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Feasibility Design Studies for the Polar Research Vessel

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This report addresses the initial science and operational requirements for a new Polar Research Vessel (PRV) for Antarctic and potentially Arctic operations. Individual special design studies are presented that include investigations into towing seismic systems and nets in ice; a hullform and appendages for improved bathymetry in ice; geotechnical drilling; moon pool sizing for deployment and recovery of ROVs, AUVs and possibly CTD rosettes; increased icebreaking capability and propulsion concepts; and compliance with IMO requirements for Arctic vessels. A design history is reviewed, and the PRV feasibility level design is presented. The report closes with a cost estimate and recommendations for future phases of the project.

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FOREWORD

Science and Technology Corporation (STC) is pleased to submit this final report entitled "Feasibility Design Studies for the Polar Research Vessel," by Mr. James St. John, Mr. Aleksandr Iyerusalimskiy, and Mr. David Karnes of the STC Polar Technology Office in Columbia, Maryland. This report describes the design studies conducted and the results of the first iteration of the design. The authors gratefully acknowledge the support and encouragement of the Contracting Officer's Technical Representatives for the work, Mr. Richard Voelker, MAR-750, U.S. Maritime Administration.

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1. EXECUTIVE SUMMARY

The feasibility design studies for the Polar Research Vessel undertaken in this work have resulted in a design concept with increased operational and science capabilities over the Nathaniel B. Palmer (NBP), the ship it is intended to replace. Icebreaking performance has been increased as well as ice class so the ship will be able to work in more areas of the Antarctic and also independently in the coastal shelf areas of the Arctic in summer and in the Central Arctic basin when escorted. A box keel design has been integrated into the efficient icebreaking hullform to give good performance of acoustics sensors including swath bathymetry in ice and open water. Azimuthing podded propulsors have been incorporated to greatly improve maneuverability in ice and open water as well as improve stationkeeping and towing in ice.

The ship is 62% larger than the NBP in the displacement, and this increases the science lab space by 128% and the working deck area by 33%. New features such as a moonpool and a totally enclosed scientific drill rig have been incorporated into the design. The moonpool includes capability for working with large remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), as well as the current capabilities such as rosettes that are now worked over the side.

The design presented is 378 ft long, 74 ft wide and draws 29.3 ft of water at full load. Endurance is 20,000 nm at 12 kt or an approximate mission time of 80 days. A rendering of the new ship is shown in Figure 1.

Figure 1. Polar Research Vessel

2. INTRODUCTION

At the end of its lease, the *Nathaniel B. Palmer* (NBP) will be 20 years old and approaching the end of its service life. This fact, coupled with interest within the polar science community in research capabilities beyond those of the NBP, provided impetus for feasibility design studies of a new Polar Research Vessel (PRV). Specific desired areas of increased capability include geotechnical drilling, use of remotely operated vehicles (ROV), and use of autonomous underwater vehicles (AUV). The purpose of the special design studies was to examine how the major factors affect the overall ship design, e.g. enhanced icebreaking capability and greater endurance drive ship size.

A further reason for the design effort is to better define the new features and how they would work aboard a new ship before requesting proposals for design and construction. Presenting this design information would reduce the cost of bidding to potential bidders as well as reduce their risk. As a result, it is believed that this would stimulate more interested bidders, inspiring greater competition.

This report first addresses the initial science and operational requirements, the starting point of this design effort. Next, individual special design studies are presented. These include investigations into towing seismic systems and nets in ice; hullform and appendages for improved bathymetry in ice; geotechnical drilling; moon pool sizing for deployment and recovery of ROV, AUV and possibly CTD rosettes; increased icebreaking capability and propulsion concepts; and compliance with IMO requirements for Arctic vessels. A design history is reviewed, and the PRV design is presented. The report closes with a cost estimate and concludes with recommendations.

3. INITIAL SCIENCE AND OPERATIONAL REQUIREMENTS

3.1 APPROACH

It was an owner and design team approach that the PRV procurement activity is different from the *Nathaniel B. Palmer* (NBP). NBP procurement had very limited design guidance in the RFP technical specifications and bidders were to submit competing designs at all levels of detail including science spaces.

The PRV procurement will contain significantly more details in the specification, including a conceptual design of the vessel and guidance drawings of laboratory spaces that reflect the preferences of the science community. This approach should minimize the risk for bidders and, therefore, increase the competition. It will also reduce the risk for the owner and science community because the greater details including conceptual design will insure the ship quality and target specification regardless of bidders' qualifications and experience in designing and building icebreaking research vessels.

3.2 INFORMATION RESOURCES

Major information sources that have been used to form the initial set of requirements are as follows.

- Two Science Workshops
- Antarctic Oceanography Planning Workshop, Final Report, June 25-26, 2002
- Antarctic Marine Geology and Geophysics Planning Workshop, Final Report March 23-24, 2002
- NBP procurement specifications as modified during refit, about 2000
- ARV design, 1994
- ARRV design, 2001
- Data base of research vessels

3.3 SCIENCE AND OPERATIONAL REQUIREMENTS PROVIDED TO DESIGN TEAM

Requirements provided to the design team were as follows:

- Acoustic profiling including bottom mapping during icebreaking
- Towing of nets and instruments from the stern during icebreaking
- Conduct of AUV/ROV operations from a moon pool
- Geotechnical drilling through a moon pool
- Guidelines for Drilling ?
    Use ShalDril as representative drilling system for PRV
    Moon pool is needed for other science requirements - located in an ideal location on the ship for drilling
    Rig over the moon pool and enclosed

  Part of system is permanently installed in the vessel and the remaining part is portable.
  Provide access from deck for drill pipe and access forward to labs for cores to be handled

- Bow thruster in the hull for station keeping in open water
- Acoustically quiet
- Comply with IMO guidelines for Arctic vessels
- Accommodations for 50 scientists
- 80-day endurance
- Reduced air emissions from diesels and incinerator
- Enhanced icebreaking capability
- Helicopter hangar

4. SPECIAL DESIGN STUDIES

4.1 TOWING SEISMIC SYSTEMS AND NETS IN ICE – RECOMMEND A HULLFORM, STERN ARRANGEMENT, AND PROPULSION SYSTEM THAT IMPROVE TOWING IN ICE.

4.1.1 Approach

Towing seismic equipment and nets in the ice has been done in the past, and results have indicated that the track behind the vessel is often filled with ice that can cause some problems for the science and the equipment. The present study is aimed at a solution which will insure reliable and safe towing operations. The drawings of existing icebreaking research vessels and icebreakers involved in towing were studied and visits were made to the icebreaker *Oden* and the German Alfred Wegener Institute for Polar and Marine Research to study their experience. The current study is focused on the following potential areas of improvement Polar Research Vessel (PRV) towing capability in ice.

- making a clear channel behind the vessel using a non-conventional shape of the ship's hull;
- reducing the ice concentration in the ship's track by means of auxiliary devices for ice management;
- reducing the ice concentration in the ship's track by a non-conventional propulsion system
- reducing the risk of contact in the ship's channel between the ice cover, the towed equipment. and towing line by means of special devices and stern arrangements

Most of the above mentioned concepts have some practical application and were studied for a number of years both in the laboratory and in natural conditions. The approach to the current study was to draw the conclusions based on the experience and test results available to date.

4.1.2 Clearing the channel by ship's hull

The overwhelming majority of the icebreakers built to date have the so-called conventional lines characterized by a raked stem and a wedge-like waterline. At the same time as far back as in forties in Russia, another principally different concept of icebreaking bow was developed and tested in full-scale conditions. This bow is notable for a flat section through the waterline (instead of a pointed stem). These studies were completed in 1963 with the trials in the Arctic of the nuclear icebreaker *Lenin* with a ski-like flat attachment at the stem [i]. The experiment was considered to be not quite successful, however, and authors of the concept abstained from patenting and further development (the chief designer was V.G.Neganov).

The idea to replace the stem by a flat panel was patented later in a number of countries, for example in Canada (patent of Canada N 1026160, 1974). One of the modern examples of such technical solution to icebreaking is the Swedish icebreaker *Oden* (see Figure 2). In addition, in the seventies and eighties, bow lines of the "spoon", "cylindrical" and "conical" shape were tested and found application. These bow lines also have no wedge-like stem (Figure 3).

