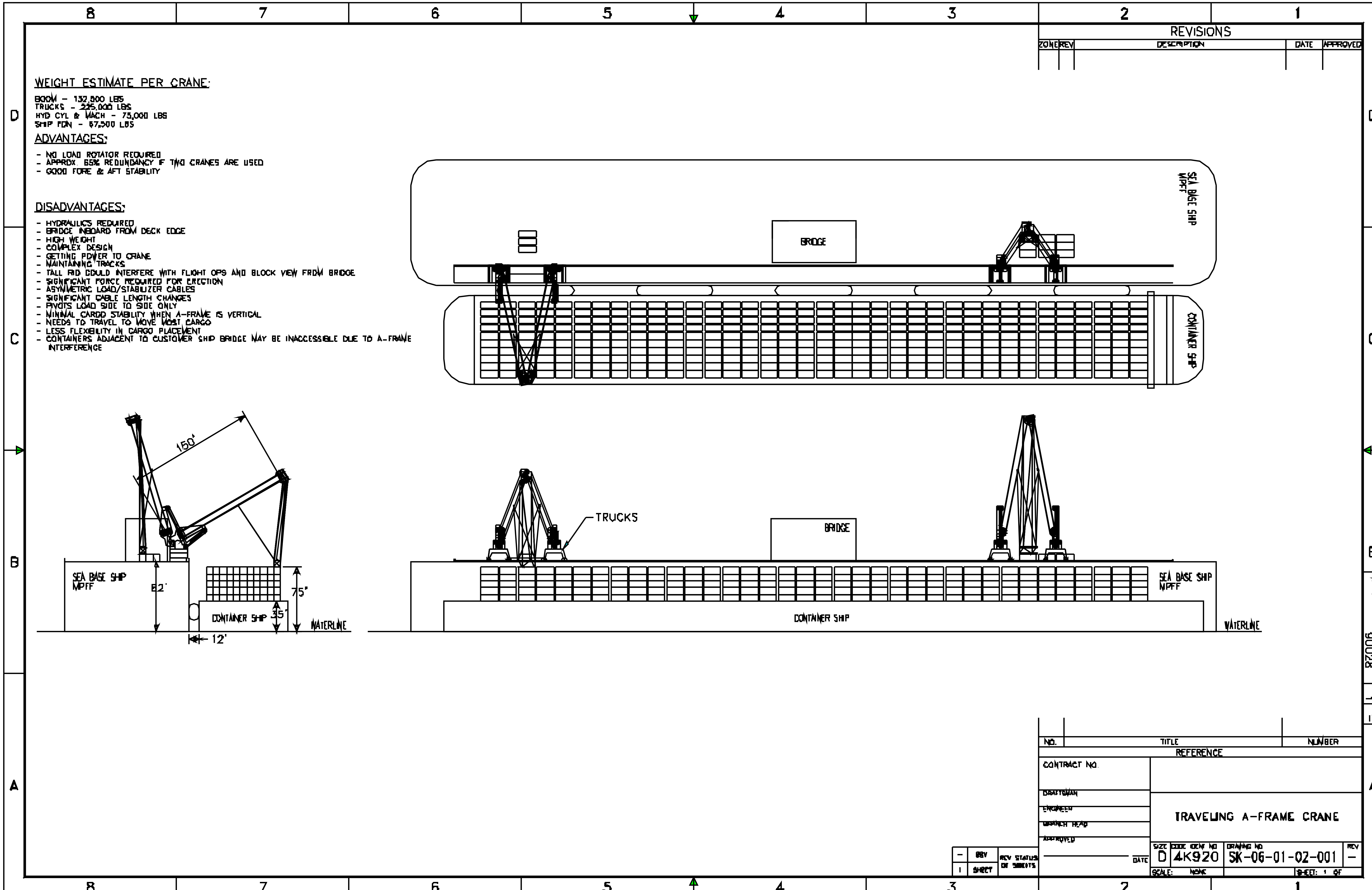
The sea-state 5 environment ship motions for the candidate ships involve significant displacements and velocities in all six degrees-of-freedom. The team members familiar with dynamic motion compensation control advised that both feedback as well as feed-forward control logic would be required to achieve the required precise load control in a sea-state 5 environment. The load could be affected by wind gusts in a sea-state 5 environment, and, unlike ship motions, wind could be not be predicted accurately a second or two ahead of time. The team concluded that systems that depended on a force balance to achieve motion compensation could not be designed without accurate wind prediction sensors and software. Since no such wind gust

prediction technology was known or envisioned, the concepts to be investigated further were limited to those capable of positive position control of all six degrees of freedom.
A second constraint imposed by the team was to use crane hoist winch horsepower and acceleration rates that were within known feasibility limits. While crane hoist winch horsepowers of up to 500 or more could be envisioned, the team felt that such winches would be sluggish in comparison with smaller winches, particularly if they were driven by electric rather than hydraulic motors. Electric crane hoist winches were preferred by the team. The team selected 250 HP as the upper limit on crane hoist winch horsepower. Winches of this horsepower were known to be feasible, and could be made highly responsive without resorting to the use of hydraulics in the age of the all-electric ship.
Seven crane concepts were selected for formal trade study. These included:

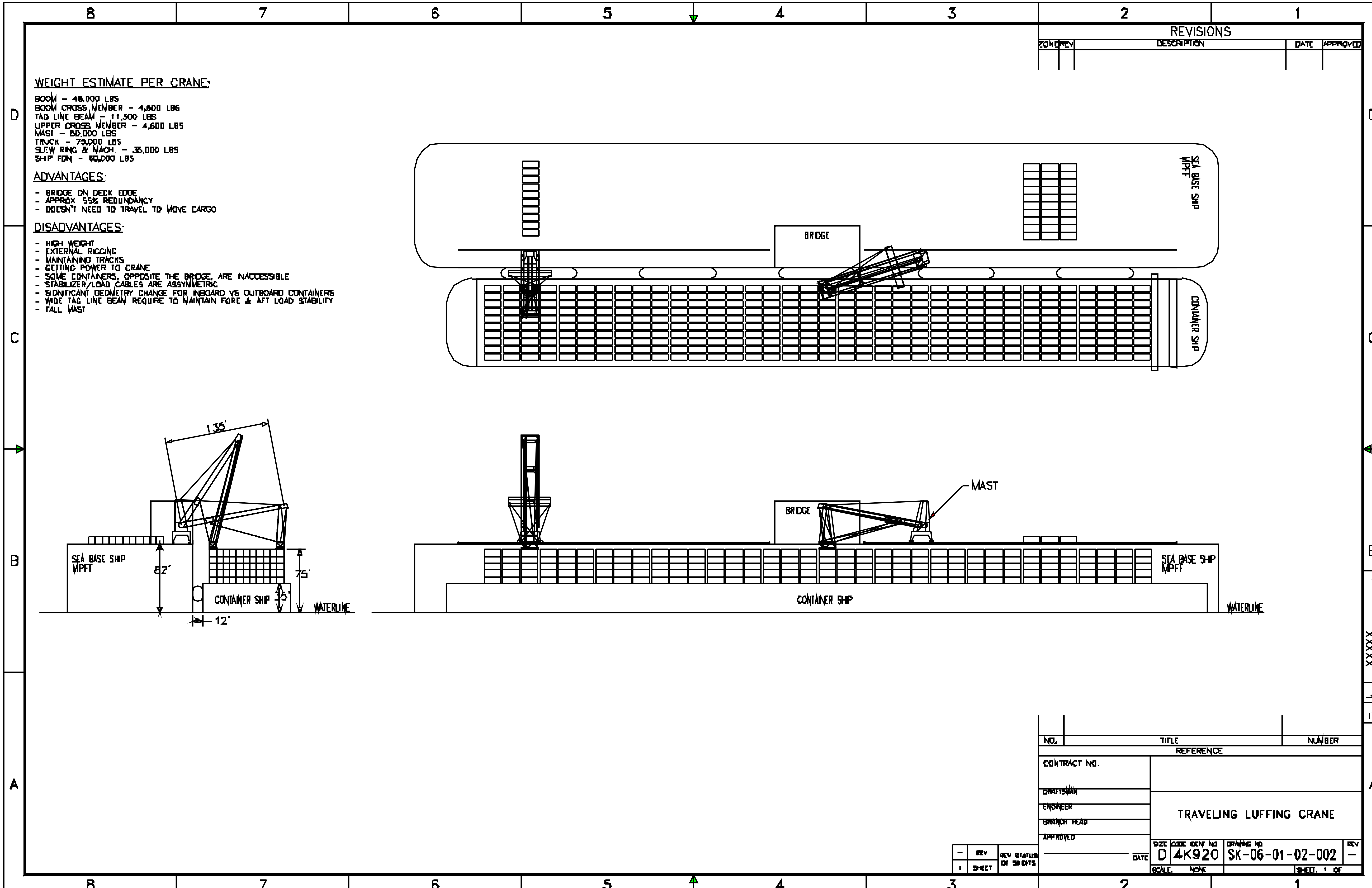
- Traveling A-Frame Crane (Two cranes per ship)
- Traveling Luffing Crane (Two cranes per ship)
- Traveling Boom Crane (Two cranes per ship)
- Traveling Single Arm Crane (Two cranes per ship)
- Traveling Double Arm Crane (Two cranes per ship)
- Fixed Pedestal Double Arm Crane (Three cranes per ship)
- Fixed Pedestal Double Arm Crane (Four cranes per ship)

