“Concept Study for Offshore Wind Foundation Decommissioning Cost-savings Using a Removal Jetting System”

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Abstract:

The purpose of this paper is to explore a concept for offshore wind turbine foundation removal by preemptively including exterior jetting nozzles. This paper reviews current uses of underwater suction and discharge on suction caisson-type turbine foundations, illustrates a concept design for removal jetting nozzles to be included inexpensively during a suction caisson’s construction on the Universal Foundation developed and tested by Fred. Olson, and includes discussion of applicability and feasibility of the system, sample calculations for system and pump sizing, and a cost savings model.

Contents

1 List of Variables

An	Nozzle area
Cd	Discharge coefficient
Db	Branch pipe diameter
Di	Skirt inner diameter
Do	Skirt outer diameter
Dm	Main header pipe diameter
Dn	Nozzle diameter
Dp	Nozzle start diameter
f	System friction loss
h	Skirt depth below mud line
L	Skirt length
nb	Number of branches
nn	Number of nozzles per branch
P	Net pressure desired at nozzle
$P1$	Pressure before nozzle
$P2$	Pressure outside nozzle
Pp	Pump head required
Q	System flow rate
Qb	Branch flow rate
Qn	Nozzle flow rate
Re	Reynolds number
t	Skirt thickness
V	Desired pipe flow velocity/velocity before nozzle
Wp	Pump power
Wt	Pump motor power
$z1$	Head height at suction inlet (water surface)
$z2$	Head at discharge exit (depth to skirt bottom)
β	Nozzle diameter ratio
μ	Water kinematic viscosity
ρ	Water density

2 List of Terms

Below is a non-exhaustive list of terms useful for understanding the descriptions in this paper, some of which are industry standard and some of which arose out of a need to describe this specific concept.

Branch – system section consisting of nozzle pipe, associated piping and split hose
Caisson - the bucket assembly at the bottom of the tower used to suction into the sea floor
Header – main pipe providing full flow down to caisson
Nozzle – flow orifice that produces a velocity increase
Nozzle Pipe – pipe section with nozzle holes welded vertically to skirt
Skirt – vertical bulkhead of bucket
Suction side – piping and components between sea suction and pump under suction pressure
Transition piece – the portion of a traditional monopile foundation that sits on top of the monopile, which is leveled during installation and contains the "guts" of the foundation

3 List of Figures

4 Introduction

The first offshore wind farm, “Vindeby,” was commissioned off the coast of Denmark in 1991. It was the first commercial, multiple-turbine installation in a long line of ever increasing scale projects since. As of 2015 there was 12GW of offshore wind capacity worldwide with that number expected to skyrocket over the next decade. (14) The abundant, steady winds over the oceans, and remote siting of these behemoth turbines, coupled with mature turbine technology (but still improving mostly through size increases), perfected installation methods, and well-developed supply chains have caused the cost/kW to plummet and offshore wind becomes ever more favorable as a renewable energy option.

Figure 4-1 Vindeby Offshore Wind Farm
(Photo: Danish Wind Industry Association)

The aspects of offshore turbines that have been most extensively developed to this point have been in design, efficiency, capacity, construction, and installation. However, with so much focus on upfront cost reductions and technology improvements, relatively less attention has been given to realizing cost savings on the removal end. In light of the fact that most efforts are now consolidating around raw capacity increases (ever larger nacelles and larger numbers of turbines) and with the world’s oldest offshore installation, Vindeby, now at the end of its service life and scheduled for removal, (24) the author finds it prudent to consider how new cost-saving methods on removal of turbines might be investigated.

5 Project Goals

The goal of this project is to investigate the viability of a removal jetting system for a wind turbine foundation by creating a conceptual design and calculation set. The overall approach taken is a systems approach, which looks at the first major rounds of design and calculations that must be done in a variety of functional areas: conceptual followed by physical/structural design, integration with the caisson, system sizing, and cost modeling. For a systems approach these functional areas must be developed together, as they are all ultimately interconnected and rely upon one another.

5.1 Project Deliverables

1) CAD Design (AutoCAD file) - shows global foundation dimensions and water depth for system sizing calculations, global nozzle layout and nozzle detail.
2) Design calculations (Excel file) – calculations for nozzle flow rate, total system flow rate, head losses, pump sizing and a cost model.
4) This paper.

6 “Borrowing” From Oil and Gas

One of the greatest benefits the offshore wind industry has had is the abundance of technologies that were first perfected in the offshore oil and gas industry and have been successfully adapted for offshore wind use. This is perhaps most evident when it comes to offshore foundations. A rudimentary example is the many, many concepts for placing wind turbines on pre-existing converted oil platforms. A more in-depth example has been in the development of complex designs for monopile, jacket, semi-submersible, and TLP foundations, where the designs have been nearly “perfected” already for offshore platform use. Thus the expertise, calculations, and software optimization methods were in place for quick adaptation and precise optimization of the structures for turbine use. Indeed, the company that designed the first offshore wind platforms installed in the United States was an engineering firm with extensive experience in the oil & gas industry. (25)

6.1 Offshore Platform vs. Turbine Foundation Design

That is not to say that there is a direct translation from offshore oil platforms to offshore wind. Major differences between offshore platforms and wind turbine foundations exist, both in scale, and loading modes. By scale, what is meant is that most existing offshore platforms are a “one-off” design, where a single or only a couple large foundations of a particular design are constructed. This is different from a utility scale wind farm which requires many inexpensive essentially mass-produced foundations that are more or less identical.

Another major difference is that the horizontal loads and moments from tower reactions are generated at a height above the water substantially higher than on a typical oil platform which creates much larger overturning moments than a typical platform will see. Similarly, cyclic loads from blades whirling and vibrations are crucial considerations for turbine foundations b/c concern for fatigue failure. These differences between oil foundations and turbine foundations must be taken into consideration when designing for what otherwise appear to be a similar applications. (7)

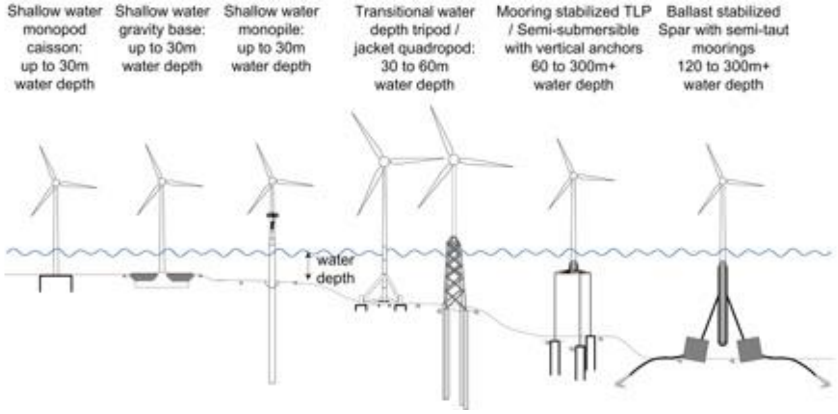

Figure 6-1 Offshore Turbine Foundation Types
(Graphic: http://www.dosits.org/images/dosits/AlternativeEnergyImage_500.jpg)

7 The Suction Caisson

One specific area where foundation technology from the oil & gas industry has made a crossover is that of suction caissons. Suction caissons are inverted bucket-shaped anchors that are embedded into the seafloor via suction. The first documented use of a suction caisson occurred in 1958 for an underwater inspection apparatus, but scale use wasn’t seen until 1982. (1)

By eliminating the need for pile-driving, suction caissons can be installed at a substantially reduced cost. Pile-driving must be halted when sensitive marine life comes too close to the construction site, so elimination of pile-driving reduces delays and makes the installation process much more environmentally friendly. Additionally, suction installation can be continued in weather conditions that would halt pile driving, (1) a welcome change since wind turbines are, by their nature, located in areas with the strongest winds. Weather delays are a chief cost overrun concern. One of the most visible benefits is that typically the need for a jack-up installation vessel is eliminated when no pile-driving hammer is needed. The savings here alone can be substantial due to the very expensive day-rates of self-elevating vessels. Suction caissons can allow installation of monopiles into deeper waters where previously a jacket-type foundation would need to be installed instead. (1) The suction caisson is seen as a transitional foundation, filling the gap between widely-used monopiles, and the rarer but sometimes necessary jacket foundations. When placing a multi-story tower on top of which sits a set of whirling blades, proper leveling is critical. Studies show that adequate leveling can be achieved with suction alone. (9) This further reduces the costs of design and installation, because the foundation can be made in a single piece and installed in a single step, instead of the more conventional method where a two-piece foundation is used: a monopile and "transition piece" where the final leveling occurs between the monopile and transition piece. There are also cost savings realized by avoiding the need for grouting these pieces, which has become a reliability issue for some European wind farms. (23)

Put simply, suction caissons tend to avoid a variety of interrelated pile–driving, leveling, and environmental issues experienced during installation of a fixed structure in the sea. Indeed, suction caissons are being considered for new wind farm installations in the emerging U.S. offshore wind market.(4)