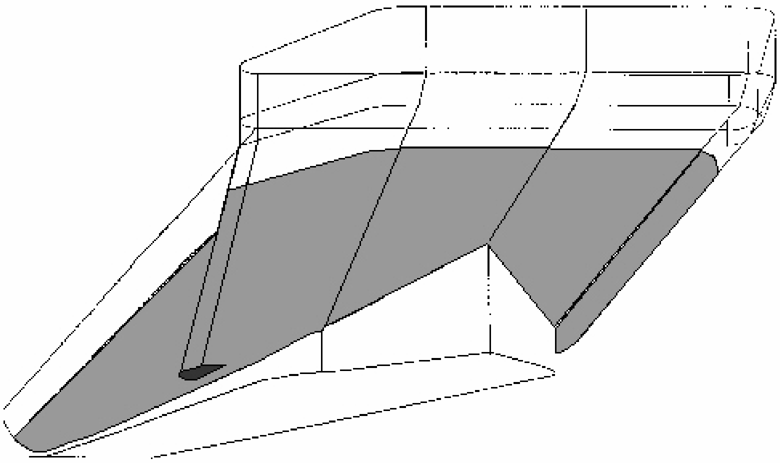

Figure 2. Icebreaker *Oden* ice-removing wedge

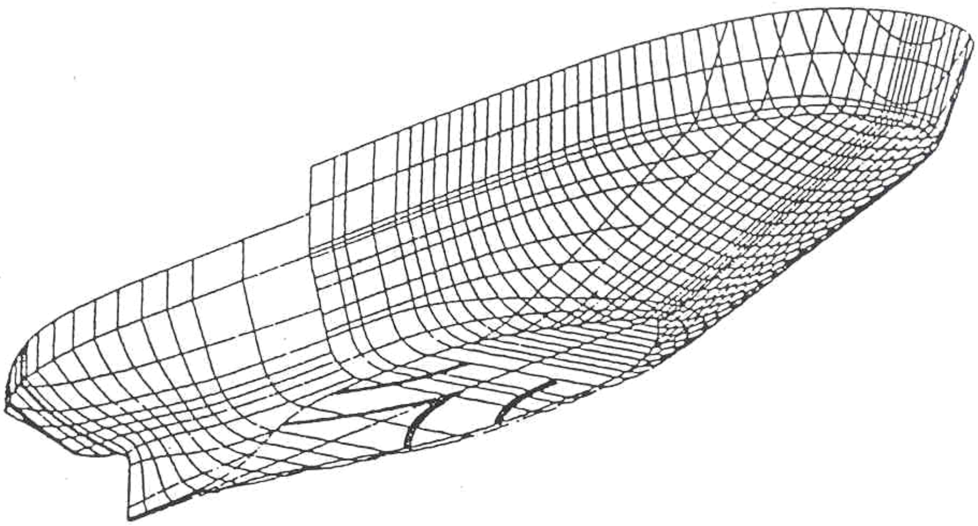

Figure 3. Icebreaker *Kapitan Nikolaev* bottom racks

All the above bow lines significantly change the icebreaking pattern and reduce the vessel resistance in level continuous ice relative to a conventional hullform. However, the ice concentration in the ship track is not reduced. In fact, the effect is opposite because the broken ice is being directed straight under the hull and then emerges in the middle of the channel. That is why designers attempted to shape the hull additionally or to use appendages pushing the ice pieces aside under the edge of unbroken ice cover. Icebreaker *Oden*, for example, was fitted with the large ice removing wedge intended to prevent the ice blocks going under the ship bottom. Icebreaker *Kapitan Nikolaev* with a conical bow has specially shaped ice removing racks welded to the flat bottom. These ideas are also presented in Figure 2 and Figure 3.

Operational experience, nevertheless, has shown that the channel fills with ice to approximately the same extent despite all the above features. Similar to conventionally shaped icebreakers, a wake of almost ice free water can be observed immediately behind the propellers. That wake gradually disappears at the distance 300-500 ft from the ship depending on ice conditions. As one can see from the pictures of Figure 4 and Figure 5 there is virtually no difference in the conditions of the channel behind *Oden* (flat barge-like bow) and *Botnica* (conical bow).

Figure 4. Icebreaker *Oden* track

Figure 5. *MSV Botnica* track

In the fifties and sixties, a concept of regulated icebreaking was also put forward. It consisted of cutting the ice with lateral structures (knives), ice plates being subsequently broken by a bow inclined plane and the broken ice driven under the channel edge by means of an ice directing wedge. Examples of such proposals are the "River icebreaker" by G.M.Tekuchev (inventor's certificate of the USSR No 125735, 1959) and a pushed “Attached Icebreaking Bow" by G.Ja.Serbul (inventor's certificate of the USSR N 310837, 1969) [i]. Figure 6 shows the G.Ja.Serbul concept.

A similar principle has formed a basis for the proposal by Ch.Waas (patent of FRG N 2530103, 1977) resulting in the development of the bow lines for the icebreakers *Mudyug* and *Kapitan Sorokin* converted by "Thyssen Nordseewerke" (Figure 7).

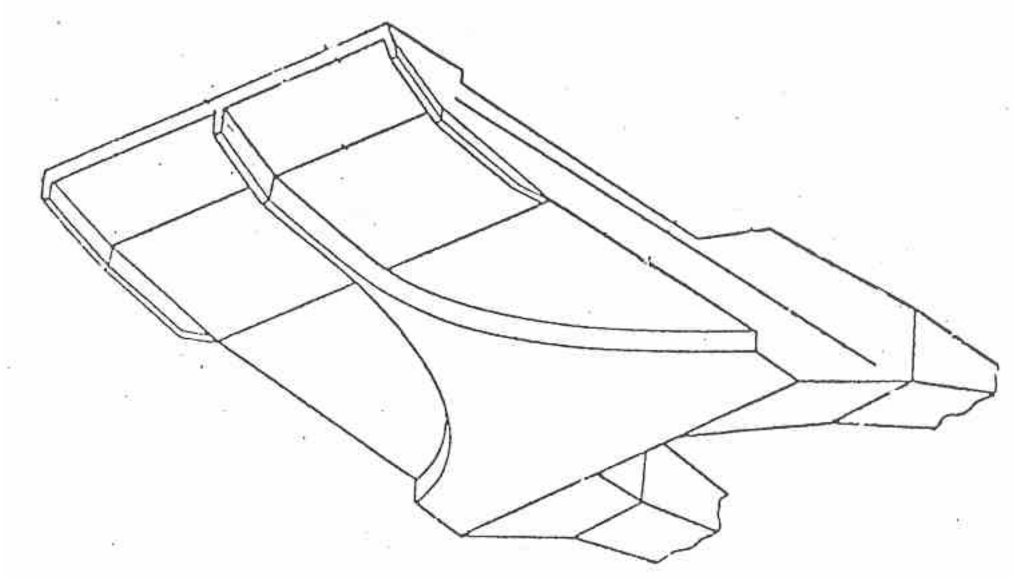

Figure 6. “Attached Icebreaking Bow" by G.Ja.Serbul

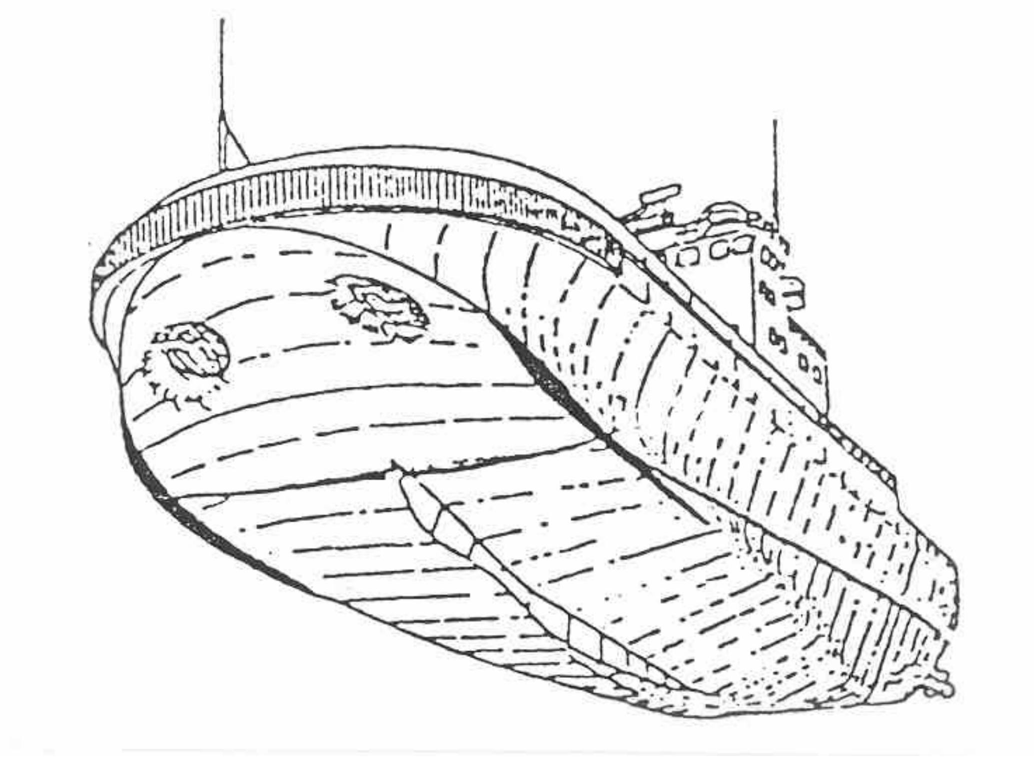

Figure 7. "Thyssen-Waas" hullform

As it is known, the tests of these icebreakers proved the high efficiency of the lines of the "Thyssen-Waas" system in breaking level ice [ii]. This hullform can provide almost an ice free track broken through the level land-fast ice. In compact broken ice, the clearing effect of the "Thyssen-Waas" shape is not that significant. The ice concentration is approximately 30% to 50% less than that behind a conventional icebreaker. As for ridges, brash ice, and frequently used channels through the land-fast level ice, the difference is marginal. At the same time, shortcomings were detected of the new bow during the operation in other than level ice conditions such as pushing the small ice floes and brash ice in front of the bow, poor maneuvering and backing performance as well as bad seakeeping. The last disadvantage practically removes the "Thyssen-Waas" hullform as well as other flat bow options out of consideration for a research vessel operating a significant period of the time in ice free waters.

Therefore, the review of both existing conventional and non-conventional hull lines shows that providing an ice free channel for towing in ice is very difficult if possible at all. This conclusion is also confirmed by 25-year experience of the authors of this report, who have tested or observed in full scale conditions most of the modern conventionally shaped icebreakers as well as most of the innovative hullforms including “Attached Icebreaking Bow" by G.Ja.Serbul (LLP-20), "Thyssen-Waas" bow (*Kapitan Sorokin*), flat bow (*Oden*), and conical/cylindrical bow (*Canmar Kigoriak*, *Kapitan Nikolaev*, *Botnica*). It should be noted that some impressive results have been achieved in model tanks using ideal level ice with uniform properties. In the natural ice, the clear channel was created only in the conditions very similar to those in model tank, i.e. level continuous land-fast ice. The operational time in that type of conditions is negligible for most of the ships.

4.1.3 Clearing the channel by means of auxiliary technical devices

In theory, clearing the ice channel can be achieved by using some auxiliary devices. Dozens of them were invented over the last 50 years but just a few were actually built and installed on the ships. Those ideas can be assembled in two groups.

1. Clearing the channel by pushing ice under the ice edge
    a. hydrodynamic devices
    b. combination of specially shaped hull and hydrodynamic devices
2. Clearing the channel by pushing ice onto the ice edge
    a. hydrodynamic devices
    b. mechanical devices

No devices belonging to the second of the above groups were used in practice. These devices are technologically too complicated and inefficient to be seriously considered for a research vessel.