A preliminary stress analysis of these different crane concepts was conducted to determine the approximate crane structural weights. Appendix D provides these calculations. Costs were calculated using predetermined values for cost per pound of structure, cost per winch of a given horsepower, cost per slew drive, etc. These costs were summarized to obtain approximate costs of each of the crane options. It is not expected that the estimates of crane cost are accurate, but since the same criteria was used for each crane option, the relative cost should be representative. This relative cost is all that was needed as an input to the trade study.
Sketches of the seven crane concepts, including a summary of the weight estimates and lists of advantages and disadvantages are included in the paragraphs that follow:

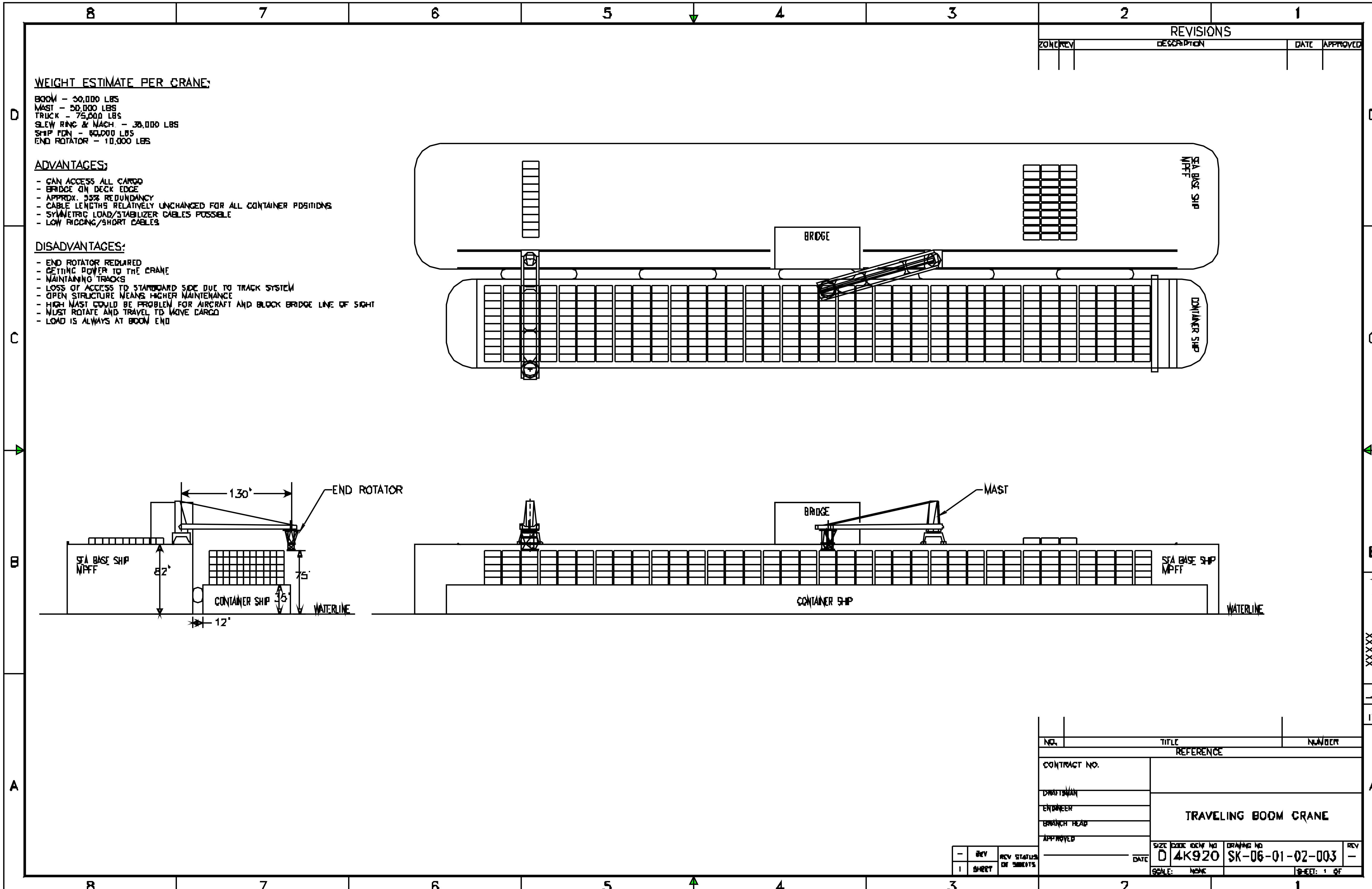
7.2.1 Traveling A-Frame Crane (Two cranes per ship)



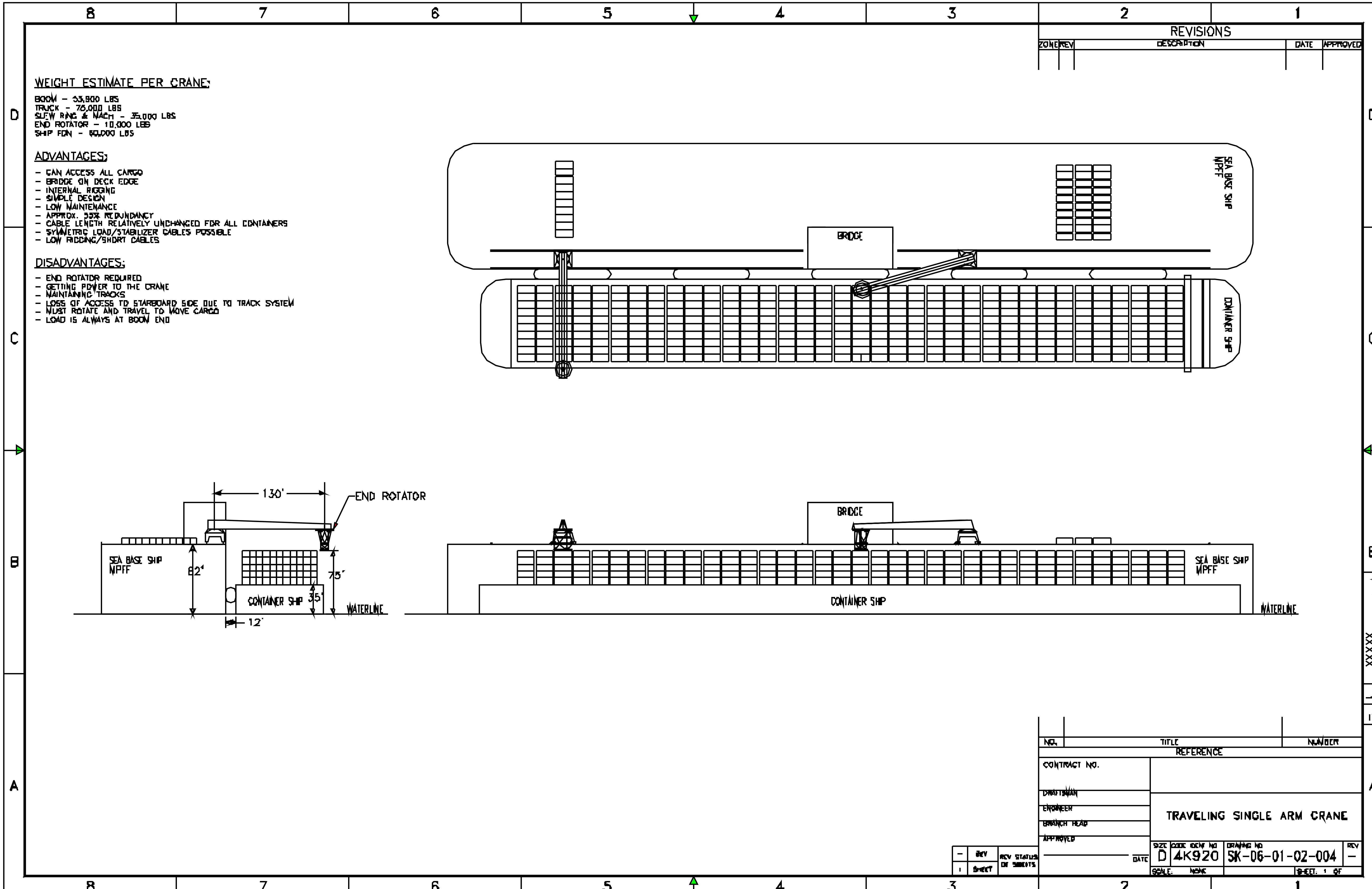
7.2.2 Traveling Luffing Crane (Two cranes per ship)