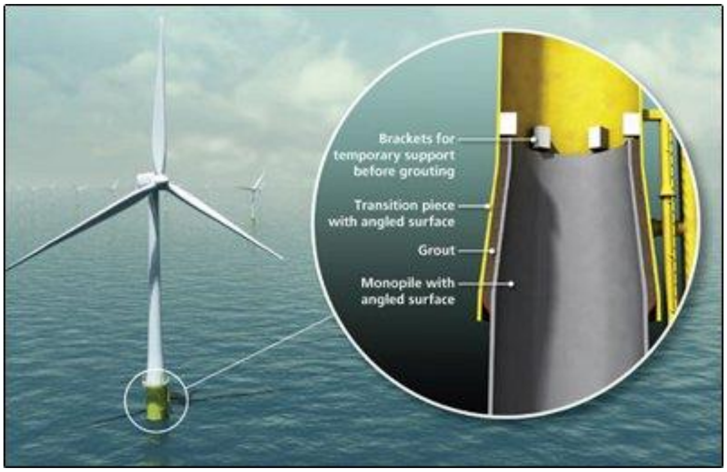

Figure 7-1 Traditional Monopile to Transition-Piece Grouting
(Graphic: DNV)

7.1 The Suction Caisson Design

In order to plan how to integrate removal jetting nozzles into a suction caisson, we must first understand how they are built. In simple terms, suction caissons can be described as adding a curved "skirt" to a round steel top plate, forming a bucket shape. Occasionally they are constructed from concrete for large offshore installations (a 28 meter diameter in one example). (1) It is assumed that steel is the most appropriate method of construction for offshore wind foundations. They are constructed with stiffeners and sectioned in a honeycomb or "triangle" pattern for strength and compartmentalized leveling control. Valves at the top of the caisson are used for flooding and suctioning with an attached hose or built-in piping from a pump located onboard the installation vessel. A typical method for lab experimentation, simulation and comparison of caisson foundations is presented by Houlsby et. al. (7,8) where dimensional similarity is set through the L/2R and t/2R ratios (see illustration below). Design and optimization of the caisson itself is outside the scope of this paper, but these variables are mentioned here so that they may be discussed as they relate to the physical design of the system.

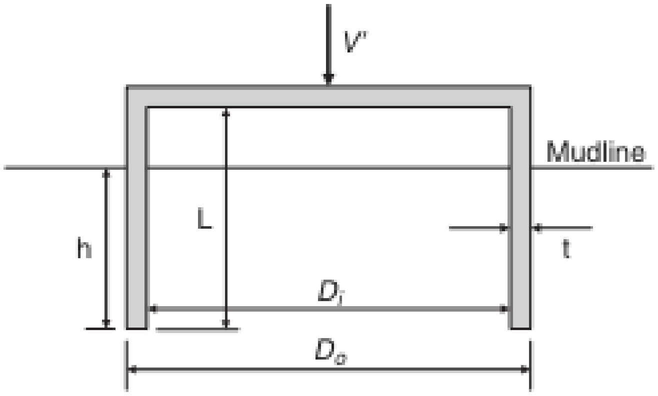

Figure 7-2 Principal Geometry Variables of Caisson Foundation
(Graphic: Houlsby et al)

7.2 Suction Caisson Installation

Installation is a two-step process whereby the caisson is constructed in a yard onshore and transported via barge or installation vessel to the site. This is where one of the major aspects of savings is realized, because a jack-up vessel is not necessarily required since the suction caisson is self-leveling. A floating crane-barge or installation vessel (pending the weather allows it) can lift the caisson into the water, which allows time, day-rate, and fuel savings. The flood valves at the top of the caisson are opened and the entire structure is lowered into the water, so that air escapes from the top. Upon reaching the bottom, first the structure is allowed to sink under its own weight. (1) One can see how this is a natural first step because the thin walls of the bucket sections (the skirt) cut down into the seabed much more easily than a monopile's thicker walls, or a solid steel cylindrical pile can. In fact, perhaps an under-appreciated cost-savings for suction caissons is that gravity itself starts the process.

After reasonable sinkage has occurred, the second stage involves connecting suction pumps to the flood valves and suctioning water from the chambers that are now sealed against the seafloor, to create a low pressure zone inside them. The caisson sinks under the forces created by this pressure difference until the desired depth has been reached when suction is shut off. Correlation cone tests (as in monopile tips) have been performed in studies referenced by Cotter, (1) that proved the addition of even small amounts of suction negated the tip resistance of the skirt, leaving only the skin friction between skirt and soil to resist installation.

7.3 Existing Caisson Jetting Uses (for Jetting During Caisson Installation)

The most notable existing suction caisson turbine foundation design, by Universal Foundation, a Fred. Olson company, has been prototyped and trialed, between 2012-2015. The joint venture tested the foundations verticality, penetration and skirt stresses over multiple scale simulations at different sites. (20)

The design does utilize tip jets during installation, located at the edges of the skirt. They are activated if needed during installation to keep the foundation level. However, these jets are not particularly useful during removal, as they are not located in the proper location for breaking the friction of soil on the skirt surface. So, there is an opportunity to take the foundation “to the next level,” with removal jetting. Since the Universal Foundation is the current commercial project with the most traction, it was chosen (or perhaps it’s dimensions at least) to serve as the starting point for adding removal jets to a suction caisson design.

7.4 Soil Type

Soil type plays a major role in the design of any offshore foundation. It will be useful here to define two failure modes to quantify foundation type and installation type performance: moment resistance and pull-out resistance. Both of these are affected by soil type, as well as installation type. For example, it is a reality that a suction-installed caisson will have less moment resistance than an equivalent caisson that was driven into place, because the soil inside the caisson has been exposed to a negative pressure. It’s also the case that sand is much more affected by the suctioning process than clay with greater reduction in skin friction on the skirt, which can make the installation faster, but sand also yields an even lower moment resistance. Similarly, soil type will play a role in a removal jetting system, because sand will experience liquefaction at a different point than mud or clay. The jetting system for turbine foundation removal will be most cost beneficial in clay soils, as these are the most difficult and time consuming to remove. (1) These considerations will become important when developing a physical nozzle design so as not to further reduce moment resistance.

8 Removal Jetting Systems

The lift boat market has experienced growth as demand and capacity requirements have increased. One relatively newer area of technology is that of pad jetting. A lift boat has three or four pads or spud cans that typically sink substantially into the mud in order to provide vessel stability at high lift capacities. Above a certain size vessel, (lift boats are commonly categorized by leg length and crane lift capacity) many owners are beginning to consider a leg jetting system to be a must-have feature in order to remain competitive when bidding for contracts by speeding up pad liberation and reducing this down-time. Now, there is relatively little research comparing the cost effectiveness of including such a system on a lift boat. The designer must include extra pumps, hoses, fittings, piping inside the hull and legs, and the owner must take on the additional responsibility of maintaining the added equipment and piping. The leg bending and rack stresses alone make installing piping that will have to be serviced and maintained into lift boat legs daunting, especially when leg access is typically only from the very top of a sealed cylindrical leg. However, as lift capacities increase and legs sink further into the soil on ever larger vessels, we are reaching the arena of viability of pad jetting systems.

8.1 Removal Jetting for Permanently Installed Systems

A brief aside must be made here to explain that one of the aspects of lift boats that make pad jetting systems so appealing is the frequent cycling of lift boats. They jack up and down and move from place to place more frequently than any other type of jack-up vessel. This is one reason they usually feature rack-and-pinion jacking systems, whose expense can be justified by the jacking speed gains over “poke-and-stroke” systems found on non self-propelled jack-up barges and many European wind installation vessels. The Universal Foundation by Fred. Olson, is designed for re-use, but it is very likely that most installations will be installed and removed once and recycled. So, when proposing a system that comes from the realm of frequent cycling times, and translating that to a system that may only be cycled once in it’s service life (jetting once for removal) a bit of explanation is helpful.

The pad liberation process on a lift boat is carried out using the buoyant force of the vessel as it lowers into the water and pulls upward on the leg. More than enough removal force can be generated almost “for free” as it requires relatively little energy to lower the vessel back down into the water and float, using buoyancy to pull up on the pad. However, the force used to lift or pull a monopile platform free of the sea floor must come from the removal vessel through a crane or other lifting means.

In the case of a suction caisson, some force can be generated by the reversal of the suction system itself, pumping water or even air, but the process of removal still may take many hours to complete, spent waiting on the caisson to pop free from the sea floor. The Fred Olson Universal Foundation has averaged 7 hours waiting time for removal. (20) Scouring around the pile to remove soil could potentially more quickly free the foundation however, scouring for removal adds an entirely new type of equipment and labor expense to an already expensive process. This is where a pre-installed jetting system can be employed to automate the scouring process similar to a lift boat leg jetting system, and substantially reduce the costs. In fact, considering that lift boats are able to generate ample lifting force through their own buoyancy relatively “cheaply,” this makes a jetting system perhaps even more useful on a “dumb” monopile foundation than on a “smart” liftboat leg.

8.2 Effectiveness

Quantifying the effectiveness of the jetting system is critical to modeling the cost-savings of the system being considered in this project. Despite the fact that water jetting systems for larger jack-up rigs are common and are beginning to become common on large lift boats, the actual effectiveness of pad or spud can jetting systems is not well researched from an academic standpoint. Most of the data showing the effectiveness of jetting systems is from real-world usage, and is difficult to collect from the various companies doing work in the real world. Some discussions were had with offshore jack-up operators and the general consensus was that the jetting system for a spud-can in a jack-up rig typically cuts extraction time “in half.” These massive rigs can sometimes take a week to extract from the sea floor, so the savings for them is promising.