Devices of the first group are widely used. They are typically intended to reduce the ice resistance of the vessel or to serve for both ice resistance reduction and channel clearing. Many icebreakers were equipped in 70’s through 90’s with the air-bubbling and bow water-wash systems. All those concepts have claimed the cleaner channel if the system is used. However, as experience of operation has shown, the actual achieved reduction of ice concentration in the channel was very limited, about 5-10%.

4.1.4 Reducing the ice concentration in the ship's track by the non-conventional propulsion system

A more efficient way to reduce the ice concentration in the ship track was found in 90's when azimuthal propulsors became a more and more common system for icebreakers. After the first large icebreaker with the azimuthal thrusters was built in 1993 they have been tested and used for clearance and widening of channel. The effect of the thruster angle on the ice concentration in the icebreaker track was most extensively studied during the *M/V Fennica* ice trials [iii]. The thruster angle here means the outwards angle on both sides. Angles of 10 to 90 degrees were used, and ice concentration recorded from helicopter varied from 10% to 80%. The angle of 30 deg. was found optimum for both channel clearing and channel widening. The test determined, however, fairly strict limits for this method. It should be noted that the ship was tested in thin 55 cm ice having stated icebreaking capability of 1.8 m. The thrusters turning resulted in a sharp loss of icebreaking performance. At thruster angles exceeding 30 deg the vessel was not able to achieve the speed above 3 to 4 knots. It clearly demonstrates that any clearing and track widening effect can be considered only for ice thickness within 10% to 40% of design icebreaking capability. The use of azimuthal propulsors for cleaning the track during towing with higher speed is only feasible in very thin ice. This method, in spite of its limits, seems to be one of the most efficient practical ways to clean the channel broken by the icebreaker.

4.1.5 Reducing the risk of contact in the ship's channel between the ice cover and towed equipment and towing line by means of special devices and stern arrangements

Reducing the risk of contact between the ice cover and towed equipment and towing line can be achieved by submerging the towing line as close as possible to the stern where some area of ice free water is always present during icebreaking ahead. This can be done, for example, by using the lead line and heavy weight attached to the A-frame or with the help of some other devices that are not the part of the ship.

Bringing the line under water close to the stern can be done also by means of special stern design. Two solutions were studied.

- Stern slip similar to those used on fishing boats: Figure **8**a
- Special channel or tube for the towing line: Figure **8**b

Both methods enable bringing the towing line under the water immediately from the hull without crossing the water surface where the ice can be floating and hitting the line.

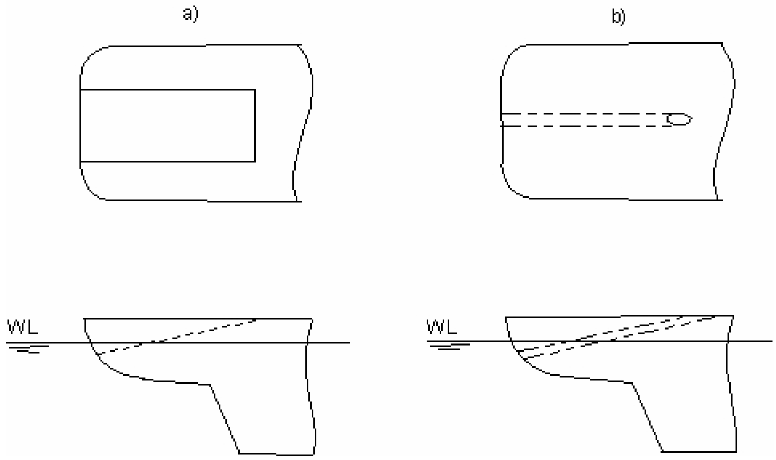

Figure 8. Example of stern arrangements for towing

The selection of specific stern arrangements does not affect the ship design overall and can be made on any design stage after science community consideration.

4.1.6 Conclusions

The study of existing non-conventional hull lines and other various technical solutions shows that providing conditions for towing in ice similar to those while operating in open water is very difficult. The most practical way of reducing the ice concentration in the broken channel is the use of a modern propulsion system providing opportunity for changing the propeller water flow directions. This will be limited however in terms of speed and ice thickness.

It is recommended to use the special devices or stern arrangement for submerging the towed equipment and minimizing its interaction with ice in the ship's track.

4.2 BATHYMETRY IN ICE – RECOMMEND A HULLFORM AND APPENDAGES THAT PROMOTE IMPROVED ICE MANAGEMENT AND REDUCE BUBBLE SWEEP DOWN OVER THE ACOUSTIC WINDOWS FOR THE MULTI-BEAM SWATH BOTTOM MAPPING SYSTEM, SUB-BOTTOM PROFILERS, ADCP, FISH FINDING SONARS AND OTHER ACOUSTIC SENSORS.

In order to understand the problems of conducting bottom mapping operations in ice, the technical team met with Dr. Hans Schenke of Alfred Wegener Institute (AWI), a researcher with extensive experience with swath bathymetry in ice. He has been involved with the 2 bottom mapping systems on the *Polarstern* and the modifications to improve performance. Originally *Polarstern* had a SeaBeam 16 beam system with a 42 deg sweep angle. The arrays were mounted in a box keel 1 m below the hull and 2 m wide. A Kevlar window over the arrays failed every time in ice. The problem with this system was mostly the placement of the array too far aft of the bow (40 m). When the ship went fast in ice, ice would be shot down from the bow and float up to impact the bottom near the array and damage the window. There was a lot of bottom damage as well over the middle 1/3 of the ship. When the SeaBeam system was replaced wit a Krupp-Atlas (now the company is Atlas System Technik) Hydrosweep system with a 90 deg sweep angle, the box keel was widened to about 4 m wide and 7 to 8 m long in way of the array and it was position farther forward, about 25 m from the bow. This system has titanium windows and has suffered no damage. A reverse flare was built into the sides of the widened portion to trap the air bubbles coming down the sides of the keel. This system works well both in open water and ice, and they are incorporating this type of structure into their open water ship, *Meteor*, to reduce the bubble sweep down that ship sees.

Dr. Schenke listed the features that he recommends for good swath bathymetry in ice. First is an appendage to get the array off the bottom for bubble sweep down. Next is deep draft to make it harder for the ice to be forced down onto the bottom. Place the arrays forward so that ice moving to the bottom may go by the arrays before it hits the bottom and keel.

Dr. Schenke has also been involved recently with the system on *Healy* to the extent that he has compared data taken by *Polarstern* with *Healy* in the same area in the Arctic Ocean. He said that the data was very comparable and the system on Healy, in his view, performed well. This is the same SeaBeam 2000 system that the *Nathanial B. Palmer* (NBP) had trouble with but of course a newer version. He said that the *Healy* seemed to perform better at high speeds and had trouble getting or could not get data at slower speeds or when stationary. Dr. Schenke felt this was a problem with the inertial reference unit, not the SeaBeam system itself. He further stated that the *Hesperus, James Clark Ross,* and the NBP all have been unable to gather data in thicker ice typical of the areas in the Antarctic where swath bathymetry is needed. We know from Raytheon Polar Services Corporation (RPSC) that the NBP has not gotten data in ice. They have recently changed the SeaBeam 2000 system for a SimRad system, but we have not heard whether it has been tested in ice. Bubble sweep-down and acoustic interference were significant problems with the original system. Both the new and the old system are flush-mounted on the bottom and in the forward part of the ship. The new system is not as far forward as the original system due to the larger array size.

Polarstern has been the most successful ship for swath bathymetry in ice. The design for the Polar Research Vessel (PRV) is therefore a development of the *Polarstern* box keel with the ends incorporated into the bow ice knife and the stern skeg (See Figure 9). Incorporating the ice knife and skeg into the keel will divide the broken pieces sliding down the bow or stern before they get to the box keel proper. This feature should help in keeping pieces off the bottom though it will probably not be completely successful in keeping the bottom clear. The cross-section will be similar to *Polarstern* with reverse flare on both sides. The array will be positioned as far forward as possible. Dr. Schenke said that damage to the array is possible during ramming with the array in a very forward position but the ice knife should prevent the ship from riding up too high on a ridge. The width of the keel is determined from the width of the arrays (assuming a SimRad system currently) and the moon pool. Both are of similar width. There is plenty of room forward for other acoustic sensors to port and starboard of the longitudinal array.

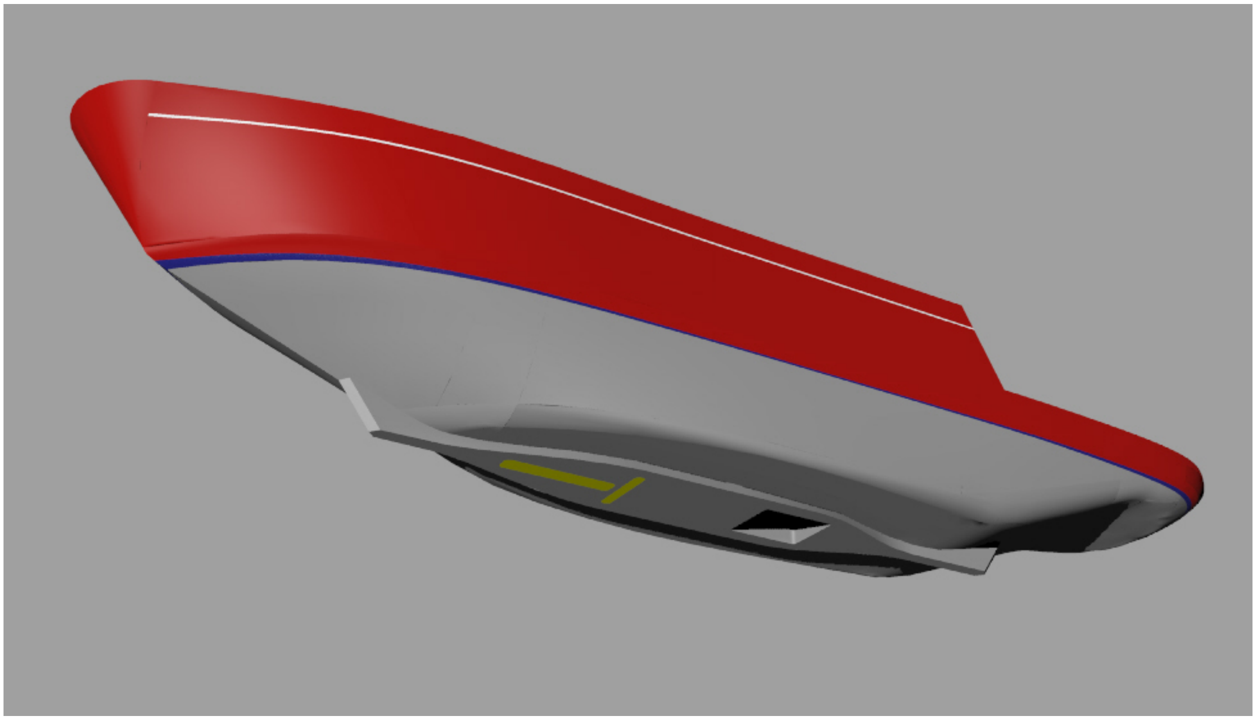

Figure 9. First estimate of hull shape for the PRV showing the box keel and other appendages.