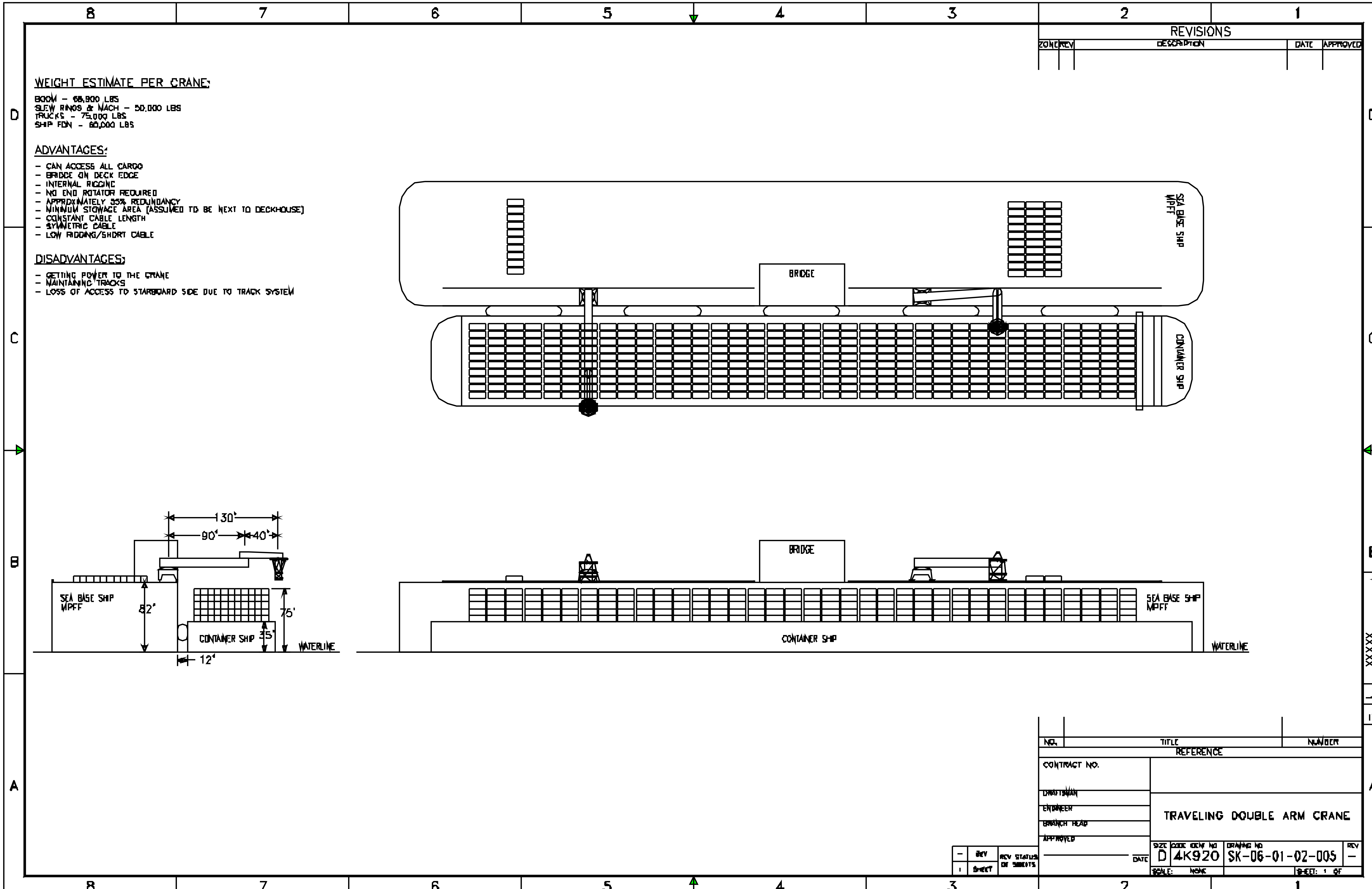
7.2.3 Traveling Boom Crane (Two cranes per ship)



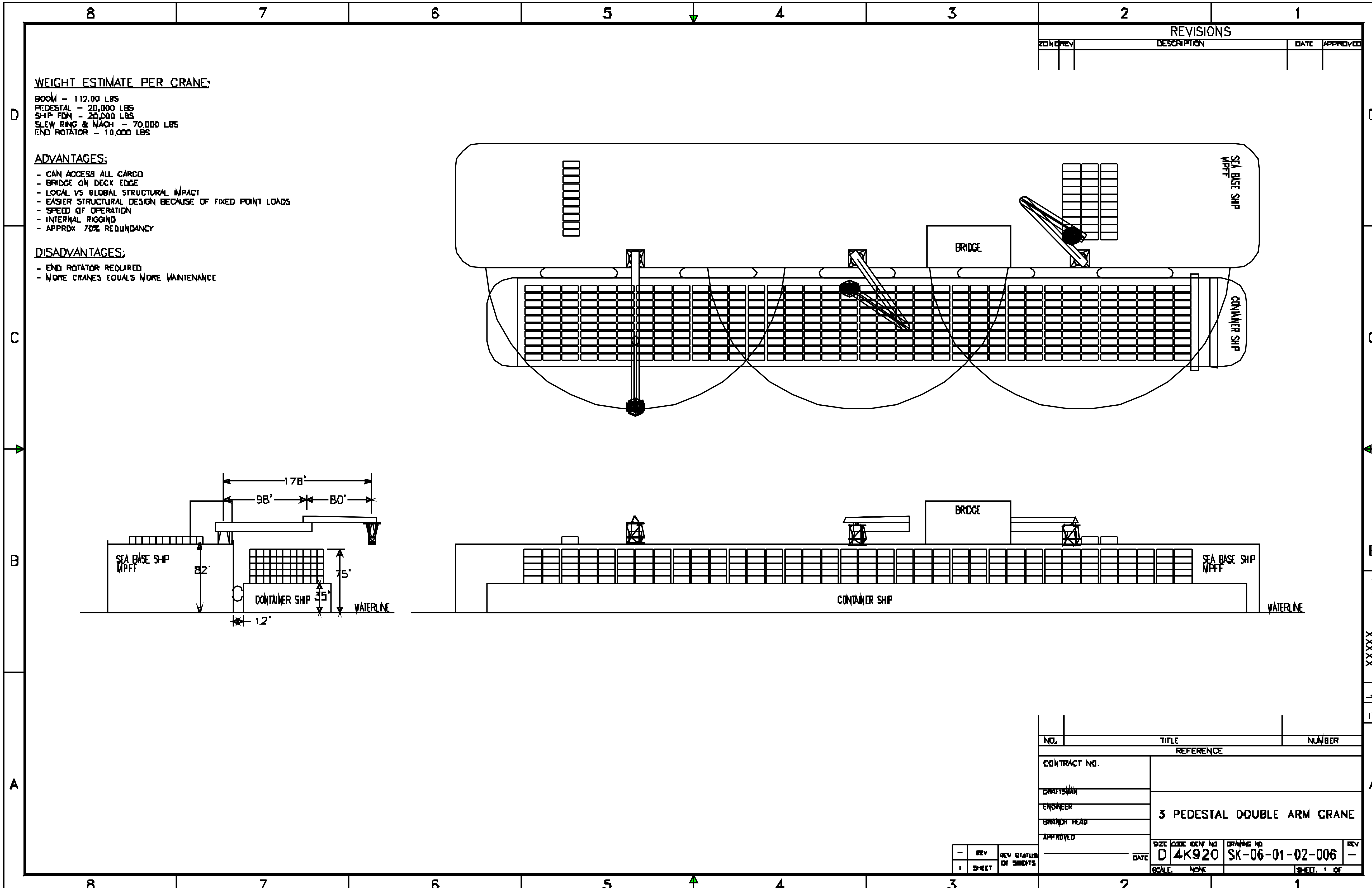
7.2.4 Traveling Single Arm Crane (Two cranes per ship)