Experiments by Gaudin, Bienen and Cassidy, (5) building heavily off of previous work by Lin (12) generated plots that can be used to predict the effectiveness of jetting for a spud can. Some studying and interpretation of their pull-out resistance force results in an improvement of on the order of 70%. This suggests that extraction of a full-scale jack-up spud-can with jetting might be done within ~16hrs, vs. the ~60 hrs. average seen with no jetting systems.

It’s difficult to compare a pad or spud can jetting system to the caisson scenario because these systems are physically designed differently, shearing along a load bearing surface, rather than a vertical one. It’s also difficult to compare laboratory experiments where pull-out force is measured with time spent removing a full-size caisson, because vessel crane capacities will vary widely. So, a reasonable assumption must be made so that the other functional areas can be explored and the project completed.

A reduction in extraction time was assumed to be 60%, which is an average of the real-world reported (“half”) and experimental values (“~70%) commonly discussed in practice. The design calculations, as in other ways, are set up for easy adaptation and updating for more refined data.

9 The Removal Jetting Design

In order to facilitate removal of an object that is suctioned into the muddy seabed, jets are typically oriented parallel to its surface. This allows the jets to shear across the surface separating the soil and breaking the seal. This requires a nozzle assembly to project proud of the surface in question but this creates a problem for our usage scenario. On a lift boat, the pads are usually relatively thin and flat, placing the nozzles on the bottom surface. So, these nozzles must be designed to withstand the crushing loads of the weight of the vessel, distributed across the pad surface area. Apart from this design requirement, there are no other strong geometry and layout considerations that must be made. So long as they can withstand the forces, the jets can be built in whatever configuration optimizes their use without interfering with operation of the legs.

9.1 Design Requirements of Skirt-Mounted Caisson Removal Jets

On a suction caisson skirt, where the surface to be liberated is vertical, nozzles are subjected to different requirements. Although the nozzle assembly will not see the same crushing loads as if it were mounted on the bottom of a pad, it will be subjected to forces during insertion of the caisson. Thus, a requirement for the nozzle assembly is that it should either be completely recessed into the skirt surface, or be oriented axially with the insertion direction, so that it slides into the sea floor with the skirt, and does not interfere with insertion or create pockets where displaced soil must backfill. This is especially important since the suctioning action of installation puts a negative pressure on soils inside the caisson; proper friction on the outside of the caisson is paramount. In order to minimize the impact of adding such a system and capitalize on the design testing already done on the Universal Foundation without creating new questions and problems, this requirement became a key aspect of the design.

Summary of key design requirements for suction caisson jets:
1) Must be designed to slide in and out of mud without creating pockets for backfill.
2) Must be designed to slide in and out of mud without clogging nozzles.
3) No need for area load design since is on vertical surface, however bending moments may affect.
4) Minimal interference with existing structure to minimize retesting.

9.2 Design Description

A full set of design drawings can be found in Appendix 2 for reference.

9.2.1 Nozzles

In order to meet this requirement, the nozzle assembly concept developed here utilizes a ~3/4-pipe section (as opposed to merely half-pipe) welded vertically to the outside of the caisson. Jets oriented so they discharge perpendicularly from this nozzle pipe will orient the jets so that they shear across the skirt surface as shown in Figure 9-1. Due to the curved surface of the skirt, the nozzles would tend to actually point away from the surface with merely a half-pipe arrangement because they would be at a much shallower angle rather than tangential to the circular skirt surface. By offsetting the centerline of the ~3/4-pipe sections so that they are not coincident with the skirt surface and orienting the nozzle discharge axially they are pointed as “parallel” as possible with the skirt surface.

One-inch holes drilled into the nozzle pipe provide the jet openings. A reducer was included on the leading tip of the nozzle pipe (Figure 15-6) for this very purpose as well: to minimize resistance to insertion and avoid damage to the nozzle pipe. A calculation for the additional skirt tip area was also included. A 1” reducer at the tip of the nozzle pipe would add approximately 3% to the tip area of the suction caisson, an important consideration for the caisson installation calculations. Traditionally pads or spud cans may also have jets on top in order to facilitate removal of any soil that backfills above the pad, but that scope is not considered here.

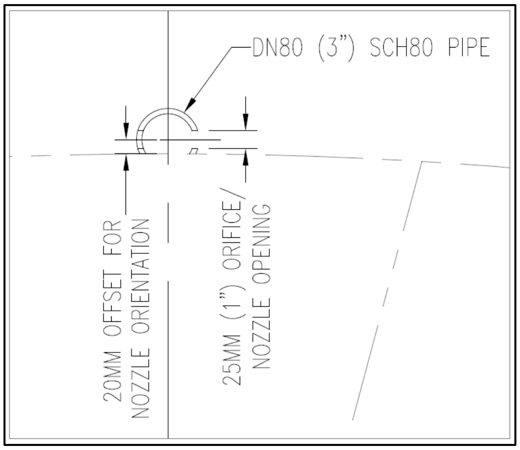

Figure 9-1 Section through skirt and nozzle pipe looking down showing nozzle detail

9.2.2 Piping System

A variety of combinations of permanent and temporary piping scenarios were considered. Two major places where piping could vary are on the installation vessel, and on the foundation itself. The shipboard piping could be permanently installed, as in the case where a dedicated installation and removal vessel with properly sized pumps for suctioning and removal was used, or it could be temporary, in the case where a barge or OSV was outfitted for the specific removal job. A temporary installation could involve submersible pumps and/or suction hoses, or simply an added centrifugal pump on deck with steel piping to a seachest. In the case of permanently installed pumps and piping, a centrifugal pump with steel pipe and sea chest would be the likely scenario and is considered here. Also of note is that the calculation sheet developed for this concept could be used to check whether an existing vessel's onboard pumps are adequately sized for removal jetting.

The more interesting design decision comes at the foundation. Piping down to the suction and removal systems at the sea floor could be an integral part of the foundation or separate hoses could be utilized. Most illustrations of the Universal Foundation suction system show hoses used with connection points at the sea floor on top of the caisson. Considering that any piping is used only for installation and/or removal of the foundation and not during regular operation of the wind turbine, it seems prudent to minimize the amount of permanently installed piping. The cost model will consider a few scenarios to facilitate making this decision for a variety of wind farm sites and design scenarios.

9.3 Design Trade-Offs

Some discussion for the design decisions and trade-offs is in order. Some nozzles found during research were more “complicated” than the relatively rudimentary “pipe-with-holes” in this concept. A smooth transition from one size to another is usually best for smooth nozzle flow and optimum performance. The nozzles in this design concept could really better be described as orifice holes, which will create higher pressure drops and more turbulent flow than a smooth nozzle. Design calculations from the *Fundamentals of Fluid Mechanics* textbook (13) utilized the proper equations for orifices over nozzles to account for this. The pipe-with-holes orifice design was chosen for three major reasons: 1) The cost of fabricating a more complicated design would eat into the cost savings gained by installing the removal jetting system, 2) a more complicated design would require even more efforts to make it streamlined enough for insertion into dense soils without risking damage or backfill as previously discussed and 3) This design can be added to an existing caisson with minimal impact to existing structure. The design presented will adequately balance added fabrication costs while providing a system useful for removal jetting.

The options presented for hoses vs. installed piping will also create trade-offs. With Option B and C, an additional design trade-off is that a diver will be required to connect the hoses during removal because the design forgoes a permanent header pipe down to the caisson. This should be a relatively quick process compared to the alternative of manual scouring, and a diver will likely already be needed to connect the hoses needed to reverse the caisson suction itself. However, as mentioned above for the piping design, multiple scenarios are considered:

Piping Scenarios Considered	
Option A	Permanently installed main header pipe up to surface, permanent pipe for branches
Option B	Permanently installed main header at caisson bucket top, permanent pipe for branches
Option C	Minimal permanent piping, no main header, temporary hoses splitting to each branch for jetting

10 Design Calculations

A full set of design calculations and more detailed user manual can be found in Appendix 1.

Calculations were performed in order to design the caisson removal jetting system in two major phases. The first (Steps 1-3) is a calculation to find the flow rate needed through each nozzle. Discussions with a client shipyard and studying lift boats with pad jetting systems listed in their spec sheets suggest that approximately 10 bar is needed at the nozzle in order to successfully jet. So, a first-principals calculation was used to find the flow rate produced through a selected nozzle size in seawater with a 10 bar pressure differential. This flow rate is then multiplied by the number of nozzles on the caisson, dependent upon the design and caisson skirt dimensions and number of branches and nozzles per branch in turn. Preliminary pipe sizes are calculated based on typical flow and the nozzle interior velocity from the previous section. The second major section (Steps 4-6) calculates the pump size needed to produce this flow rate against the pressure head of the sea outside the caisson and the head losses at that flow rate through the piping and nozzles. The entire excel sheet was intentionally set up with linked cells (noted by formatting with two underlines per Excel's standard formatting options) so that it is a flexible tool. It can be used to iterate to find an appropriate nozzle size and can be scaled and adapted for any wind farm sight, foundation size, and shipboard pump installation type, such as submersible or built-in pumps.