4.3 GEOTECHNICAL DRILLING – RECOMMEND A HULLFORM, PROPULSION SYSTEM, THRUSTER SYSTEM, AND DRILLING ARRANGEMENT FOR SHALLOW WATER DRILLING IN LANDFAST ICE AND OPEN WATER.

The start of this study was a visit to *Botnica*, the newest Finnish icebreaker. The ship is chartered to the oil industry in the summer. For that work, *Botnica* is equipped with a large drill rig. The drilling rig is removable and quite large, about 34 m high. It has never actually been used but a smaller rig was used in open water during the last summer season. For drilling, the moon pool is covered and only a portion of the area is open for the drill string.

The representative system for the PRV drill rig was taken from the Shaldril that will be used on the NBP in 2005. The rig to be used is 40 ft high (12.2 m) high and 13 ft wide (4 m). It is modular and comes in 7 containers. A more permanent arrangement is envisioned for the PRV where the upper portion of the rig could be built into the ship above the moon pool room and the lower portion, about 22 ft (6.7 m) would be installed between the moon pool and the overhead during drilling operations. The moon pool would have to have a bell mouth near the bottom and a cover at the working deck. Pipe for this system is 5 inch commercial drill pipe in 20 ft sections. The arrangement provides direct access to the aft deck to move pipe into the moon pool area.

Therefore, adding geotechnical drilling and a moon pool to the vessel has a significant impact, if not the most significant impact of all science requirements, on the ship. The rig is large but manageable and should be placed near the center of gravity of the ship to reduce motions and better control the motion of the drilling string during dynamic positioning. The concept used in this new ship is to position the drill rig over a moon pool that is centered laterally in the ship near the longitudinal center of gravity. Much of the drilling rig can be built into the ship above an enclosed “hangar” or workroom above the moon pool. This workroom must also be suitable for oceanographic casts, ROV and AUV operations, diving, and other scientific missions. In this regard, the moon pool size is larger than what might be needed for drilling so a “drilling capable” cover would be fitted during these operations.

The moon pool would have to be covered to prevent ice ingestion during icebreaking. For drilling in landfast ice, the covers would be in place during break-in to the site. The moon pool has been located within the fairing around the acoustic arrays intended to move ice away from both the arrays and the moon pool. The fairing is likely to be only partially successful and some ice will undoubtedly end up on the bottom. Some method for clearing ice from the moon pool will likely be required, therefore. No additional considerations were included in the hull shape for drilling other than the need for excellent seakeeping and icebreaking required for all missions.

In open water, dynamic positioning will be required to keep the ship on station during drilling operations. The selection of podded propulsors that can be rotated azimuthally was partially based on their good thrusting capability for dynamic positioning. A bow thruster will likely be needed in addition to the two podded propulsors. A hull-mounted tunnel thruster is recommended instead of the usual thruster mounted in a bow ice knife. The hull-mounted unit moves the thrust opening up and aft causing fewer disturbances to the acoustic arrays on the bottom. The thruster will be effective in open water but will fill with ice in heavy pack. Even if cleared of ice, the bow thruster cannot produce enough thrust to be effective in ice. The bow thruster will only be used in open water for dynamic positioning and to assist in maneuvering alongside piers.

Movement of drill string and equipment to and from the moon pool is an important consideration for the arrangements. A large roll up door is provided just off centerline aft of the moon pool that opens to the aft deck. Laboratories are placed forward of the moon pool with access directly to the moon pool room or through a longitudinal hallway running forward of the moon pool.

4.4 ESTABLISH REQUIREMENTS FOR A MOON POOL TO DEPLOY AND RECOVER ROVS AND AUVS IN ICE AND CONSIDER CTD/ROSETTE DEPLOYMENT THROUGH THE MOON POOL.

The start of this study was a visit to *Botnica*, the newest Finnish icebreaker. The ship is chartered to the oil industry in the summer. For that work, *Botnica* is equipped with a moon pool to support deep sea Remotely Operated Vehicles (ROVs) as well as a removable drill rig. The moon pool is 6.5 m square on centerline and well forward on the ship. *Botnica* has a typical supply boat afterdeck that provides a large area for ROV work around the moon pool. There are holes in the side plating of the moon pool to damp surge experienced at sea. The moon pool is typically uncovered in the summer season. Both the bottom and top of the moon pool are covered for ice operations. The bottom cover for ice operations is a semi-permanent arrangement; the cover has a buoyancy chamber that is flooded in shallow water. It is then lifted into place by a ship's crane. A diver is required to attach the crane cable to the cover through the moon pool. Once in place, the buoyancy chamber is pumped out and the cover is secured with turnbuckles.

During the trip and after, RPSC and NSF provided information on the types of packages that could potentially be deployed through the moon pool. Initially, this set of packages included an Autonomous Underwater Vehicle (AUV), towed systems such as a biomass instrument, a CTD and rosette and diving support. AWI suggested that we should also consider ROVs since they could also be useful in polar science missions. This was later confirmed with NSF and RPSC. The moon pool was initially sized by estimating the hook height above the bottom of the ship and, using the maximum package size and the roll and pitch limits of the ship, the required length and width were computed as 20 and 16 ft (6.1 m by 4.9 m), respectively. The basis for the length was a 10 ft AUV and a 5 ft width for a rosette. Approximately 3 ft (1 m) of margin was included in each dimension to arrive at the size. When the ROV was included, it was clear that that ROV would likely drive the moon pool size but the size of future ROVs was in question. Further, it was suggested that some kind of captured lowering system to eliminate ship motion would need to be incorporated. STC investigated other deep ocean moon pool design to deploy ROVs and found that they were in the range of 4.0 to 6.5 m square. The new German drillship for the Arctic will have one 4 by 5 m and one 6 by 8 m moon pool. AWI indicated that the *French Victor* ROV that they have been using is 2 by 2 by 4 m long so the smaller moon pools are probably not big enough for a large deep ocean ROV. For the feasibility studies and given the fact that little is known about the future size of scientific ROVs, the original size will be used in the design. If it is necessary to increase the size somewhat in future iterations of the design, the impact of the ship will be minimal.

The moon pool was located at the longitudinal center of gravity to reduce the effect of ship motions. This location also allows better control when maneuvering to keep station in open water. A large area around the moon pool was provided to maintain the ROVs and AUVs and prepare packages for deployment. Since this space occupies a significant area at the center of the ship, the Baltic room similar to the NBP was incorporated into the forward starboard corner of this space. The space must be two decks high to provide enough space for an overhead crane to lift packages into the moon pool and provide space for the boom for over-the-side deployment through the Baltic room door. An overhead crane was selected to reach all staging areas and the area over the moon pool. A control room was positioned above a wet lab at the starboard side of the space to view the moon pool, staging areas and the starboard side outboard of the ship (See Figure 10).

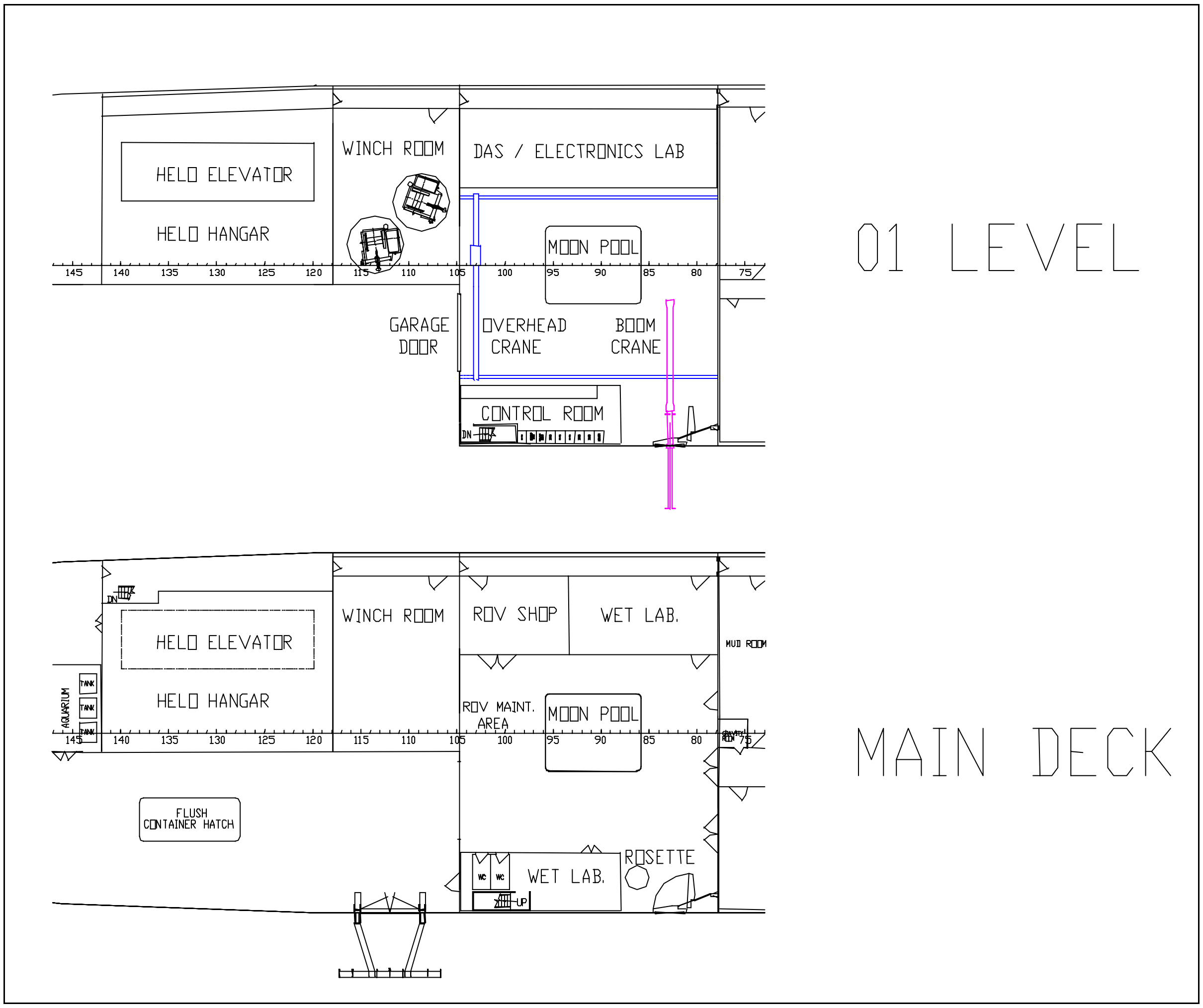

Figure 10. Deck plan of the moon pool area.