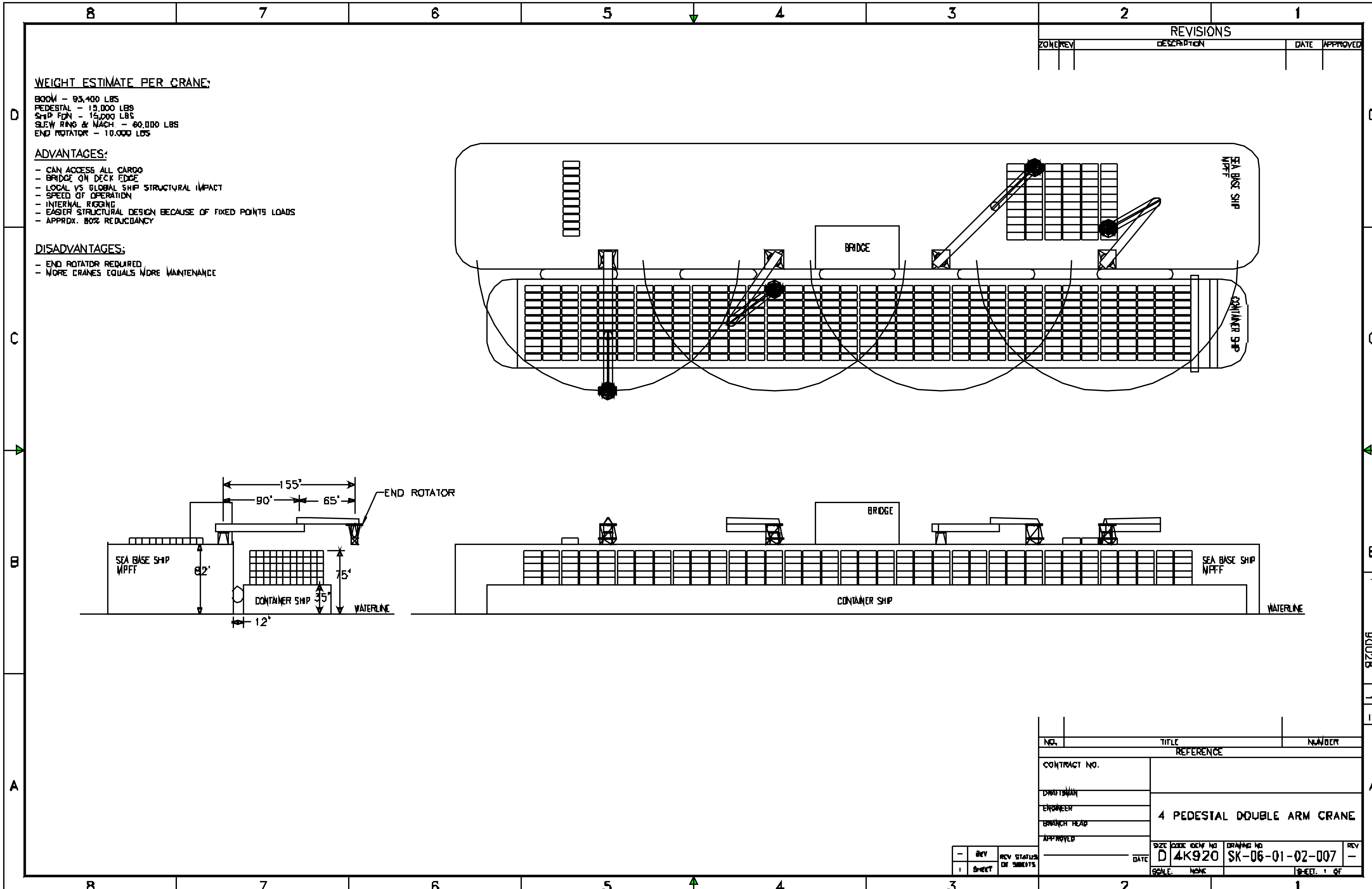
7.2.5 Traveling Double Arm Crane (Two cranes per ship)



7.2.6 Fixed Pedestal Double Arm Crane (Three cranes per ship)



7.2.7 Fixed Pedestal Double Arm Crane (Four cranes per ship)



7.3 Review Known Fuel Transfer Concepts

Two methods of fuel transfer were considered. Both methods are currently used successfully for ship-to-ship alongside transfer. The two methods include:

- Tensioned Spanwire Supported Hose Handling, and
- Crane Supported Hose Handling

7.3.1 Tensioned Spanwire Supported Hose Handling

This method is currently used by the US Navy for Underway Replenishment. It is well developed for that application, but would require that some permanent installations be fitted on the commercial tanker. Figure 7.3.1 shows a typical US Navy probe fueling system.

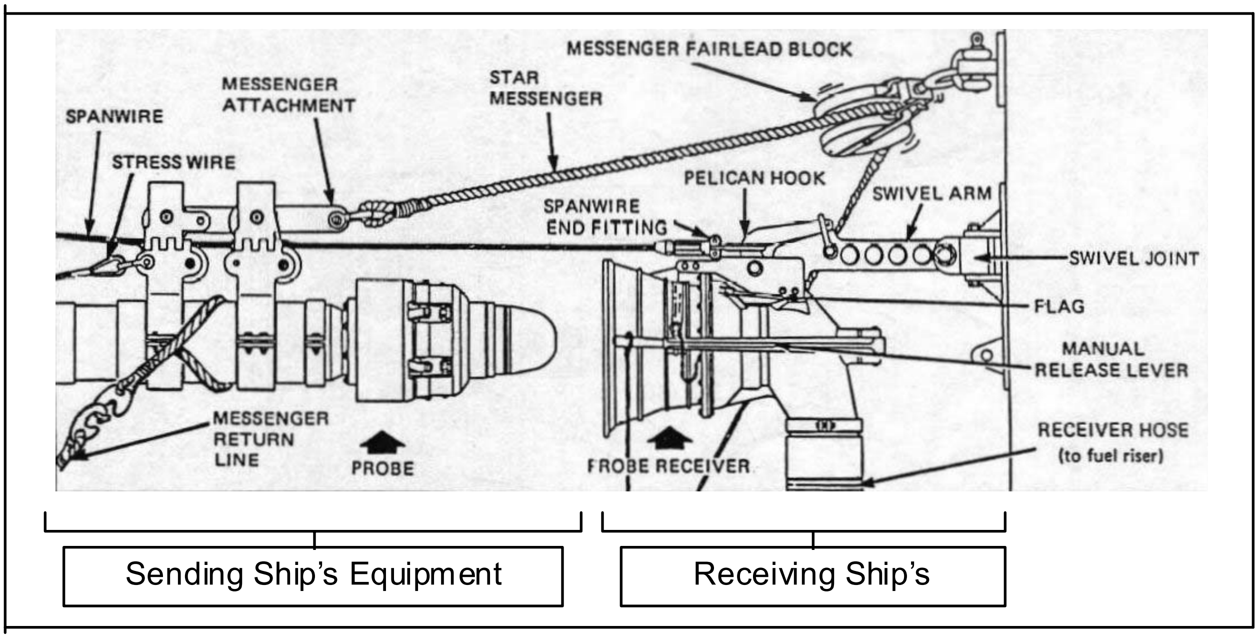


Figure 7.3.1 – US Navy Probe Fueling System

The probe fueling system is designed for ship separations of approximately 150 feet. This is far greater than would be required in a skin-to-skin connected replenishment. Additionally adaptations would have to be made to provide for larger hoses. The system is scalable both in shorter hose length and larger hose diameter, and could be adapted for a skin-to-skin replenishment operation.

7.3.2 Crane Supported Hose Handling

Commercial Tankers are typically equipped with amidships fuel risers that are used for loading and unloading in-port. Typical in-port operations have port cranes lift hoses from the pier to the amidships station for manual connection. The hose handling cranes support the hoses on by a saddle located at the hoses midpoint. This allows the the end of the hose to be positioned in the vicinity of the risers to allow the manual connection. Once the connection is made, the saddle can be lowered to provide slack in the hose suitable for the expected sea-state 5 ship motions. Historically, most U.S. Navy charter product tankers have a maximum discharge rate of 4000 gpm. Generally these tankers have two discharge stations with a common discharge pipe size is 8-inches in diameter with a flange fitting.

This method is currently used in tanker skin-to-skin lightering operations. No special adaptations are required to be made to the tanker as would be the case if a modified probe fueling system were used. For this reason. The fuel transfer operation, while the sea-base ship is skin-to-skin with a commercial product tanker, would be conducted as close to the way that they would do it in-port as possible.

It is recognized that as the product is transferred, both ship's draft and handling characteristics (i.e., trim and stability) will change. In addition, the ships must consider what tanks the product is being transferred to and from so that their hulls do not become overstressed (hog and sag) during the transfer operation.

Based on the above, it is envisioned that the sea-based ship would provide the hose(s) and the fitting(s) to the tanker. It is envisioned that one or two hoses would be lifted onto the tanker and support by the sea-based ship's crane(s) during fuel transfer operations. The sea-base ship would provide NATO spool(s) (both the "A" and "B" ends) and/or ROBB coupling(s) (both male and female ends) that would be mated (bolted) to the tanker's discharge riser's flanges. When charter tankers transfer to U.S. Navy oilers, NWP 4-01.4, *Underway Replenishment*, recommends that a NATO spool be bolted to the discharge riser and a ROBB coupling be placed between the spool and the hose. This provides a shut-off valve at the discharge riser in case of a break in the hose. This will also retain product left in the hose after transfer when returning the hose(s) to the sea-based ship.

While either a modified probe fueling system or a crane supported hose system is workable, the crane supported hose handling system is simpler and has been proven in tanker lightering operations. It would not require any ship modifications to the commercial tanker, so that the sea base ship would have more supplier options. For this reason, the crane supported hose handling approach is recommended. Since the technology for this system exists, no further research is needed in this area.