Now that we've established an overall picture of the calculation phases, each step of the calculations is detailed below. The full set of excel calculations is included in section 14 for reference.

10.1 Nozzle Flow Rate

The nozzle calculation is based on well-established methods for orifice nozzles, from the *Fundamentals of Fluid Mechanics* (13) textbook, and includes Reynolds numbers and diameter and discharge coefficients in order to accurately characterize the nozzle flow. Nozzle flow is based on the 10 bar requirement from typical lift boat jetting systems, and a velocity before the nozzle specified from typical desired pipe flow velocities. The spreadsheet is set up in such a way that a different requirement can be input and the calculations update throughout (except where a table or figure lookup is needed). Nozzle orifice size can be adjusted to achieve reasonable results and corrected if more flow rate is needed depending on system optimization. A 3mm nozzle was settled on for the configuration in this paper.

$$Q = C_d A_o Y \sqrt{\frac{2\Delta P}{\rho\left(1 - \beta^4\right)}}$$

10.2 Total System Flow

Total system flow is dependent upon the number of branches and number of nozzles per branch, which is dependent on the nozzle spacing and caisson diameter or the number of nozzle pipes around the skirt. The calculation is set up to allow these numbers to quickly multiply the resultant flow for different combinations of branch and nozzle per branch and other parts of the calculations reference these original cells so the entire sheet updates, making it a useful tool for optimization.

10.3 Pipe Diameter

Pipe diameters were selected based on typical desired pipe flow velocity based on pipe cross-sectional area. The resulting diameter of the main header was a nominal 8” pipe, and the resulting diameter of the branches was 2”, which was increased to 2.5” in the next section to minimize friction losses. One assumption was that ~3/4 pipe section had at least an equivalent diameter to that of a 2” pipe and that the transition from nozzle pipe to nozzle approximated the same flow characteristics. Figure 15-7 shows that there is even greater cross sectional area than that of a 2” pipe, but the flow must also make a sharp bend as it exits the nozzle. So, these two assumptions effectively cancel each other out and play a minimal impact in the overall pressure needed when compared to the water depth and flow requirement.

$$\text{Pipe Diameter} = \sqrt{\frac{4 \cdot \text{flow rate}}{\pi \cdot \text{velocity}}}$$

10.4 System Friction Loss

The system friction loss uses the typical Darcy-Weisbach method also found in the *Fundamentals of Fluid Mechanics* (13) textbook for calculating friction loss in pipes and equivalent losses in fittings. A table of the piping and fittings for the system calculates the equivalent pipe length for each component in the system. This table contains lengths of piping for suction piping and discharge piping assuming use of an onboard pump in a dedicated installation/removal vessel. An additional scenario would be to use a submersible pump installed on an existing vessel with added lengths of hose and hose reel instead which can be adapted into this calculation by changing a few rows. Pipe fitting factors and losses/100ft are from established data, with the primary source in notes on the calculation sheet.

10.5 Total Head Summary

The total head summary takes the system friction loss, needed internal nozzle pressure, and water depth (plus skirt depth) to calculate the resulting pump head required to operate the system. This is the section of the calculations most useful for adapting the system to various water depths and foundation sizes because the calculation quickly scales based on water depth.

10.6 Pump Sizing Estimate

Finally, after the total pump head is calculated, pump power can be estimated, and using typical centrifugal motor-pump efficiency, a pump motor power can be estimated. Using manufacturer selection software, pump size and HP can be confirmed and a specific pump model and motor selected. For the Universal Foundation at the full depth it is designed for, it would require a single 130 HP pump, or two 65HP pumps.

11 Cost Model

The most common method of offshore platform removal involves cutting and removal of the foundation sections in pieces, by a lift boat and barges. It is common practice in oil and gas to cut the pilings below the level of the sea floor and backfill the holes to cover the remaining steel. The advantages of this method include costs saved from the otherwise expensive removal of pilings buried in the seabed but a drawback is the costs required to perform the cutting: done with expensive, high-tech cutting machines. Also of concern is the environmental impact of leaving steel in the water after decommissioning. It is desirable to have a fully removable foundation, especially when dealing in the forward-looking renewable, sustainable energy field. Apart from the environmental appeal of complete foundation removal, are costs gained back by completely reusing the whole foundation instead of just "most" of it. Thus, the suction caisson, which is fully removable and fully reusable/recyclable comes into play. The removal jetting system can play a role by speeding up the removal process, reducing the portion of project cost that includes vessel day rates, crew payroll, avoiding manual scouring costs, and energy costs associated with lifting the suction caisson to free it from the mud. The benefits of reduced harmful diesel emissions both from a reduction in time spent and energy expended to lift the caisson is a huge benefit to the renewables sector.

A model was developed to calculate the cost savings by implementing removal jetting. Three options are considered as outlined in the design section. An estimate of the added costs to include the jetting system on the foundation was performed as a first step. For each option A though C, a piping material take-off based on the dimensions of the Universal Foundation and estimated labor rates and man-hours for fabricating the system give an added fabrication cost based on estimated labor rates for a Gulf of Mexico shipyard. The materials/labor cost for each nozzle is multiplied by the number of nozzle pipes and then the additional costs for the permanent main header for options A and B are calculated. For options B and C, with piping connections below the surface, divers will be needed to connect to the header(s) for jetting. Estimated labor rates for divers were taken from a prominent Gulf of Mexico lift-boat vessel operator, Montco Offshore. The recommended day rate for estimating this type and scope of work was $12,500/day which gets divided out into an hourly rate for estimating purposes. It's important to note that for the current Universal Foundation design, this diver is already necessary because suction release is performed at the top of the bucket on the ocean floor. So, it's assumed that the equipment and procedures are already in place for this effort and does not significantly add to the removal process. Additionally, the hook-up of the jetting header can be undertaken concurrently with hooking up the hose to reverse suction on the caisson (while the removal jack-up vessel is settling into the sea floor in preparation for lifting) so it is assumed that this does not add to the overall time per foundation required. An operator might wish to perform more in depth time studies to verify these assumptions.

Finally, a calculation table creates a comparison data set, plotting removal costs for different sized wind farms, from 10 turbines up to 300. Only those costs directly affected by the jetting system are considered, so turbine removal, securing, jack-up pre-loading, jacking up and down, and relocating/transit times are not considered and assumed to be equivalent in each option. Thus, it is important to remember that the comparison here is solely removal costs due to time spent by the vessel.

The details of the data set columns are as follows: the first column shows a baseline removal cost at 7 hrs per foundation, with the $/hr. based on vessel day-rates estimated from appropriate sources. (3) Then an "expedited" removal cost with the 60% reduction in time discussed in the "Effectiveness" section previously is calculated, based on 2.8 hrs per foundation as. Next, a column calculates the added costs from the jetting system for that number of turbines. Finally, a net removal cost, cost savings, and % reduction column round out the data. A plot of the baseline and expedited removal costs was created to illustrate how the jetting system improves removal costs of a wind farm especially when used on a large scale. An initial investment amount for each option (summarized below) will yield the lifecycle cost savings:

Initial Investment per Turbine for each option		
Option A	Permanently installed main header pipe up to surface, permanent pipe for branches	$ 27,625.21
Option B	Permanently installed main header at caisson bucket top, permanent pipe for branches	$ 16,608.75
Option C	Minimal permanent piping, no main header, temporary hoses splitting to each branch for jetting	$ 16,564.89

Because the Universal Foundation already requires a diver to release the suction portion of the caisson for removal, option B would seem to be a good choice because it would balance the conflicting goals of minimal piping installation/fabrication, and simple removal activities. Option A would provide the easiest removal, as the connection to jetting is made at the surface, but the cost of the 8" header is greatly reduced in option B by only using it to tie each branch together at the sea floor and not running it all the way up to the surface. However, this calculation will vary depending on each scenario. The water depth, caisson size/design, installation/removal methodology, will mean this decision will need to be made for a specific wind farm site and set of circumstances. So, each option was developed and presented to show how these design trade-offs affect the cost and aid this decision making.

The cost model shows that with an initial investment of $16,609 per turbine, a modestly sized (for European standards) commercial wind farm with 80 turbines could realize a lifecycle cost savings of just over $1 million simply from including and utilizing a pre-installed removal jetting system of the Option B variety (a short main header). The model shows a 27% cost savings for any wind farm size (it scales linearly since it is calculated on a per turbine basis.)

The next major wind-farm likely to be installed in the United States is currently planned off the coast of Long Island. Initial phases will include 15 turbines, but with the eventual plan to install up to 200 turbines, (6) a removal savings of $2.8 million could be realized according to this cost model. The figure below plots removal costs with and without the improvement in time from jetting.