4.5 EVALUATE INCREASED ICEBREAKING CAPABILITY AND EVALUATE ONE OR MORE PROPULSION CONCEPTS TO SATISFY MISSION REQUIREMENTS AND DEVELOP RECOMMENDATION.

4.5.1 Icebreaking capability

Icebreaking capability can be evaluated directly for a given design. The problem of evaluating the increased capability to break ice for a new design is that ship grows in size as the capability goes up. If the original design were evaluated with higher power for instance, performance would be over-predicted because the increased power and subsequent increased fuel capacity will probably not fit in the original design. The ship would have to get bigger (probably wider) and the actual performance increase would not be as large.

The only way to accurately predict the impact of icebreaking capability on the ship is to design different ships for each capability. If each design is done by hand, the work quickly becomes a large effort. STC instead tried to assemble a design synthesis model to tie together the basic parameters of the design so that different designs could quickly be produced for a given level of capability. The work is then in developing the model but, once the model is developed, many feasible design solutions can follow quickly. It is the perfect tool to investigate effects of design or performance criteria at the early design stage. The model balances hydrostatics with weights, computes open water speed, and computes the fuel capacity to meet endurance. It designs the propeller based on Ignatev icebreaking propeller series and B series regressions. The power and towrope pull to meet an icebreaking performance criterion are calculated. The hullform and general proportions are defined, and non-dimensional resistance characteristics appropriate to this form are taken from model and full-scale data for other ships.

The hullform incorporated into the design model was developed with some specific objectives: efficient performance in level ice and good maneuverability in ice while preserving good open water seakeeping and resistance. The selected hullform was evaluated using STC ice resistance model and found to be more efficient than the icebreaking hullform used on the NBP. This analysis has shown that the suggested hullform is significantly more efficient and allows an increase in the icebreaking capability up to 25% without increasing the shaft power. These results are illustrated by Figure 11.

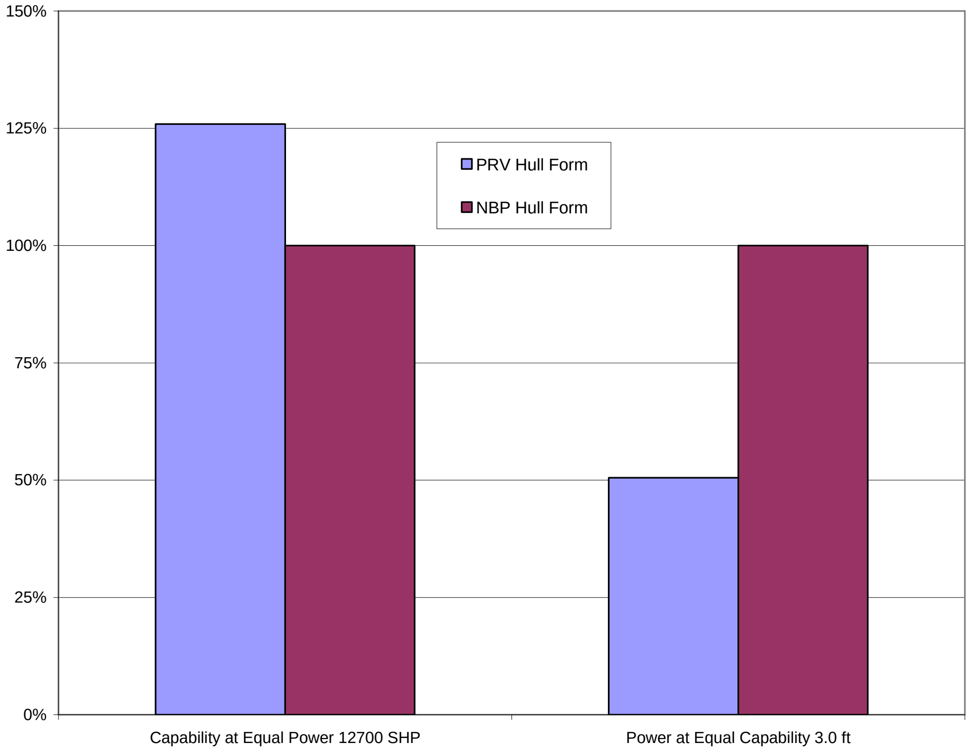

Figure 11. Relative efficiency of the developed icebreaking hullform relative to the NBP.

Results of the model runs, that is characteristics of the ships, are presented as a function of icebreaking capability (thickness of level ice of 100 psi flexural strength at 3 kt) with two curves for the current endurance of the *Nathaniel B. Palmer* (15,000 nm at 12 kt) and the proposed increased endurance for the Polar Research Vessel (PRV) (20,000 nm at 12 kt). Figure 12 shows the change in displacement with icebreaking capability and endurance. Displacement increases significantly with increasing icebreaking capability. The NBP falls close to the left end of the lower blue curve for displacement at 6800 LT and slightly more than 3 ft capability. The NBP broke 4 ft of level ice during the ice trials but the strength was somewhat lower that the specified strength and she was only able to go 1 kt. If the PRV should have a 4.5 ft capability, the displacement will be about 11,000 LT. Note that the fuel weight does not increase significantly with increased icebreaking capacity because it is based on open water transit at 12 kt. Fuel weight increases slightly more than proportionally with increased endurance.

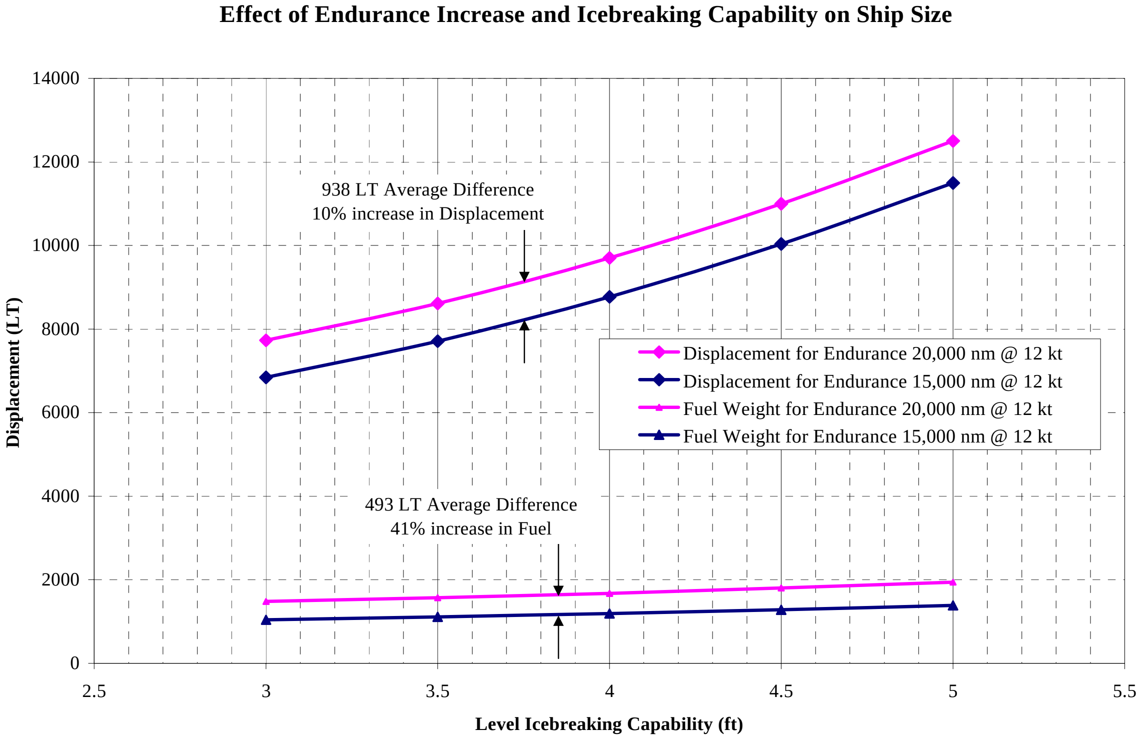

Figure 12. Change in displacement and fuel weight with icebreaking capacity and endurance.

Figure 13 illustrates the change in ship characteristics, length, beam and draft, with icebreaking capability and endurance. All characteristics increase between 3 and 4 percent with the increase in endurance from 15,000 to 20,000 nm. As one can see, the increase in characteristics is more significant with increasing icebreaking capability.

The variation in shaft power is presented in Figure 14. There is a significant need for increased shaft power with increasing icebreaking capability. At 4.5 ft of capability for the PRV, the ship will require about 23,000 HP. In this analysis we have tried to incorporate the largest propeller practical for the hullform and propulsion arrangement. The twin podded propulsors with large open propellers are very efficient and should reduce noise at cruising speeds and below. Large propellers increase thrust for icebreaking and allow the propulsion plant to run at lower shaft speeds in open water. Fuel consumption is reduced, and a quieter ship results. The large propeller diameters are shown in Figure 14 as well.