7.4 Other Cargo Transfer Technology

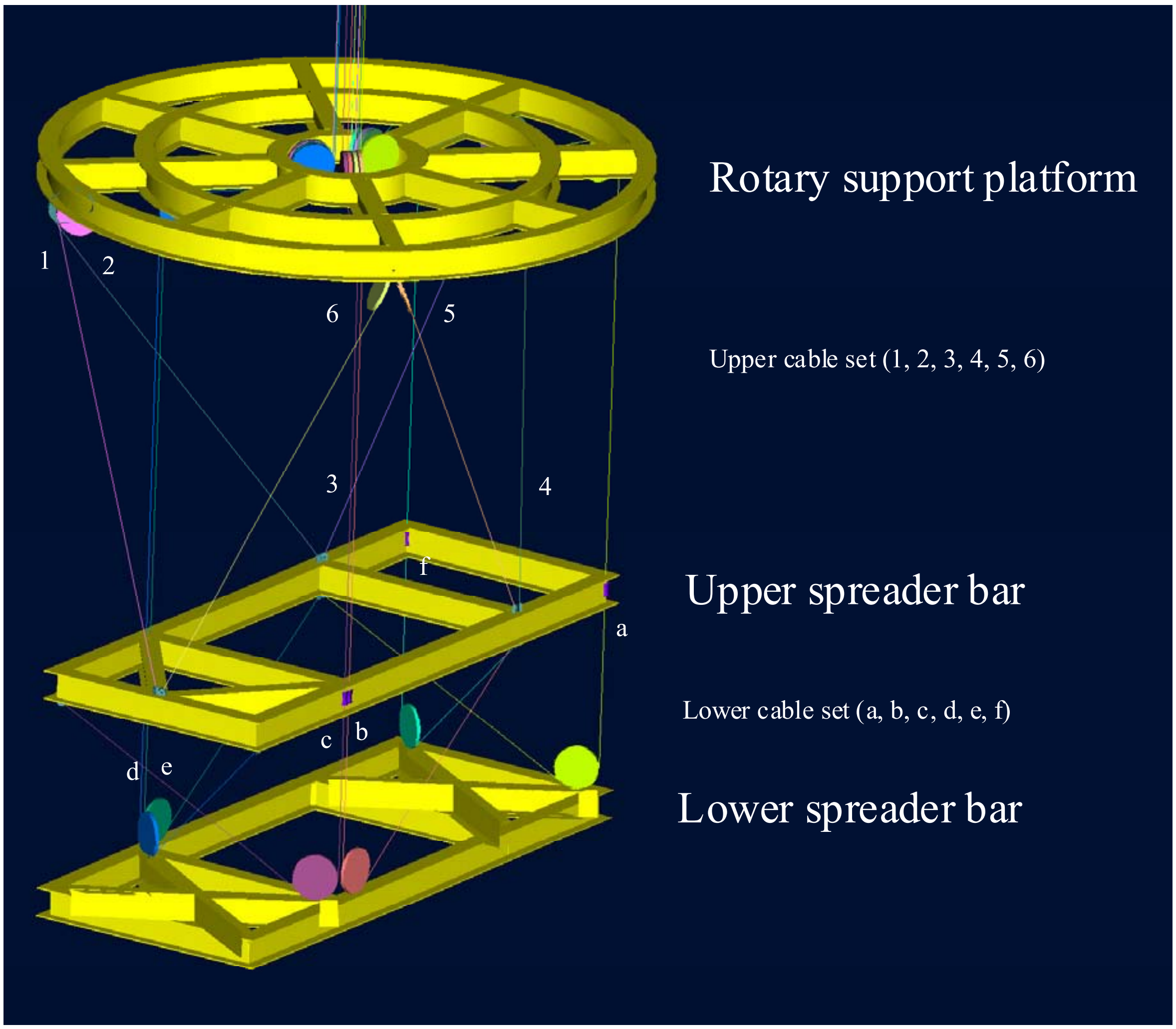
7.4.1 <u>Rigging Concepts for Six-Degree-of-Freedom Cranes</u>

The team considered alternate rigging arrangements based on the criteria set forth as described above. Additional self-imposed requirements included the ability to pick up a container without moving the containers on any of its four sides. While other configurations could be considered, the concept described below appears workable, and was used for this initial study effort.

As shown in Figure 7.4.1-a, the end-effector of the proposed crane consists of a rotary support platform, and upper spreader bar, and a lower spreader bar. The upper spreader bar is connected to the rotary support platform by six cables (1, 2, 3, 4, 5, 6). The lower spreader bar is connected to the upper spreader bar by the six cables (a, b, c, d, e, f).

The end-effector for the proposed crane consists of a rotary support platform, an upper spreader bar, and a lower spreader bar. Cables 1 – 6 connect the rotary support platform to the upper spreader bar. Cables a – f connect the upper spreader bar to the lower spreader bar.

Figure 7.4.1-a Proposed Crane End-Effector – Overall View



As shown in Figure 7.4.1-b, cables 1 – 6 terminate on the top of the upper spreader bar at the sites (1e, 2e, 3e, 4e, 5e, 6e). So long as cables 1 – 6 remain in tension, the rotary support structure and the upper spreader bar form an inverted Stewart platform. Lifting cables 1 – 6 are driven by a set of six crane hoist winches so as to control the position and orientation (in all 6 degrees of freedom) of the upper spreader bar relative to the rotary support structure at the end of the boom.

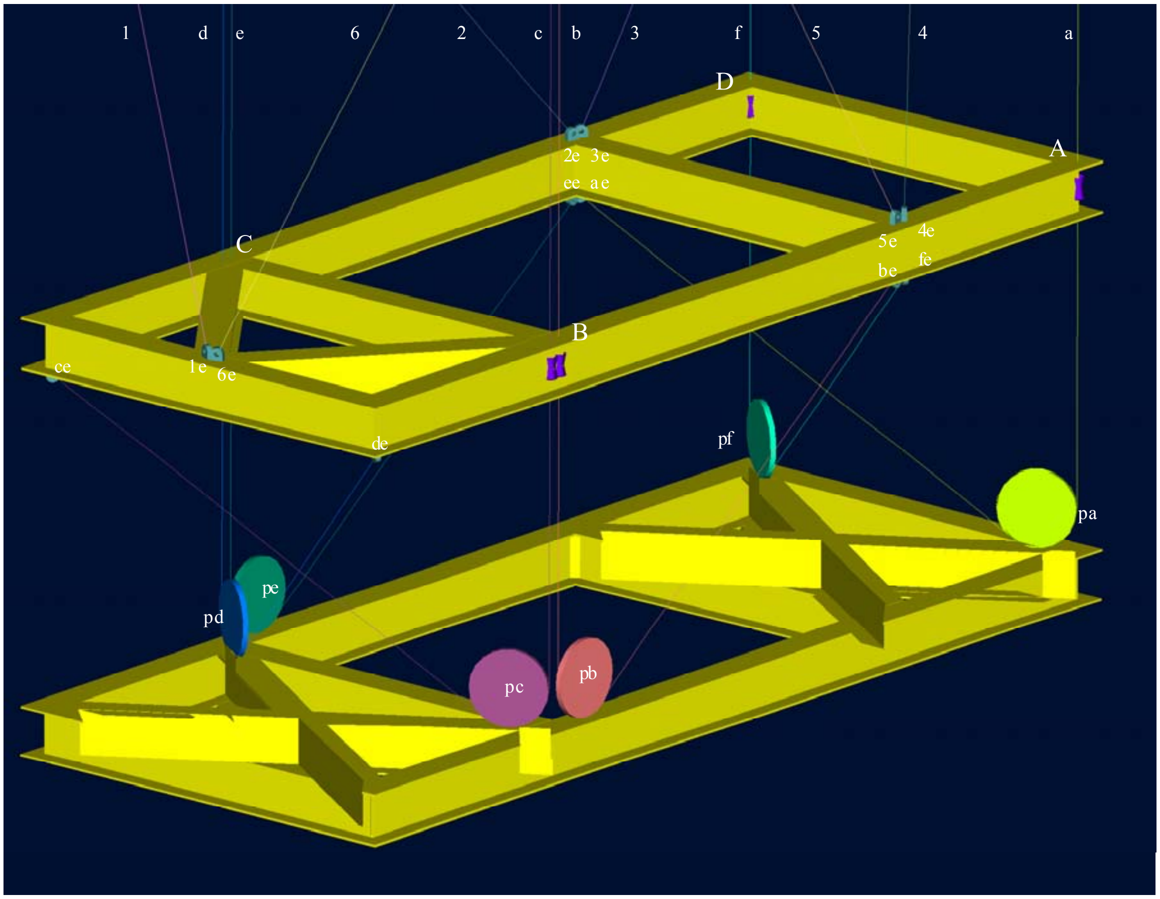


Figure 7.4.1-b Upper and Lower Spreaders with Cables – Detailed View

Cables (1, 2, 3, 4, 5, 6) support the upper spreader and allow it to be positioned in 6-degrees of freedom with respect to the rotary support structure at the end of the boom.

Also shown in Figure 7.4.1-b, the lifting cables a – f pass freely through the upper spreader bar at sites (A, B, C, D), pass under pulleys (pa, pb, pc, pd, pe, pf) mounted on the lower spreader bar, and terminate on the bottom of the upper spreader bar at the sites (ae, be, ce, de, ee, fe). Lifting cables a – f are driven by a second set of six crane hoist winches so as to determine the position and orientation (in all 6 degrees of freedom) of the lower spreader bar relative to the upper.

This arrangement allows the crane to drive cables 1 – 6 so as to cause the position and orientation of the upper spreader bar to track the motion of the freighter relative to the crane. Cables a – e can then be driven so as to maneuver the lower spreader bar into a vertical cell even if the cell is surrounded by containers stacked on all sides.

7.4.2 Possible Enhancements to the Crane Rigging Concept

Proposed enhancements recommended for further study include:

1) **Extend the size of the support structure** for cables 1 – 6 at the point where they exit from the rotary structure at the end of the boom. This will increase the effective work volume and enable the system to track larger ship motions. It also will increase the lateral stiffness and enables the system to exert more positive control over the load. See sketches in Figures 7.4.2-a and 7.4.2-b.