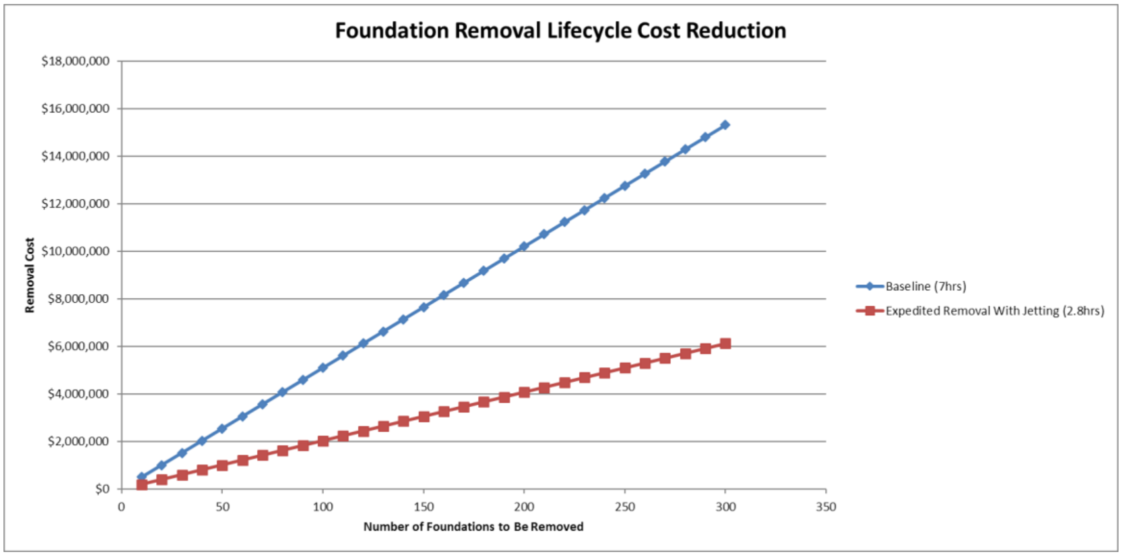

Figure 11-1 Foundation Removal Cost Comparison

12 Conclusion

This paper illustrates the feasibility of integrating a removal jetting system into an offshore wind turbine suction caisson foundation, in order to lower often overlooked decommissioning and removal costs. By greatly speeding up the removal process, the jetting system provides cost savings while minimally adding to the initial cost of the foundation. The concept developed and outlined herein can serve as a resource for implementing removal jetting nozzles into the foundation design and decommissioning process and for optimizing the various pieces of such a system.

Although planning for decommissioning and removal is not always as rigorously considered as upfront installation is, the ethos of renewable, green technology is forward-thinking: how do our actions impact the environment and planning for the future? So, the unique perspective that prompted this investigation is critical to truly renewable technology.

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14 Appendix 1: Design Calculation Set

Spreadsheet User Manual

A description of the calculations can be found in Section 10.

1	Input value
2	Calculated Value
3	Important Calculated Value
4	Linked value (automatically updates from elsewhere in the calculation)

1) Nozzle flow rate steps:
    a. Desired pressure at nozzle exit and ambient pressure are input which yields the pressure needed inside the nozzle.
    b. Nozzle diameters are used to calculate the diameter ratio
    c. Properties for water and desired velocity are hard-coded
    d. Reynold’s number is calculated and then Cd must be looked up from a table p.422 in Fundamentals of Fluid Dynamics book.
    e. Nozzle area and flowrate are then calculated

2) Total System Flow steps
    a. Flow rate per nozzle is carried down in a linked cell, and then the number of nozzles and nozzles per branch are input
    b. Yields system flow rate

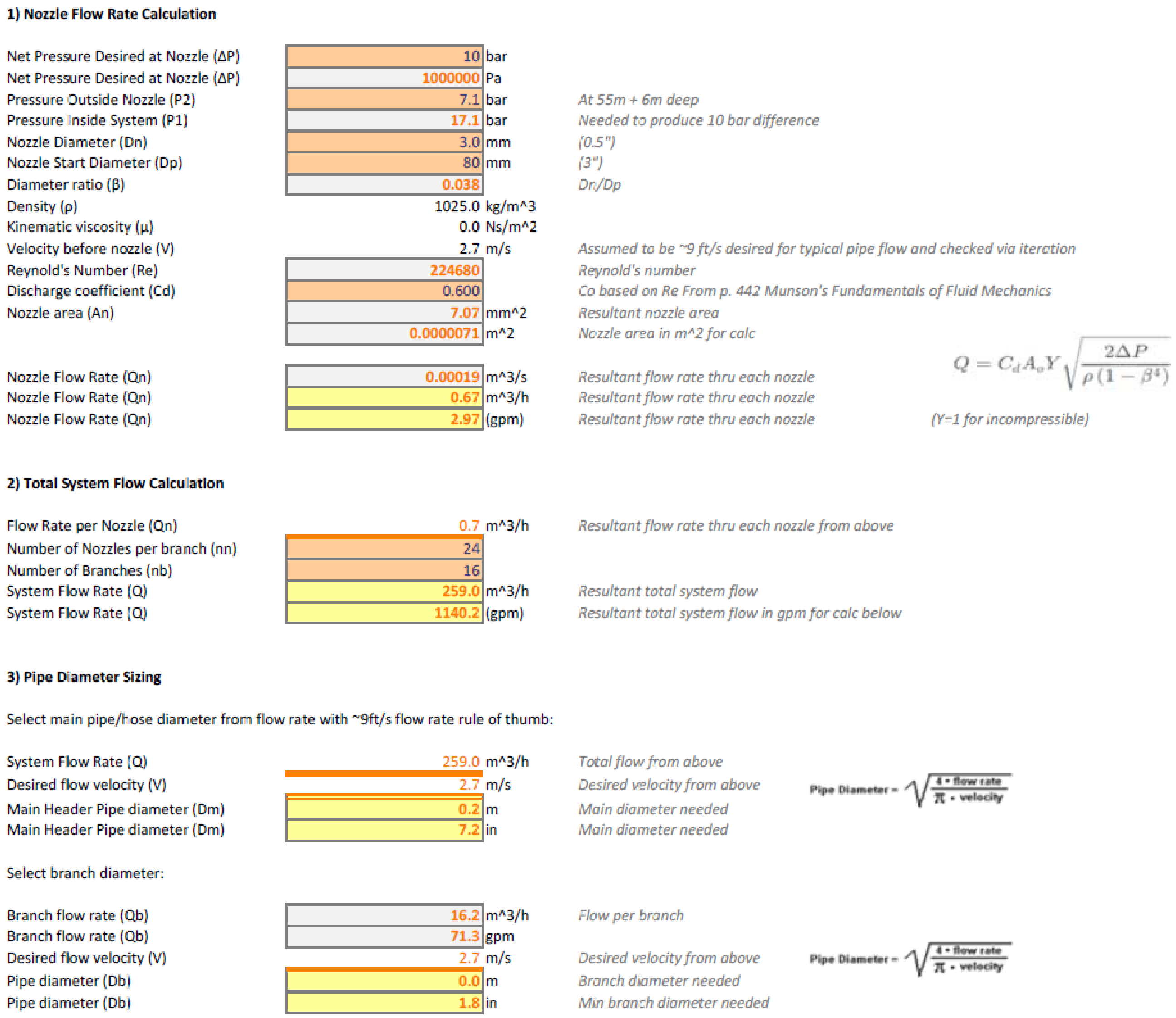
3) Pipe Diameter steps
    a. System flow rate and velocity are carried from above and main header and branch diameters are calculated

4) System friction loss steps
    a. Losses per 100 ft of pipe and fitting factors can be found at the links in the spreadsheet. Enter system fittings and quantities as line items with to calculate the total plus margin.

5) Total head summary steps
    a. Friction losses are carried from above in a linked cell.
    b. Water depth plus skirt depth is entered as z2-z1
    c. Yields total pump head required

6) Pump sizing estimate
    a. This section fills automatically

7) Cost steps
    a. The cost sheet is a combination of fabrication take-off calculations and a plot of the time-savings data. Take off is entered in the top section and multiplied by branch.
    b. Cost data is calculated from the removal time entered, and subtracts the fabrication cost



1) Nozzle Flow Rate Calculation

Net Pressure Desired at Nozzle (ΔP)	10	bar	
Net Pressure Desired at Nozzle (ΔP)	1000000	Pa	
Pressure Outside Nozzle (P2)	7.1	bar	*At 55m + 6m deep*
Pressure Inside System (P1)	17.1	bar	*Needed to produce 10 bar difference*
Nozzle Diameter (Dn)	3.0	mm	*(0.5")*
Nozzle Start Diameter (Dp)	80	mm	*(3")*
Diameter ratio (β)	0.038		*Dn/Dp*
Density (ρ)	1025.0	kg/m^3	
Kinematic viscosity (μ)	0.0	Ns/m^2	
Velocity before nozzle (V)	2.7	m/s	*Assumed to be ~9 ft/s desired for typical pipe flow and checked via iteration*
Reynold's Number (Re)	224680		*Reynold's number*
Discharge coefficient (Cd)	0.600		*Co based on Re From p. 442 Munson's Fundamentals of Fluid Mechanics*
Nozzle area (An)	7.07	mm^2	*Resultant nozzle area*
	0.0000071	m^2	*Nozzle area in m^2 for calc*
Nozzle Flow Rate (Qn)	0.00019	m^3/s	*Resultant flow rate thru each nozzle*
Nozzle Flow Rate (Qn)	0.67	m^3/h	*Resultant flow rate thru each nozzle*
Nozzle Flow Rate (Qn)	2.97	(gpm)	*Resultant flow rate thru each nozzle*

$$Q = C_d A_o Y \sqrt{\frac{2\Delta P}{\rho(1-\beta^4)}}$$

(Y=1 for incompressible)