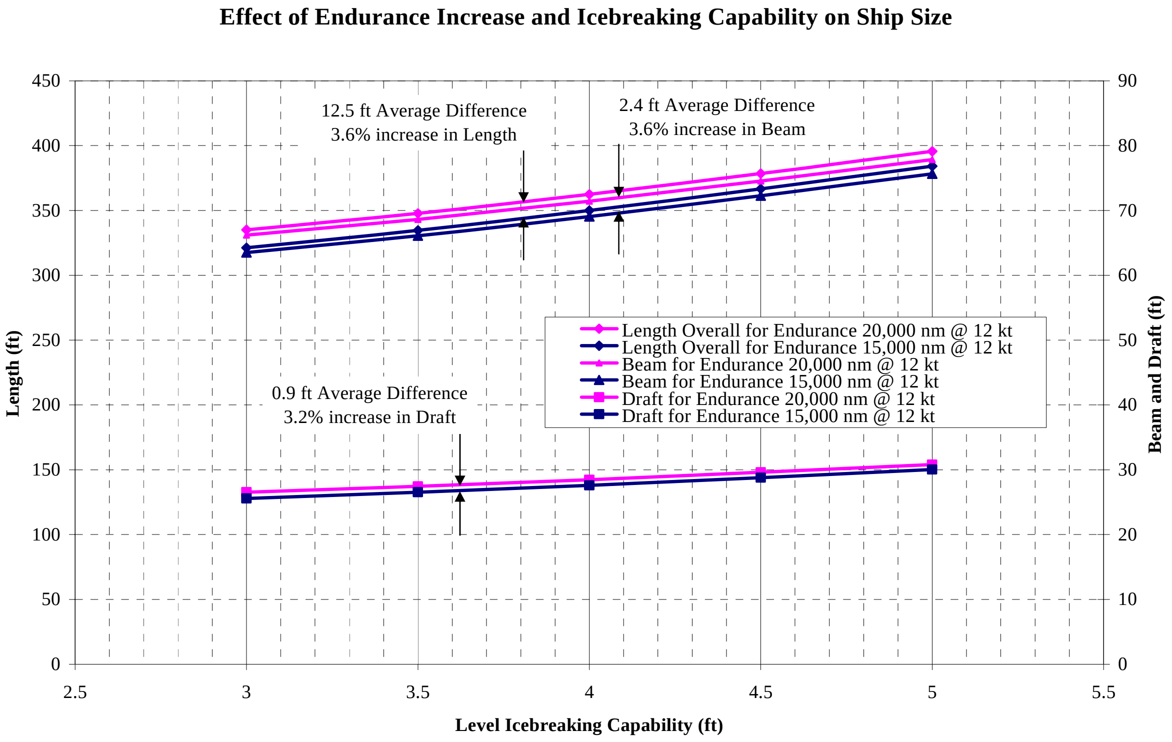

Figure 13. Change in length, beam and draft with icebreaking capacity and endurance.

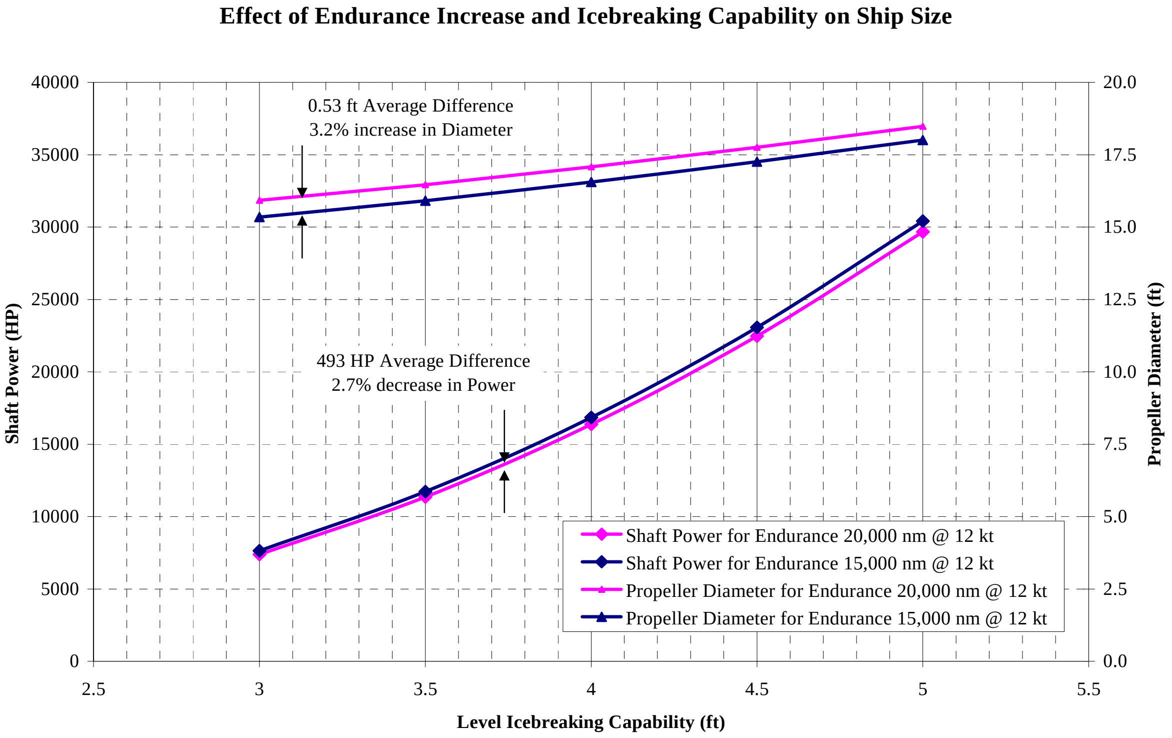

Figure 14. Change in shaft power and propeller diameter with icebreaking capacity and endurance.

4.5.2 Machinery Plant Selection

The machinery plant evaluation has been based on the observation made during the Baltic trip, many other trials and trips on icebreakers, discussions with operators, other feasibility studies and designs for icebreaking ships including model tests and a survey of the new propulsors suitable for the PRV. The advantages and disadvantages of each system are listed in a number of different categories in Table 1. Cost factors are taken from other early stage design efforts and are provided as an indication of the difference between systems. The cost factor does not necessarily reflect the PRV and must be refined in future iterations of these design studies.

Several conclusions are drawn from Table 1. The first is that the direct drive diesel system is very difficult to fit in a ship with a large moon pool, especially if the moon pool must go approximately amidships. There is insufficient space aft of the moon pool to fit the entire plant, but placing the engines forward of the moon pool means the shafts have to be outboard of the moon pool. Such a spacing is also difficult if not impossible to achieve. An electrical system greatly simplifies the arrangement. The generators can go forward of the moon pool and the electric propulsion motors aft near the propulsors. The electric system has other advantages for science as well. The generators can be isolated from the structure, reducing noise. Torque characteristics of the electric propulsion system are much better suited to ice, and this capacity to handle ice torque makes open propellers more viable. Large, low shaft speed open propellers give high thrust for icebreaking but also can be configured for high efficiency at cruising speed with low noise. The podded propulsors were selected for their maneuverability and effectiveness with stationkeeping. They are also very efficient both ahead and astern. Z-drive azimuthing thrusters can also be considered as they are cheaper and may have less interference with acoustic systems. Evaluation of podded propulsors versus Z-drives should be investigated in more detail in future design iterations. Nozzles can also be considered in this trade-off since they produce higher thrust for icebreaking and therefore need less power for a given icebreaking capability. They may be less efficient at higher speeds and have different acoustic characteristics, however.

Propulsion system potential vendors were not visited at this point of design. However, vendors are known and a list is presented below.

Podded propulsors

1. ABB AZIPOD Oy
Laivanrakentajantie 2
FIN-00980 Helsinki, Finland
Phone: +358-(0)10 22 26056
Fax: +358-(0)10 22 26060

2. Rolls-Royce AB Kristenhamn (MERMAID)
Hoje
Varnumsleden 5
SE-681 29 Kristenhamn, Sweden
Phone: +46 550 840 00
Fax: +46 550 181 90

Electric-Z-drive

Ulstein Aquamaster

ROLLS-ROYCE OY AB
PO Box 220
FIN-26101 Rauma, Finland
tel . +358 2 83 791
fax +358 2 8379 4804
Esa Uotinen
Azimuthing thrusters,
winches, windlasses

Helsinki Office
Lapinlahdenkatu 21 B
FIN-00180 Helsinki
tel. +358 9 686 6330
fax +358 9 686 63339

Table 1. Propulsion Plant Comparison for an Icebreaking Research Ship

Category	Podded Azimuthal System Open Propellers		Z-drive Azimuthal System Ducted Propellers		Diesel-electric conventional shaft system		Diesel-direct conventional shaft system. Ducted Propellers	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Ice operations								
Level icebreaking ahead	Good		Very good. Provides more thrust than open prop		Good		Very good. Provides more thrust than open prop	
Level icebreaking astern	Excellent. Provides almost as much thrust as ahead. Sustains the full power. Capability may be better astern		Excellent. Provides almost as much thrust as ahead. Sustains the full power. Capability may be better astern		Very good. Provides up to 80% of thrust ahead. Sustains the full power. Capability may be slightly better astern			Very poor. Provides 25-35% of thrust ahead. Typically can't use the full power. Capability astern much worse.
Ridges going ahead	Good		Very good. Provides more thrust than open prop	There is a probability of the nozzles clogging	Good		Acceptable. Provides more thrust than open prop	There is a probability of the nozzles clogging
Ridges going astern	Excellent. Provides almost as much thrust as ahead. Sustains the full power. Capability is better astern		Very Good. Provides almost as much thrust as ahead. Sustains the full power. Capability may be better astern	There is a probability of the nozzles clogging	Very good. Provides up to 80% of thrust ahead. Sustains the full power. Capability may be slightly better astern			Very poor. Provides 25-35% of thrust ahead. Very high probability of the nozzles clogging. Typically can't operate this way
Dense brash ice. Clogged channel. Ahead	Very good		Good	There is a high probability of the nozzles clogging	Very good		Acceptable. Provides more thrust than open prop	There is a high probability of the nozzles clogging