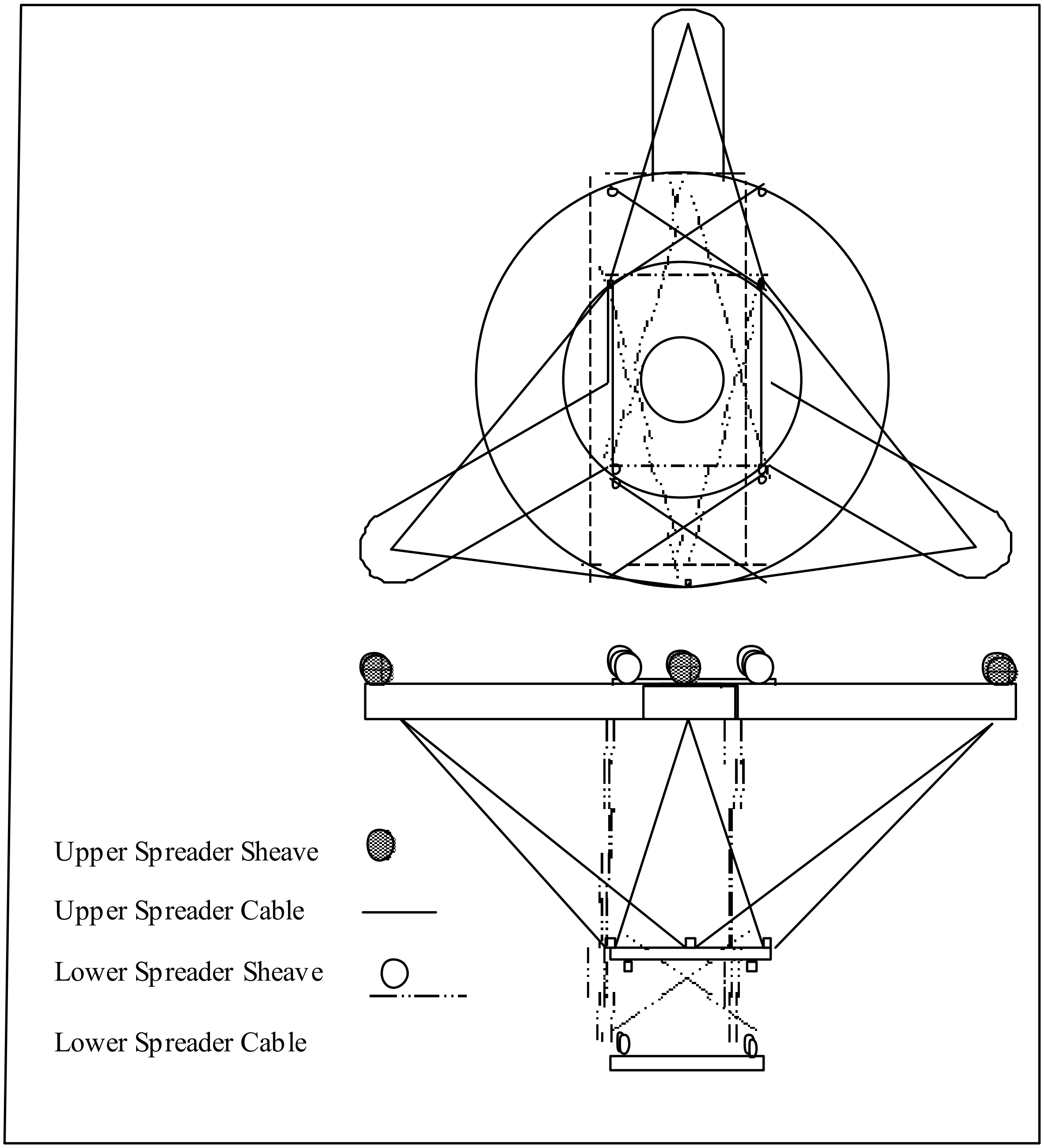


Figure 7.4.2-a Suggested Extension of Upper Rotary Support Structure

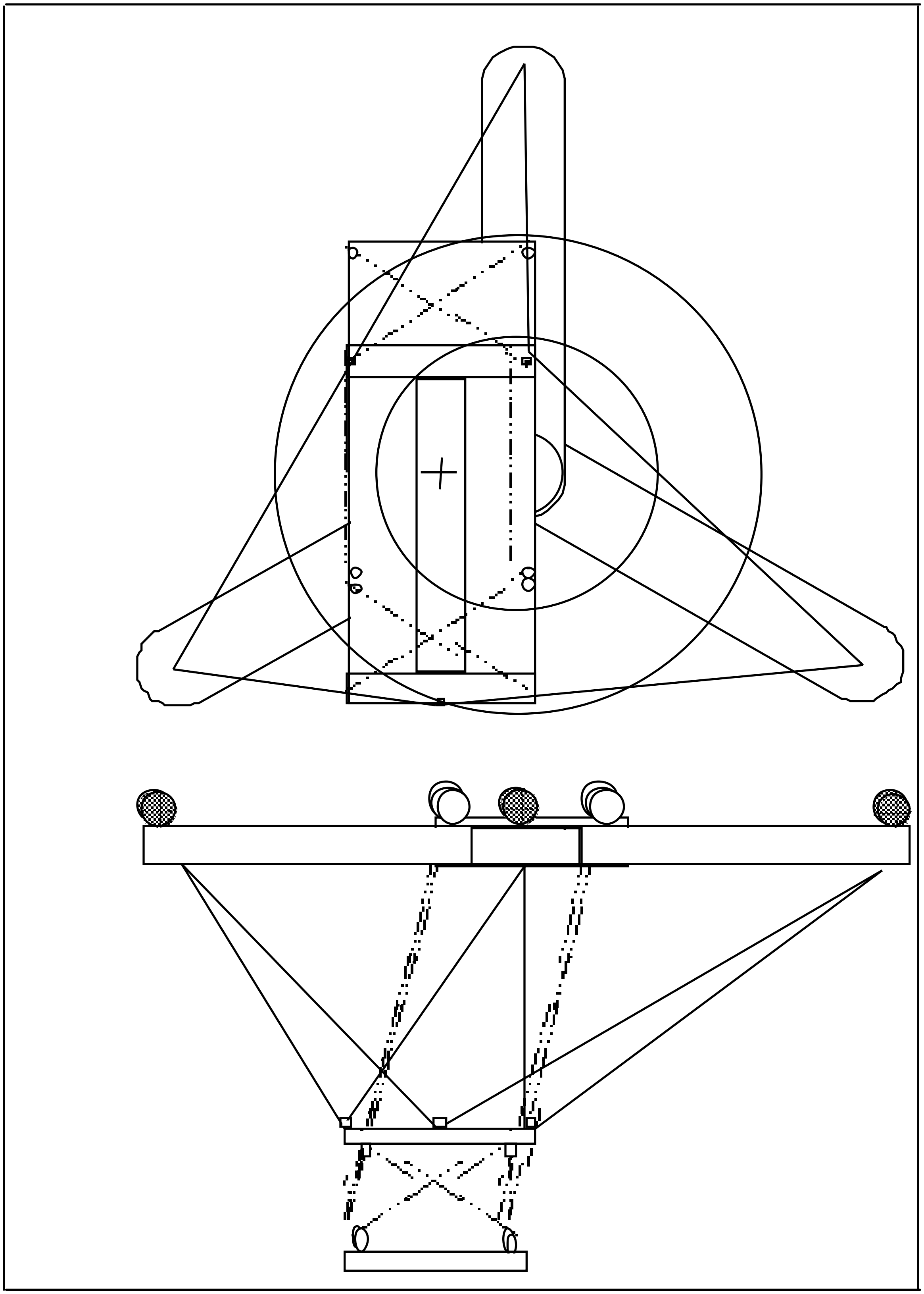


Figure 7.4.2-b Extended Work Volume from Larger Upper Support

2) **Change the shape of the upper spreader bar** to the shape of an "I" as shown in Figure 7.4.2-c. This eliminates the feed-through sites A, B, C, and D where cables a – f to pass through the upper spreader.