2) Total System Flow Calculation

Flow Rate per Nozzle (Qn)	0.7	m^3/h	*Resultant flow rate thru each nozzle from above*
Number of Nozzles per branch (nn)	24		
Number of Branches (nb)	16		
System Flow Rate (Q)	259.0	m^3/h	*Resultant total system flow*
System Flow Rate (Q)	1140.2	(gpm)	*Resultant total system flow in gpm for calc below*

3) Pipe Diameter Sizing

Select main pipe/hose diameter from flow rate with ~9ft/s flow rate rule of thumb:

System Flow Rate (Q)	259.0	m^3/h	*Total flow from above*
Desired flow velocity (V)	2.7	m/s	*Desired velocity from above*
Main Header Pipe diameter (Dm)	0.2	m	*Main diameter needed*
Main Header Pipe diameter (Dm)	7.2	in	*Main diameter needed*

$$\text{Pipe Diameter} = \sqrt{\frac{4 \cdot \text{flow rate}}{\pi \cdot \text{velocity}}}$$

Select branch diameter:

Branch flow rate (Qb)	16.2	m^3/h	*Flow per branch*
Branch flow rate (Qb)	71.3	gpm	
Desired flow velocity (V)	2.7	m/s	*Desired velocity from above*
Pipe diameter (Db)	0.0	m	*Branch diameter needed*
Pipe diameter (Db)	1.8	in	*Min branch diameter needed*

$$\text{Pipe Diameter} = \sqrt{\frac{4 \cdot \text{flow rate}}{\pi \cdot \text{velocity}}}$$

4) System Friction Loss Calculation

Reference: http://docs.engineeringtoolbox.com/documents/1146/steel-pipe-sch-80-friction-loss.pdf
http://www.reelcraft.com/pdfs/tech_bulletins/TB0001.pdf
http://www.metropumps.com/ResourcesFrictionLossData.pdf

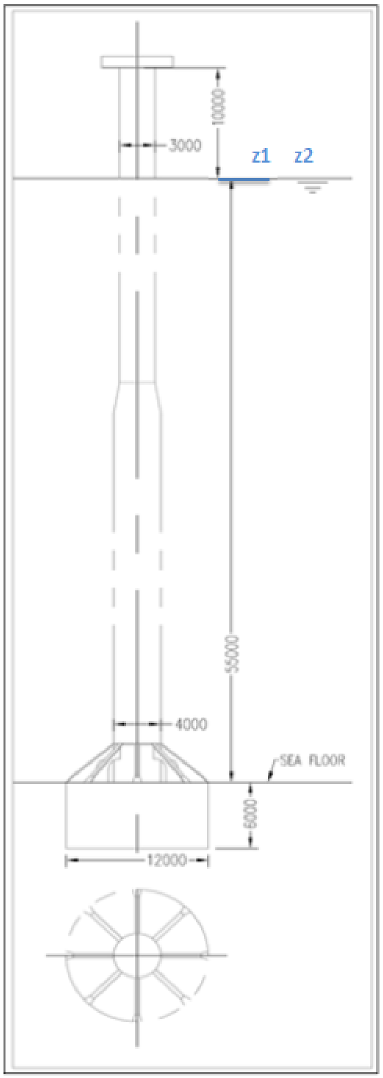
Loss/100ft table			
Pipe Size	@1140 gpm	@71 gpm	
8" Pipe	4.47		ft/100ft
8" Hose	3.8		ft/100ft
2.5" Pipe		8.90	ft/100ft
2.5" Hose		8.01	ft/100ft
3" Pipe		3.03	ft/100ft

Friction Losses									
Section	Item	L/d	Size (NOM)	Quantity	L (ft)	Flow Rate	Head Loss/100 ft	Head Loss (ft)	Head Loss (ft)
Suction Side and Pump	Shipboard Suct Pipe		*8.0*		15.0	*1140.0*	4.47	0.7	*~Pipe routing from seachest to pump*
	Butterfly Valve, Shell	40.0	8.0	1.0	26.7	*1140.0*	4.47	1.2	
	Butterfly Valve, Pump	40.0	8.0	2.0	53.3	*1140.0*	4.47	2.4	
	Check Valve, Pump	135.0	8.0	1.0	90.0	*1140.0*	4.47	4.0	
	Elbows	30.0	8.0	4.0	80.0	*1140.0*	4.47	3.6	*~Pipe routing in ER*
8" Main Header	Shipboard Disch Pipe		*8.0*		25.0	*1140.0*	4.47	1.1	*~Pipe routing in ER*
	Butterfly Valve	40.0	8.0	2.0	53.3	*1140.0*	4.47	2.4	
	Elbows	30.0	8.0	4.0	80.0	*1140.0*	4.47	3.6	*~Pipe routing to MD discharge*
	8" Hose		*8.0*		205.0	*1140.0*	3.80	7.8	*55m water depth + 25ft margin for hose connection*
Branch Splitting and Branch	Split Tee	60.0	2.5	2.0	25.0	*71.0*	8.90	2.2	*Branch Split, (Increased to 2.5 for minimizing losses)*
	Reducer	85.0	2.5	2.0	35.4	*71.0*	8.90	3.2	*Branch Split, (Increased to 2.5 for minimizing losses)*
	2.5" Hose		*2.5*		40.0	*71.0*	8.01	3.2	*Branch Hose, (Increased to 2.5 for minimizing losses)*
	Discharge Pipe		*3.0*		3.0	*71.0*	3.03	0.1	*Connector Stub Piece*
	Nozzle Pipe		*3.0*		20.0	*71.0*	3.03	0.6	*6m skirt caisson depth*
							Subtotal=	36.0	ft
							10% Margin:	3.6	ft
							Total Friction Loss (f)	39.6	ft

Pipe fittings are assumed for a typical complete system.

5) Total Head Summary with Delta z

Summary	(ft)		
Friction Losses in Piping System (f)	39.6	ft	*(from above)*
z2-z1 (depth of skirt edge)	0	ft	*(55m + 6m)*
Static Head Required at Nozzle (P)	333.5	ft	*(Converted from P1 above)*
Total Pump Head Required (Pp)	373.1	ft head	
Total Pump Head Required (Pp)	113.7	m	



6) Pump Sizing Estimate

http://www.engineeringtoolbox.com/pumps-power-d_505.html

Pump Power			
Flowrate (Q)	259.0	m^3/hr	*(from above)*
Density	1000.0	kg/m^3	
Gravity	9.8	m/s^2	
Differential Head (Pp)	113.7	m	*(from above)*
Pump Power (Wp)	80.3	kW	
	107.6	bhp	
Shaft (Motor) Power			
Pump Efficiency	0.9		
Shaft (Motor) Power (Wt)	94.4	kW	
Shaft (Motor) Power (Wt)	126.6	bhp	

$P_{h(kW)} = q \rho g h / (3.6 \; 10^6)$

where

$P_{h(kW)}$ = hydraulic power (kW)

q = flow capacity (m^3/h)

ρ = density of fluid (kg/m^3)

g = gravity ($9.81 \; m/s^2$)

h = differential head (m)

7) Summary of Results

Nozzle Calculation Results Summary			
Nozzle Flow Rate (Qn)	0.7	m^3/h	*Resultant flow rate thru each nozzle*
Nozzle Flow Rate (Qn)	3.0	(gpm)	*Resultant flow rate thru each nozzle*
System Flow Rate (Q)	259.0	m^3/h	*Resultant total system flow*
System Flow Rate (Q)	1140.2	(gpm)	*Resultant total system flow*

System Sizing Summary			
Main Header Pipe diameter (Dm)	0.2	m	*Main diameter needed*
Main Header Pipe diameter (Dm)	7.2	in	*Main diameter needed*
Pipe diameter (Db)	0.0	m	*Branch diameter needed*
Pipe diameter (Db)	1.8	in	*Min branch diameter needed*
Total Friction Loss (f)	39.6	ft	*Friction loss through system piping*
z2-z1 (depth of skirt edge)	0	ft	*delta height*

Pump Summary		
Total Pump Head Required (Pp)	113.7	m
Total Pump Head Required (Pp)	373.1	ft head
Shaft (Motor) Power (Wt)	94.4	kW
Shaft (Motor) Power (Wt)	126.6	bhp

Option B - Main Header Pipe At Caisson Top Below Surface

Number of Nozzle Pipes/Branches: 16

1) Fabrication Cost Added Per Nozzle Pipe	Cost/# or cost/ft or cost/hr	Factor per nozzle pipe (#, ft, man-hr)	Total $/Foundation	
2.5" Headers ($/ft)	$7.03	25	$2,812.00	
3" Pipe ($/ft)	$7.55	20	$2,416.00	*6m=~20ft*
3x1 Reducers ($/ea.)	$22.99	1	$367.84	
Fabrication Labor ($/hr.) - Welding Nozzle pipe	$65.00	3	$3,120.00	
Fabrication Labor ($/hr.) - Welding branch header	$65.00	2	$2,080.00	
Fabrication Labor ($/hr.) - Prep and Fab	$65.00	3	$3,120.00	
			$0.00	
			$0.00	
		Estimated Added Fabrication Cost:	$13,915.84	per foundation as a function of # nozzle pipe