Table 1. Propulsion Plant Comparison for an Icebreaking Research Ship (Continued)

Category	Podded Azimuthal System Open Propellers		Z-drive Azimuthal System Ducted Propellers		Diesel-electric conventional shaft system		Diesel-direct conventional shaft system. Ducted Propellers	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Ice operations (Cont)								
Dense brash ice. Clogged channel. Astern	Excellent. Provides almost as much thrust as ahead. Sustains the full power. Capability is better astern		Good. Provides almost as much thrust as ahead. Sustains the full power. Capability may be better astern	There is a very high probability of the nozzles clogging	Very good. Provides up to 80% of thrust ahead. Sustains the full power. Capability may be slightly better astern			Very poor. Provides 25-35% of thrust ahead. Very high probability of the nozzles clogging. Typically can't operate this way
Steering ability in ice going astern	Best known to date		Best known to date	There is a probability of the nozzles clogging	Acceptable		None	
Maneuverability in ice	Best known to date		Best known to date		Good			Very pore
Ability to clear the wake	Some, in ice up to 50% of the limit at low speed		Some, in ice up to 50-60% of the limit at low speed. May be slightly better than that for open props		none		none	

Table 1. Propulsion Plant Comparison for an Icebreaking Research Ship (Continued)

Category	Podded Azimuthal System Open Propellers		Z-drive Azimuthal System Ducted Propellers		Diesel-electric conventional shaft system		Diesel-direct conventional shaft system. Ducted Propellers	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Open water operations								
Transit speed	Provides good inflow for propellers, which improves efficiency as compared to conventional shafts	Less efficient if designed for icebreaking and vice versa	Provides good inflow for propellers, which improves efficiency as compared to conventional shafts	Less efficient if designed for icebreaking and vice versa		Less efficient if designed for icebreaking and vice versa	Most efficient propulsion train	Less efficient than other systems if designed for icebreaking, net effect probably less efficient
Fuel efficiency		Less efficient if designed for icebreaking and vice versa		Less efficient if designed for icebreaking and vice versa		Less efficient if designed for icebreaking and vice versa	Most efficient propulsion train	Less efficient than other systems if designed for icebreaking, net effect probably less efficient
Maneuverability	Best known to date		Best known to date		Good		Good	
Stationkeeping	Best known to date		Best known to date			Difficult to achieve the level required for the drilling		Difficult to achieve the level required for the drilling

Table 1. Propulsion Plant Comparison for an Icebreaking Research Ship (Continued)

Category	Podded Azimuthal System Open Propellers		Z-drive Azimuthal System Ducted Propellers		Diesel-electric conventional shaft system		Diesel-direct conventional shaft system. Ducted Propellers	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Noise								
Machinery	Diesel-generators on rafts are the most quiet possible	Propulsion motor outside hull is the source of underwater noise	Diesel-generators on rafts are the most quiet possible. Propulsion motor inside hull is the most quiet possible	Power train (gears) is more noisy than that electric one)	Diesel-generators on rafts are the most quiet possible. Propulsion motor inside hull is the most quiet possible			Diesels and power train (gears) can not be floating and are more noisy than that electric system
Propellers	Open propeller given sufficient power margin can provide the speed of 10-12 knots without cavitation at low RPM			It is more difficult to stay away from cavitaion for ducted props	Open propeller given sufficient power margin can provide the speed of 10-12 knots without cavitation at low RPM			It is more difficult to stay away from cavitation for ducted props
Hull	Icebreaking hull does not provide a good opportunity for noise reduction							
Design flexibility								
Machinery arrangements	Very flexible. 1) DG can be placed on any deck and moved around. 2) No need for motor room		Very flexible. 1) DG can be placed on any deck and moved around.		Very flexible. 1) DG can be placed on any deck and moved around.			Requires shaft alleys and fixed location of the engines. Less compatible with the moon pool and drilling equipment
Power	Common bus system does not require service generators		Common bus system does not require service generators		Common bus system does not require service generators			Requires service and/or shaft generators

Table 1. Propulsion Plant Comparison for an Icebreaking Research Ship (Concluded)

Category	Podded Azimuthal System Open Propellers		Z-drive Azimuthal System Ducted Propellers		Diesel-electric conventional shaft system		Diesel-direct conventional shaft system. Ducted Propellers	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
qReliability	More than 10 years in icebreaking service. No major problem reported	Some small oil leaks reported. Both externally and internally	More than 10 years in icebreaking service. No major problem reported	Some internal small oil leaks reported.	Proven very reliable over decades		Proven reliable over decades	
Cost								
Acquisition cost		1		1		1.025	0.95	
Annualized cost		1		0.9	0.87		0.89	

4.6 EXAMINE COMPLIANCE WITH NEW IMO REQUIREMENTS FOR ARCTIC VESSELS INCLUDING PROVISION FOR NO POLLUTANTS CARRIED DIRECTLY AGAINST THE OUTER SHELL.

The new document from IMO pertaining to Arctic vessels is the "GUIDELINES FOR SHIPS OPERATING IN ARCTIC ICE-COVERED WATERS", MSC Circular 1056, MEPC Circular 399, dated 23 December 2002. These guidelines are recommended but not mandatory requirements for ships operating in Arctic ice-covered waters. The guidelines "are intended to address those additional provisions deemed necessary for consideration beyond existing requirements of the SOLAS Convention, in order to take into account the climatic conditions of Arctic ice-covered waters and to meet appropriate standards of maritime safety and pollution prevention."

The guidelines address the structural hazards of operating in ice, the demands on ship systems to insure they operate safely and effectively in the Arctic marine environment, and attention to human factors including training and operational procedures. The guidelines cover ship structure, stability and subdivision, machinery, life-saving equipment, fire protection, ship routing, navigation systems, radio communications, pollution prevention equipment, and liability and safety management systems for the Arctic environment. They also establish a system of Polar Classes that indicate different levels of capability. These classes are intended to work with the Unified Requirements of the International Association of Classification Societies that are currently under development. The Unified Requirements will provide rules for building Polar Class ships and be the same across all member organizations including ABS, DNV, LRS, etc. In the interim, ice class rules from the classing organization must be used.

It is important to note that the guidelines work in harmony with the Class selected for the vessel and the rules of the particular classification society for the class selected. The guidelines may place additional requirements on the design such as "No pollutants should be carried against the shell in areas at significant risk of ice impact." The RVIB requirements that resulted in the *Nathaniel B. Palmer* were for an ABS Ice Class A2 ship. Given the presence of a large amount of old ice even in summer in the coastal Arctic and the desire to have the new ship be a "Polar" research vessel, i.e. designed to go to the Arctic in summer, the appropriate ice class is ABS Ice Class A3 or Polar Class PC3. Guidelines in the ABS rules recommend ABS Ice Class A3 for unescorted operation in Arctic offshore shelf and escorted operation in the Central Arctic Basin.

The guidelines with the most significant impact on the design are as follows. The guidelines require a cofferdam of a depth of at least 0.76 m (2.5 ft) between tanks with fuel and the shell. The ship is further required to have a double bottom through the length from the collision bulkhead to the aftpeak bulkhead. Small working fluid tanks with pollutants up to 20 m^3 (706 ft^3) are allowed in the double bottom but tanks larger than this value should have the cofferdam. Damage stability requirements allow damage due to ice to occur over a length of 4.5% of the deepest ice waterline length anywhere forward of the maximum beam and 1.5% of the beam elsewhere. This means that damage can occur on a bulkhead and flood two or potentially more adjacent compartments. The 2 compartment stability requirements have a significant impact on compartmentation and should be examine thoroughly in the next design iteration.

In the feasibility design studies, the effect of changing endurance and icebreaking capability were examined first with a synthesis model. A volume check was not included because weight seemed to be limiting. After the ship size was determined for the selected level of capabilities for endurance and icebreaking, the hullform was developed with the assumed hullform parameters to fit the size determined by the model. The hull volume required for all tanks and cofferdams was then checked and it was determined there is ample margin.

The guidelines also cover cold weather effects on all aspects of ship operation including shipboard icing. Many of the items have been addressed in the previous RVIB technical specifications. For this new ship procurement, the guidelines should be invoked as a requirement of the technical specification and then certain specifications from the RVIB specification may be eliminated if they are covered under the guidelines. In some few limited cases, such as the criteria for loading during icing, additional or more stringent criteria may need to be invoked from the original RVIB specification.

5. DESIGN HISTORY

The progression of the design effort is detailed chronologically in Table 2.

Table 2. PRV Design History

Date	Activity	Location	Comments
March 12 to 27, 2003	Trip to the Baltic		
March, 14 to 16, 2003	Icebreaking on Finnish IB *Botnica*	Off Rauma & Pori, Finland	Moon pool primarily used for ROV operations to date; Moon pool bottom cover is of very rudimentary design; Azipods provide excellent station keeping ability, maneuvering and reversing (more expensive than direct drive propulsion, some oil leakage); Prefer Intering (active) roll stabilization system vice passive roll tanks; Double hull environmental protection; 12 diesel engines (high-speed type) are excessive and selected based on initial cost only; Bridge is regarded by crew as best known to date. Visibility from starboard side control station is excellent; Cabin layout of interest (desk arrangement, bathroom and ceiling height); Hullform is poor with "continuous" vibration aboard vessel during icebreaking and slamming in waves
March 17 to 19, 2003	Icebreaking on Swedish IB *Oden*	Off Lulea, Sweden & Kemi, Finland	Large vessel with excellent ahead propeller thrust and icebreaking ability in Baltic; Flat bow directs broken ice under flat bottom of vessel; Broken ice channel behind vessel similar to *Botnica*; Flat bow form unsuitable for open water transit in waves; Diesel direct drive to propellers similar to NBP; Nice staterooms and cabins with fold-away upper bunk; Vessel does not back well with reamers - primarily a one-direction vessel; No intent of Swedish Maritime Administration to use this hullform again.