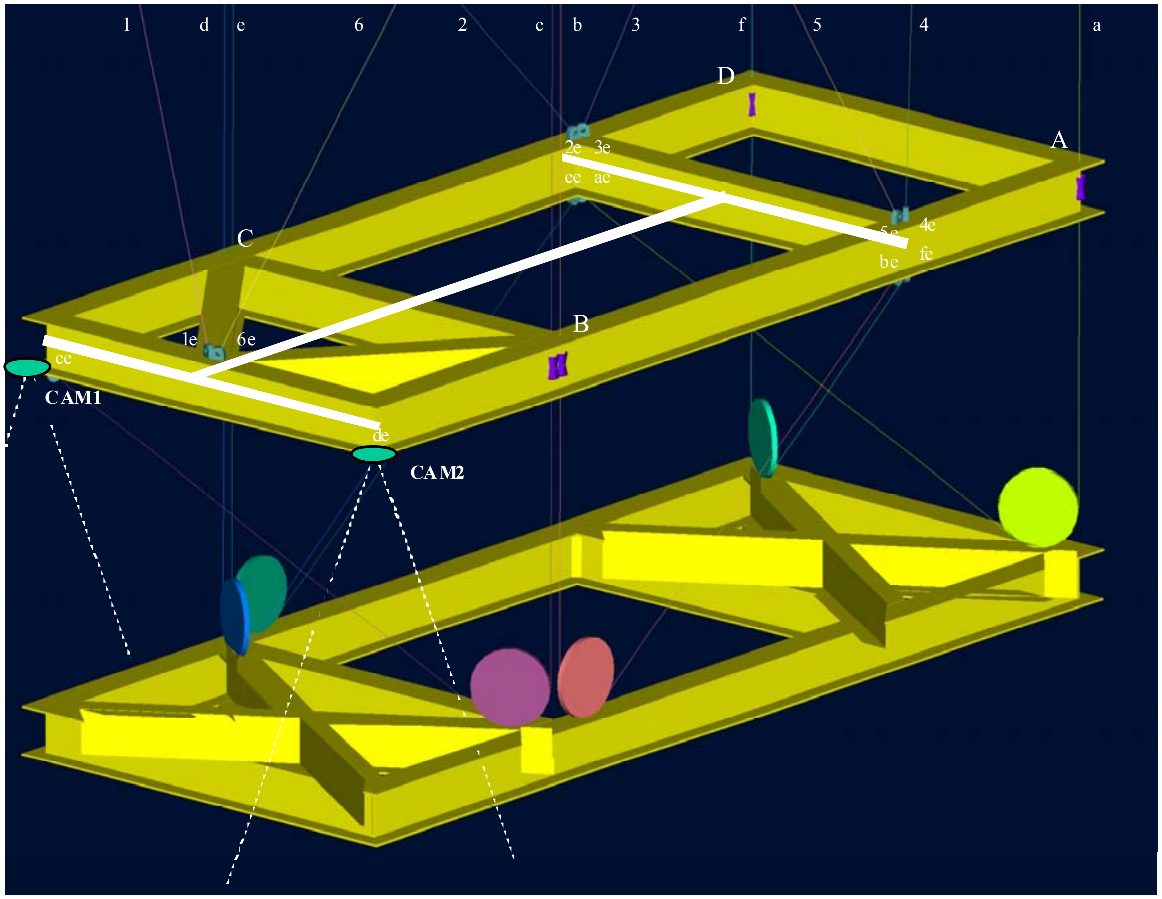


Figure 7.4.2-c. Proposed Modification of the Upper Spreader Bar is shown by the white lines. This design eliminates sites A, B, C, and D of Figure 7.4.1-a, and allows the cables a – f to pass directly from the rotary support structure at the end of the boom to the pulleys on the lower spreader bar. LADAR cameras are shown mounted at position CAM1 and CAM2.

The modification suggested in Figures 7.4.2-c both simplifies the design and improves the performance. It simplifies the design in that there is no need to design feed-through sheaves at A, B, C, and D. It also makes the upper spreader bar smaller and lighter.

It improves the performance because it eliminates side forces exerted on the upper spreader bar at the feed-through points A – D by cables a – f when the upper spreader bar is not centered beneath the rotary support structure. The current design causes cables a – f to exert side forces that fight to return the upper spreader bar to center. This reduces the effective size of work volume.

3) **Position of LADAR Cameras** – The two LADAR cameras could be mounted on the upper spreader bar at points CAM1 and CAM2. This will produce images such as shown in Figure 7.4.2-d.

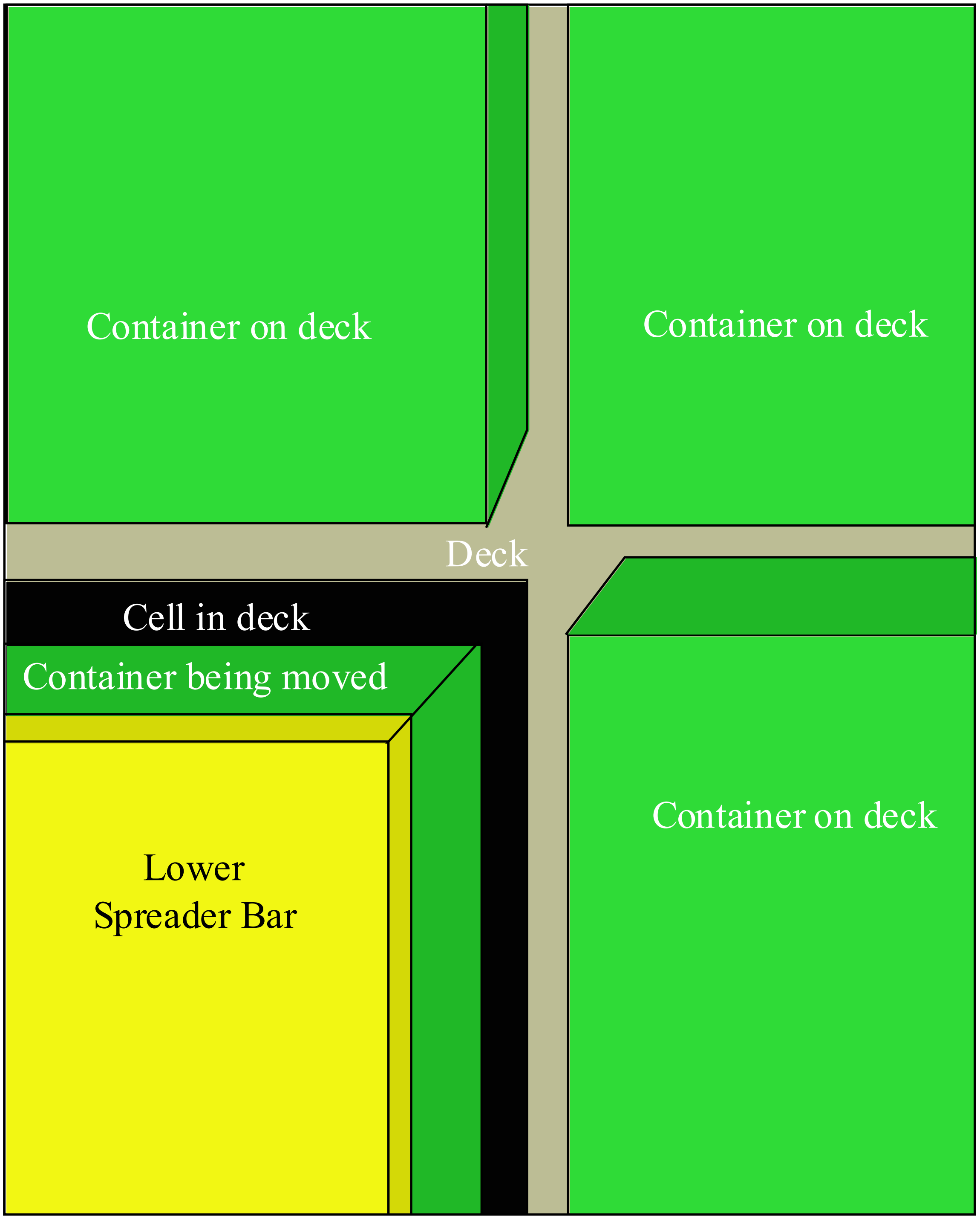


Figure 7.4.2-d View from LADAR Camera

Figure 7.4.2-d shows a view from camera 1 looking down on the front right corner of the lower spreader bar while it is holding a container and placing it into a cell between three containers sitting on the deck.

The image shown in Figure 7.4.2-d provides a range measurement at each pixel. This enables an image processing algorithm in a computer to build a precise 3-dimensional model of the configuration of the containers on the deck, the spreader bars, the container held by the lower spreader bar, the deck, and the cell opening on the deck. The computer can compute the position of the bottom of the moving container relative to the cell, the deck, and the other containers up to 10 times per second. The computer can also use this dynamic 3-dimensional model to compute the motion required to place the container in the cell. The image can be acquired, the model updated, and the proper control signals can be computed 10 times per second on a computer no more powerful or expensive than a good laptop.

It therefore possible for the proposed system to follow the motion of the container ship, compute its position relative to the container being moved, and control the motion of the crane with latency on the order of 100 milliseconds. This is sufficiently fast to servo the container into the cell.

8.0 Conclusion – System for Further Study

Based on the review of the available information, the study and analysis of the feasibility of skin-to-skin connected replenishment in sea state 5 will proceed with the following technologies:

- MPF 2010 as the cargo receiving ship as defined in this report and Reference 1.
- SL-7 as the offload containership
- A specific fender type has not been selected. The discriminator between fender types is that the solid foam filled fenders do not have the risk of complete failure if damages, as air filled or pneumatic fenders do. However, the calculations and analysis to follow will consider fender damping as a variable and fender compression load will be calculated. If the loads are acceptable, air filled or pneumatic fenders will remain an option.
- The baseline mooring line system is the composite line that is currently being used in tanker skin-to-skin cargo transfer. These are wire cables with a “grommet” of synthetic fiber or nylon rope in the center in order to add a certain amount of stretch. Ship motion and line load sensitivity to line spring constant will be investigated to determine if synthetic lines rather than wire cable provide better performance.
- Both constant tension and locked mooring winch systems will be considered.