2) Additonal Fabrication Costs per Foundation		Factor		
8" Header Pipe	$56.24	5	$281.20	
8" Header Flange	$55.99	1	$55.99	
Fabrication Labor ($/hr.) - Prep, fab, and hanging	$65.00	5	$325.00	
		Estimated Added Fabrication Cost:	$662.19	per foundation
2) Additonal Removal Labor Costs Per Foundation				
Diver for connecting jetting headers	$520.83	1	$520.83	per foundation

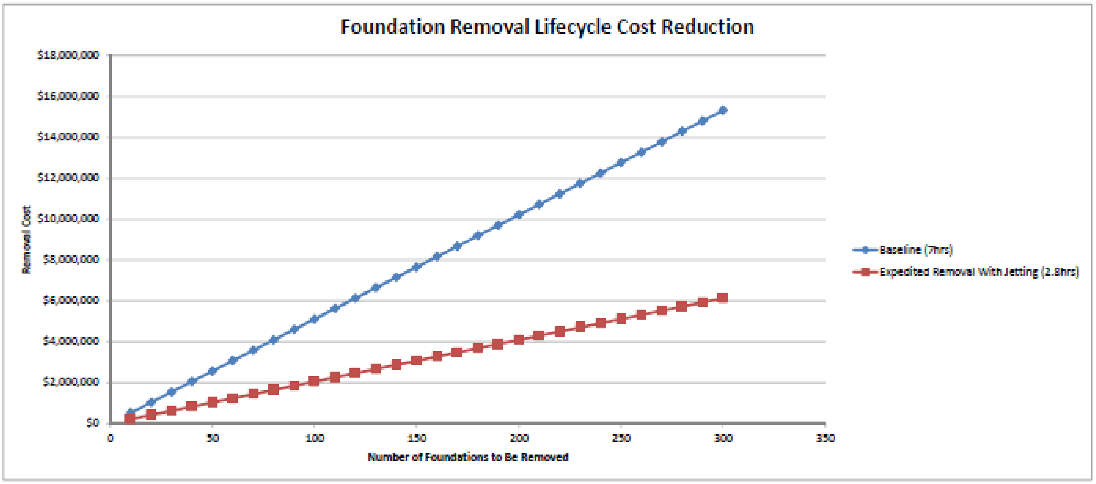
Total Additional Cost for Removal Jetting per Foundation: $15,098.86

Plus 10% Margin: $16,609 per foundation

3) Savings as a Function of Foundation Number

		Removal time
Removal Vessel Day Rate	$175,000	7
Removal Vessel Day Rate/hr	$7,292	2.8

Number of Foundations	Baseline (7hrs)	Expedited Removal With Jetting (2.8hrs)	Jetting Fabrication/Labor Expenditure x # of Foundations	Net Removal with Jetting Cost	Cost Savings	%
10	$510,417	$204,167	$166,087	$370,254	$140,163	27%
20	$1,020,833	$408,333	$332,175	$740,508	$280,325	27%
30	$1,531,250	$612,500	$498,262	$1,110,762	$420,488	27%
40	$2,041,667	$816,667	$664,350	$1,481,017	$560,650	27%
50	$2,552,083	$1,020,833	$830,437	$1,851,271	$700,813	27%
60	$3,062,500	$1,225,000	$996,525	$2,221,525	$840,975	27%
70	$3,572,917	$1,429,167	$1,162,612	$2,591,779	$981,138	27%
80	$4,083,333	$1,633,333	$1,328,700	$2,962,033	$1,121,300	27%
90	$4,593,750	$1,837,500	$1,494,787	$3,332,287	$1,261,463	27%
100	$5,104,167	$2,041,667	$1,660,875	$3,702,542	$1,401,625	27%
110	$5,614,583	$2,245,833	$1,826,962	$4,072,796	$1,541,788	27%
120	$6,125,000	$2,450,000	$1,993,050	$4,443,050	$1,681,950	27%
130	$6,635,417	$2,654,167	$2,159,137	$4,813,304	$1,822,113	27%
140	$7,145,833	$2,858,333	$2,325,225	$5,183,558	$1,962,275	27%
150	$7,656,250	$3,062,500	$2,491,312	$5,553,812	$2,102,438	27%
160	$8,166,667	$3,266,667	$2,657,400	$5,924,067	$2,242,600	27%
170	$8,677,083	$3,470,833	$2,823,487	$6,294,321	$2,382,763	27%
180	$9,187,500	$3,675,000	$2,989,575	$6,664,575	$2,522,925	27%
190	$9,697,917	$3,879,167	$3,155,662	$7,034,829	$2,663,088	27%
200	$10,208,333	$4,083,333	$3,321,750	$7,405,083	$2,803,250	27%
210	$10,718,750	$4,287,500	$3,487,837	$7,775,337	$2,943,413	27%
220	$11,229,167	$4,491,667	$3,653,925	$8,145,592	$3,083,575	27%
230	$11,739,583	$4,695,833	$3,820,012	$8,515,846	$3,223,738	27%
240	$12,250,000	$4,900,000	$3,986,100	$8,886,100	$3,363,900	27%
250	$12,760,417	$5,104,167	$4,152,187	$9,256,354	$3,504,063	27%
260	$13,270,833	$5,308,333	$4,318,275	$9,626,608	$3,644,225	27%
270	$13,781,250	$5,512,500	$4,484,362	$9,996,862	$3,784,388	27%
280	$14,291,667	$5,716,667	$4,650,450	$10,367,117	$3,924,550	27%
290	$14,802,083	$5,920,833	$4,816,537	$10,737,371	$4,064,713	27%
300	$15,312,500	$6,125,000	$4,982,625	$11,107,625	$4,204,875	27%



15 Appendix 2: Design Drawings

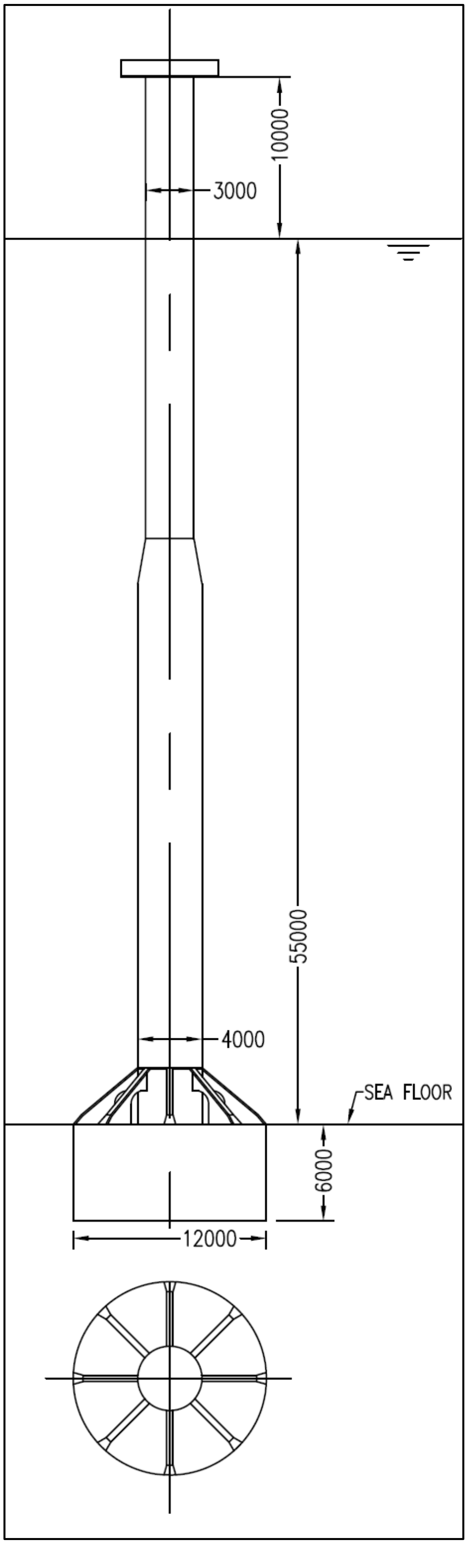


Figure 15-1 Elevation and Top View of Universal Foundation
with primary dimensions and design scenario water depth labeled.

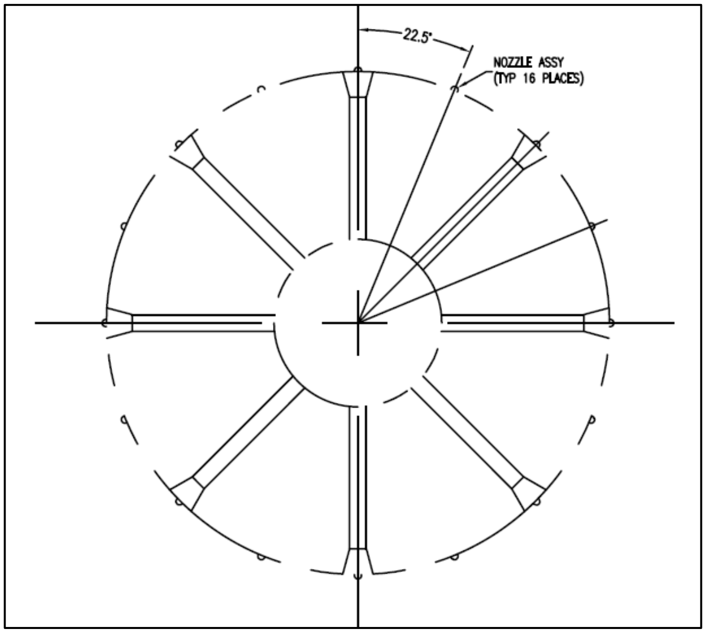


Figure 15-2 Top view with nozzle pipe location dimensions.