References

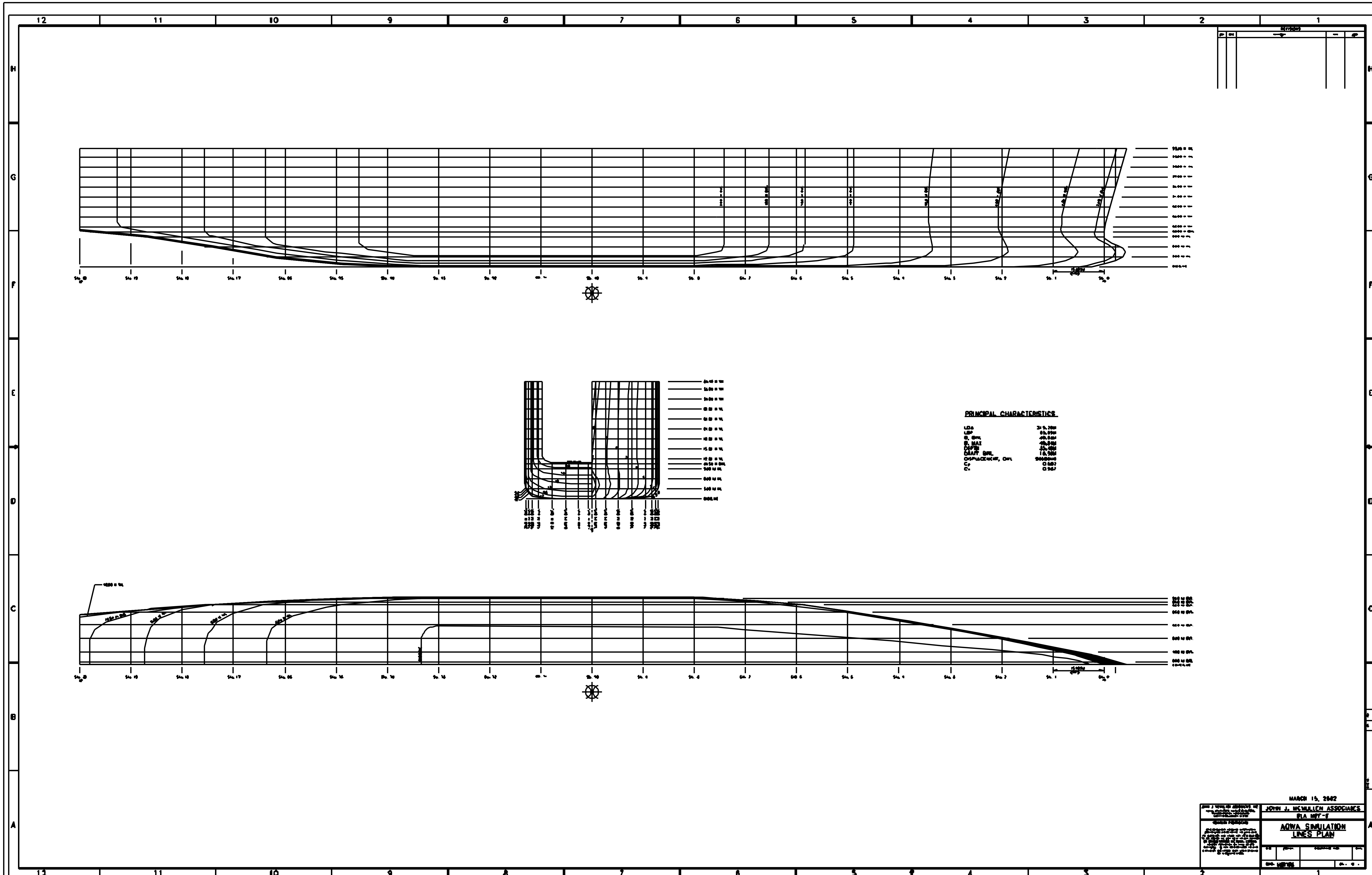
1. Manish Gupta and Daniel L. Wilkins, "Maritime Prepositioning Force (MPF) 2010 Ship Systems for Seabasing Missions, *Naval Engineers' Journal,* Jan. 2000

2. International Chamber of Shipping Oil Companies International Marine Forum (OCIMF), "Ship to Ship Transfer Guide (Petroleum)" Third Edition, 1997.

3. Society of Naval Architects & Marine Engineers (SNAME), *Principles of Naval Architecture (PNA),* (New York: 1978)

Appendix A

MPF 2010 and SL-7 Lines Plans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B. MAX
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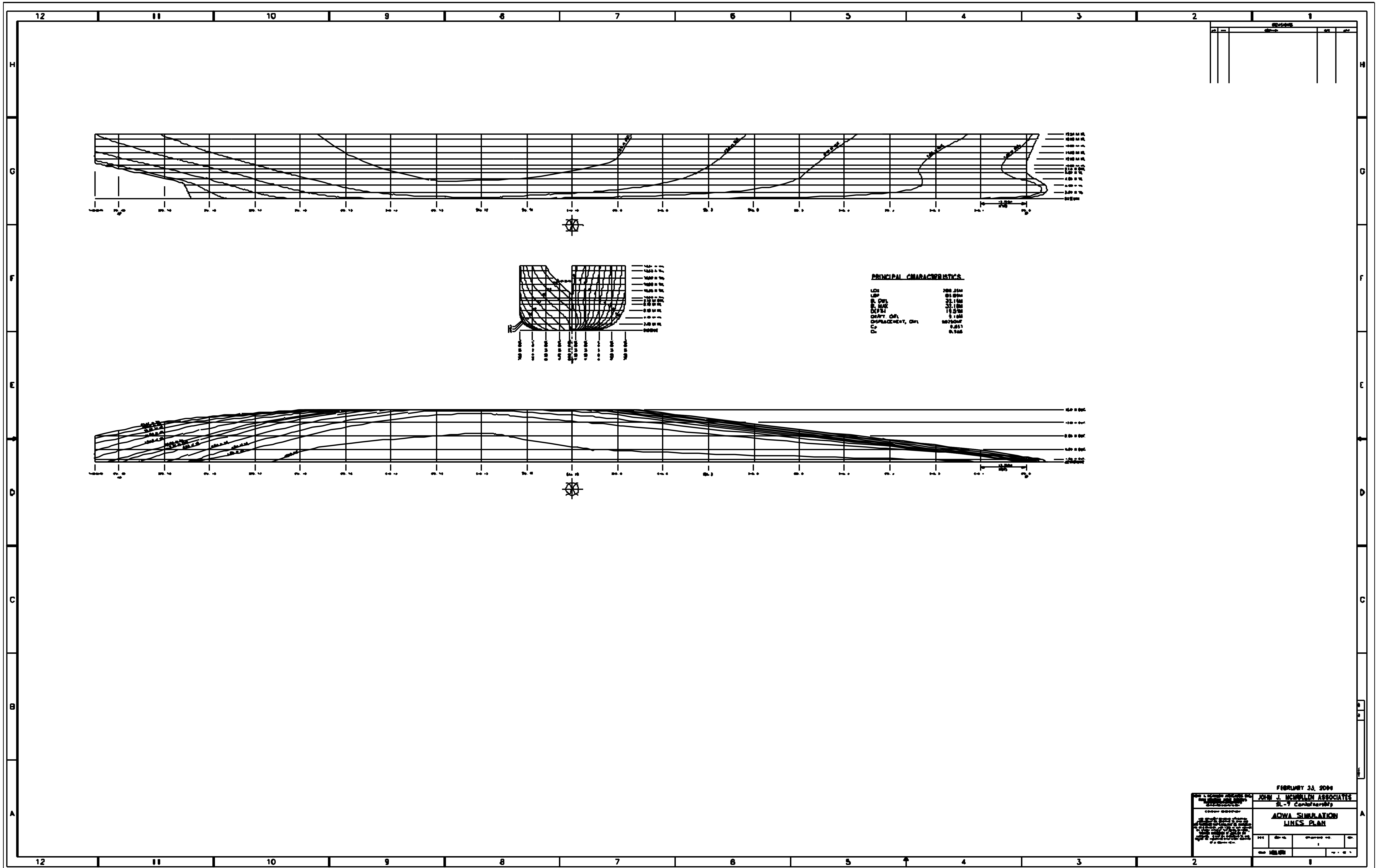
JOHN J. MCMULLEN ASSOCIATES
AQWA SIMULATION
LINES PLAN



PRINCIPAL CHARACTERISTICS
LOA
LBP
B. DWL
B. MAX
DEPTH
DRAFT, DWL
DISPLACEMENT, DWL
FEBRUARY 23, 2004
JOHN J. MCMULLEN ASSOCIATES
AOWA SIMULATION
LINES PLAN

Appendix B

Commercial Lightering Operational Assessment Study

Seaward International, Inc.

This link opens a Acrobat PDF file of the "Commercial Lightering Operational Assessment Study" prepared by Seaward International, Inc.

Appendix C

Fender Technology Assessment Study

Seaward International, Inc.

This link opens a Acrobat PDF file of the "Fender Technology Assessment Study" prepared by Seaward International, Inc.

Appendix D

Stress Calculations and Structural Weight Assessment of Alternate Crane Concepts

This link opens a Microsoft Excel file entitled: "Crane Stress and Struc Wt Estimate.xls"