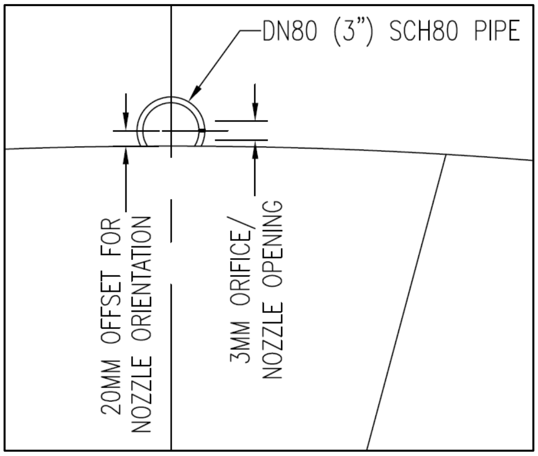


Figure 15-3 Section through skirt and nozzle pipe looking down showing nozzle detail.

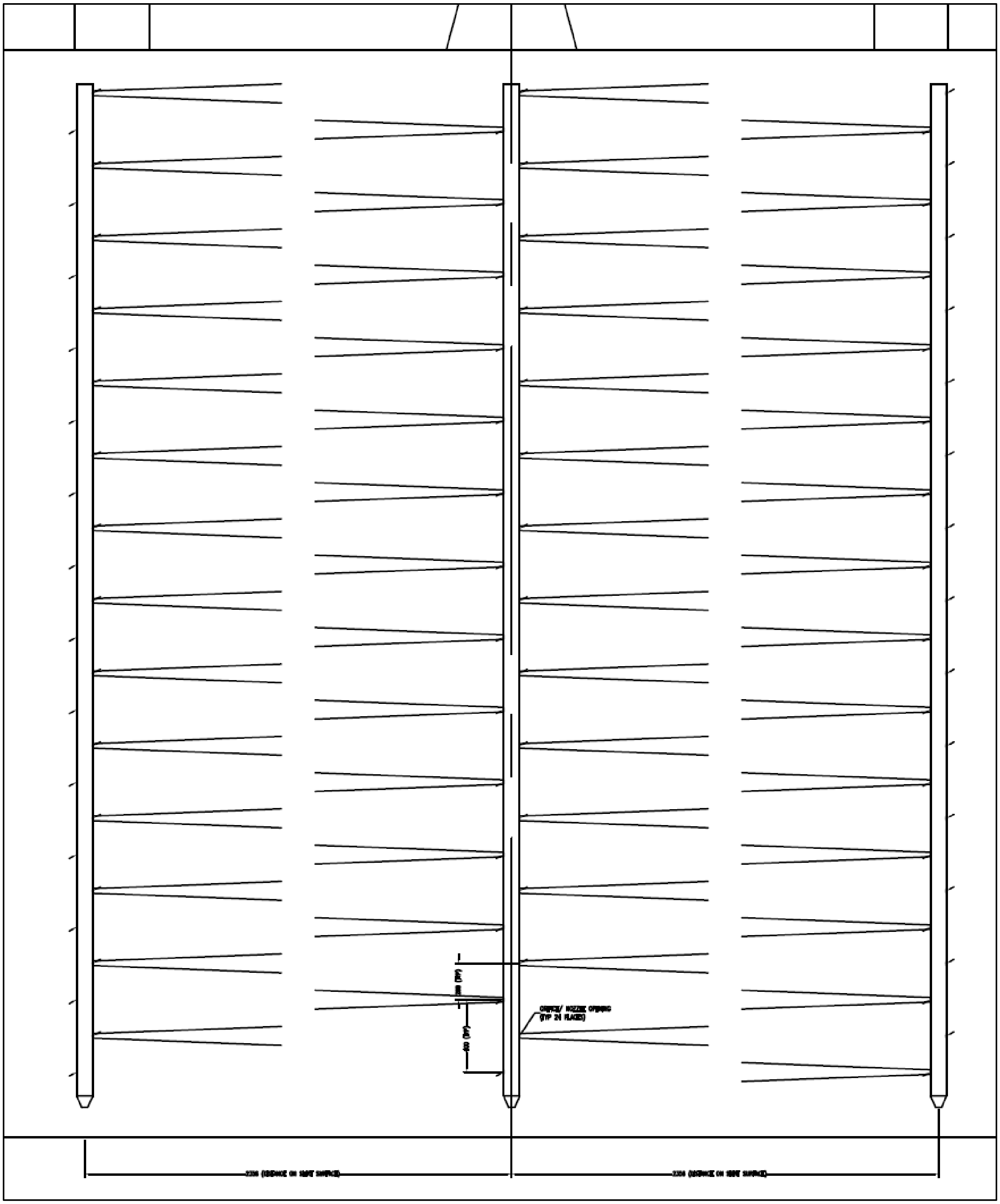


Figure 15-4 Profile View Showing Nozzle Pattern

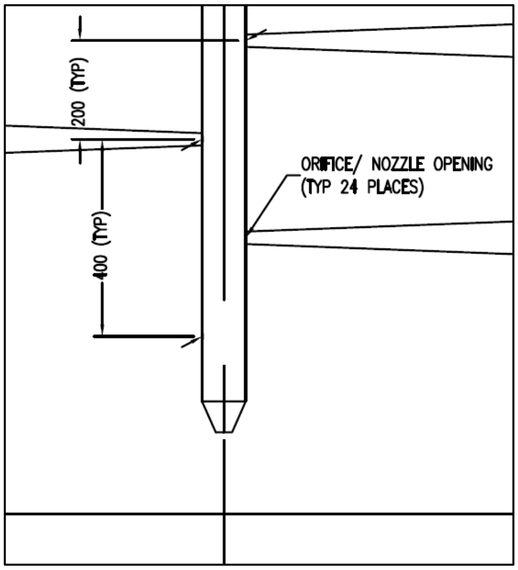


Figure 15-5 Nozzle Detail Showing Spacing

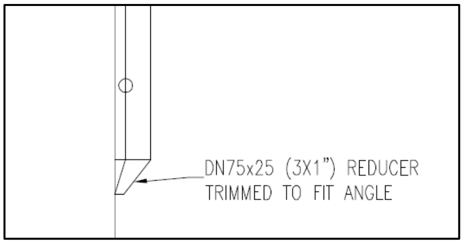


Figure 15-6 Nozzle Pipe Tip Showing Taper

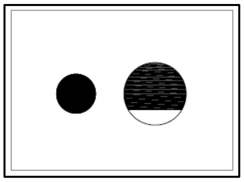


Figure 15-7 Cross Sectional Area Check in CAD

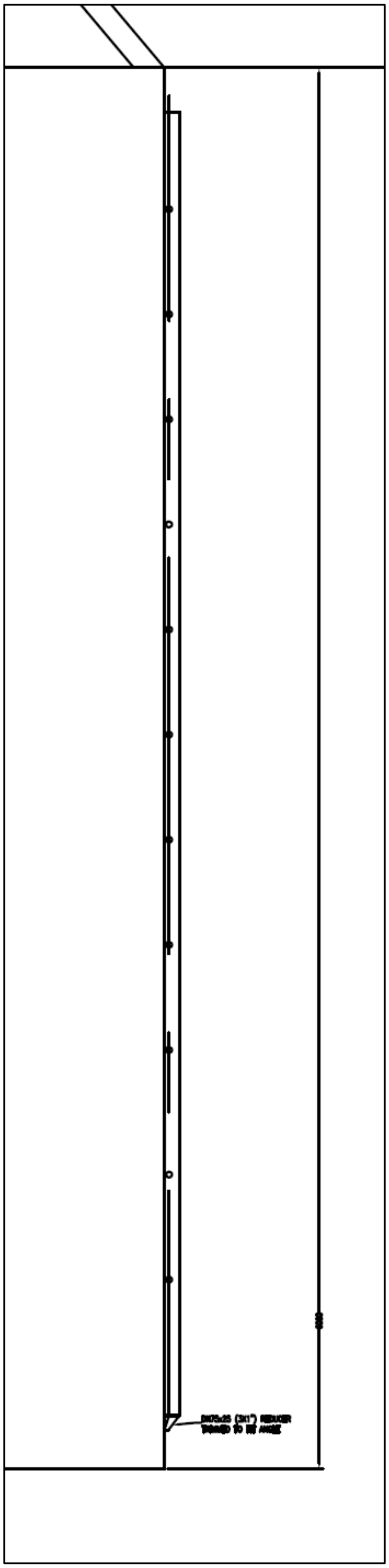


Figure 15-8 Skirt Section with Nozzle Pipe