Table 2. PRV Design History (Continued)

Date	Activity	Location	Comments
March 24, 2003	Meet with scientists and operations people at Alfred Wegener Institute	Bremerhaven, Germany	Use box keel to house all of their transducers; Avoids bubble sweepdown in front of transducers; Continuously conduct bottom mapping during icebreaking; Deep draft of *Polarstern* helps in pressure ridges transits; Recommend 1-meter deep box keel on research vessels; Will modify *Meteor* with box keel to avoid bubble sweepdown; Power of *Polarstern* insufficient to maintain speed in Arctic ice, dual ship operations preferred; Believe all ships have the same broken ice pattern behind the vessel, regardless of bow form; Stern ramp on the fantail aids geophysical operations; New Arctic drilling research vessel *Aurora Borealis* design is complete with two moon pools (4mx5m) and design will be available; Believe all new research vessels should have AUV/ROV capability; One helicopter is good for operation to 10 miles away from the vessel; for greater distances use two; Use of podded propulsion is unclear in terms of its affect on vessel acoustics and impact of electromagnetic radiation on other instrumentation; Accommodations for 50 scientists is good *Polarstern* will continue to operate for next 15 years
	Investigate icebreaking and powering for resulting hull		Developed hullform may increase icebreaking capability up to 25% Specified icebreaking capability has great impact on shaft power. Propeller diameter (draft) and pod size (ship's beam) limit the power per shaft. Maximum estimated power for PRV of the initial size: 30,800 SHP based on propeller diameter; 40,000 SHP based on pod size Machinery space required for 30,800 HP may be difficult to fit into the vessel of estimated size
	Start Design Process		Use NBP as a baseline, increase size for double hull and moonpool, ship is about 20% larger, increased beam and length more than draft, use as starting point for design spiral, start layout of moonpool area and drill rig.
	Hullform development, Rhino Modelling		Developed the concept for the false keel to protect the bottom mapping sonar arrays, incorporate the moonpool, ice knife, and skeg into this appendage. Developed the basic hullform, guidelines were low resistance in ice and open water, good seakeeping properties, accommodation of azimuthal propulsion.

Table 2. PRV Design History (Concluded)

Date	Activity	Location	Comments
	Define Operational Requirements that scientists want improved		Increased endurance - 60 days was increased to 80 days, Increased icebreaking capability, NBP's perceived 4 ft increased to 5 ft.
	Arrangement		Moonpool dominates center of ship. Concept is developed to surround the moonpool with space for working on vehicles, wet labs, and a common control room. The Baltic room is integrated with the moonpool room.
May 1, 2003	ARVOC Meeting	Arlington, VA	Size of ship – starting point NBP Length 330 ft Beam 65 ft Draft 23.4 ft No pollutants against the hull Moonpool 16 ft wide by 20 ft long Azimuthal propulsion Electrical common-bus machinery plant Hullform for ice management around acoustic windows and moonpool
	Hullform development,Rhino Modelling		Resized hullform (slightly increased length, beam, and draft) due to taking appendage draft into account - allowed larger propellers
	Arrangement, Rhino Modelling		Sized deckhouse from area/volume estimates
	Tradeoff studies		Examined how varying the endurance and icebreaking capability affected the PRV design
	Cost estimate		Added cost estimate based on ARRV and in-house methods for government procurements to the model
August 1, 2003	ARVOC Meeting	Monterey, CA	Presentation of the feasibility design studies, design and cost.
August 23, 2003	Design Studies Report		Written report draft describing the design studies and their results.
September 30, 2003	Final Report		Written report of the work on the project for FY 2003. This report includes the preliminary studies, special design studies, the design and cost.

6. DESIGN RESULTS

The Polar Research Vessel design effort produced a potential configuration of the future ship. This section addresses the PRV principal characteristics, power plant, performance, ice classification, science features, features of the main deck and 01 level, and a comparison of laboratory spaces to those aboard the *Nathaniel B. Palmer*.

Figure 15. Polar Research Vessel

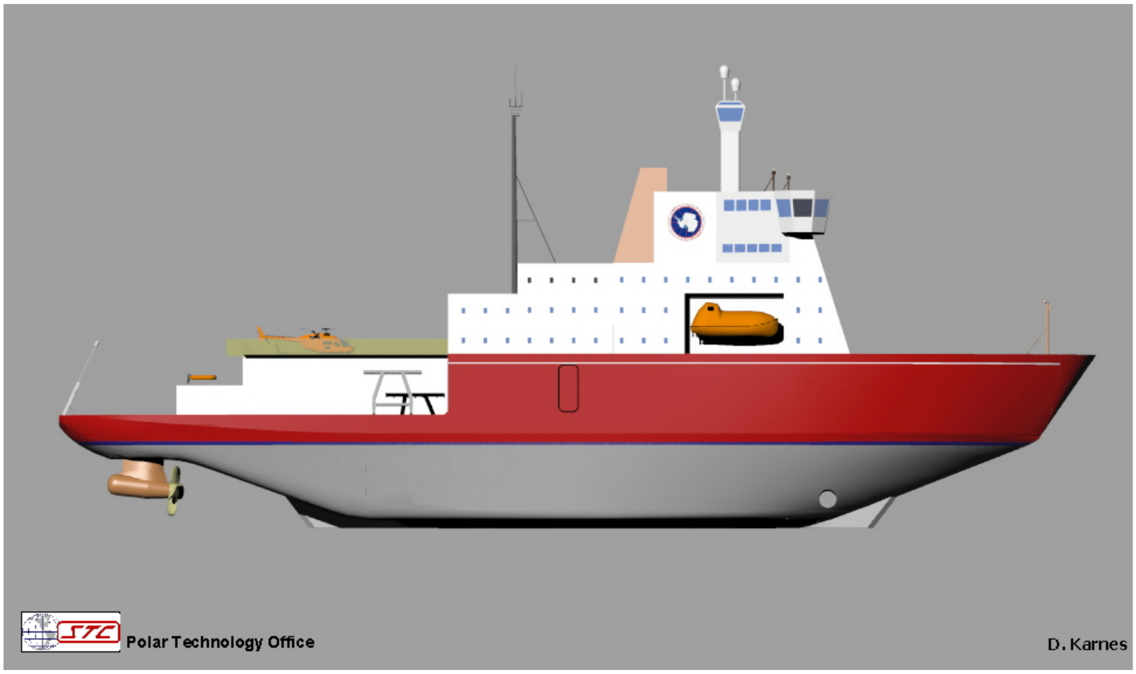

Figure 16. PRV outboard profile

6.1 PRV PRINCIPAL CHARACTERISTICS

Initial design work on the Polar Research Vessel arrived at the principal characteristics listed in Table 3.

Table 3. PRV Principal characteristics

Length, overall	378.4	ft
Length, waterline	340.9	ft
Beam	74.5	ft
Draft	29.6	ft
Displacement	11,000	LT

6.2 PRV POWER PLANT

The PRV employs a diesel-electric propulsion plant consisting of four main diesel-generator sets, two of 8046 HP and two of 6785 HP with a total brake power at MCR (100%) of 29,600 HP (22 MW). This distribution provides greater flexibility over a set of four equally sized diesel generators. These direct power to a common bus/integrated electric system. This AC-AC system uses frequency converters. In addition, one harbor diesel-generator set and one emergency diesel-generator set are included.

Propulsors on the PRV take the form of two azimuthal propeller pods. Each of these two electric (AC) podded units draws 11,200 HP (9.4 MW). They use an electro-hydraulic or electric steering gear and remote control system. Each pod drives one stainless steel four-bladed open fixed-pitch propeller measuring 17.78 ft in diameter. During icebreaking, these turn at 112 RPM.

For added maneuvering and station keeping, a bow thruster is also provided. This can be seen in Figure 16. The bow thruster was mounted in the hull to prevent bubble sweepdown in line with the bottom-mapping arrays and other acoustic sensors.

6.3 PRV PERFORMANCE

General performance data for the PRV are shown in Table 4.

Table 4. PRV Performance

Level Icebreaking Capability @ 3 kt	4.5 kt
Maximum Open Water Speed	18.5.kt
Endurance Speed	12.0 kt
Endurance	80 days/20,000 miles
Crew	22
Total Complement	80
Ice Class	ABS A3 (IMO Guide - PC3)

6.4 ICE CLASSIFICATION

Further information about American Bureau of Shipping (ABS) ice classification is presented in Table 5.

Table 5. Ice Classification (American Bureau of Shipping)

Location	ABS A2	ABS A3
Arctic Offshore Shelf	Independently August through October	Independently July through December
Central Arctic Basin	Independent operation not allowed Escort by A4 or higher, July through November	Independently July through September for short term, short distance Escort by A4 or higher, July through November
Antarctic	Independently March through April	Independently February through May

As shown in Table 5, an ABS A3 ice classified vessel gains capability over an A2 vessel. With A3, a ship can operate independently in the Arctic offshore shelf region July through December as opposed to merely August through October for A2. Similarly, an A3 vessel could operate independently in the central Arctic basin July through September for short term, short distance, whereas an A2 vessel is not allowed independent operation at all in this region. In the Antarctic, a vessel classed A3 may operate independently February through May as opposed to only March and April for an A2 vessel. For comparison, the *Nathaniel B. Palmer* (A2) operates independently all year in first-year ice while the PRV (A3) could operate independently all year in first-year ice and enter areas with second-year ice.

6.5 PRV SCIENCE FEATURES

The Polar Research Vessel design incorporates a number of science features. Bottom mapping during icebreaking operations is made possible thanks to the box keel, which diverts broken ice floes around the forward sensors and prevents bubble sweep. The sensor array and box keel are illustrated in Figure 17 and Figure 18. It should be noted that the box keel has been sized to accommodate future growth of sensors. Geotechnical drilling is made possible by an enclosed rig within the deckhouse. A completely enclosed moon pool measuring 20 ft by 16 ft can support AUV/ROV, diving, CTD rosette, and OBS operations. In addition, a traditional set of A-frames, winches, and cranes are provided onboard.

Other science features of the PRV include enhanced towing in ice and accommodation for 50 scientists. Helicopter facilities include a landing deck on the 02 Level with an elevator down to the hangar on the main deck. (See Figure 10). For ease of operation and coordination, the starboard deckhouse control station gives a clear view aft to the starboard working deck, aft deck, and A-frames. In the laboratory spaces a science/cargo elevator operates between the main deck and the 06 level.

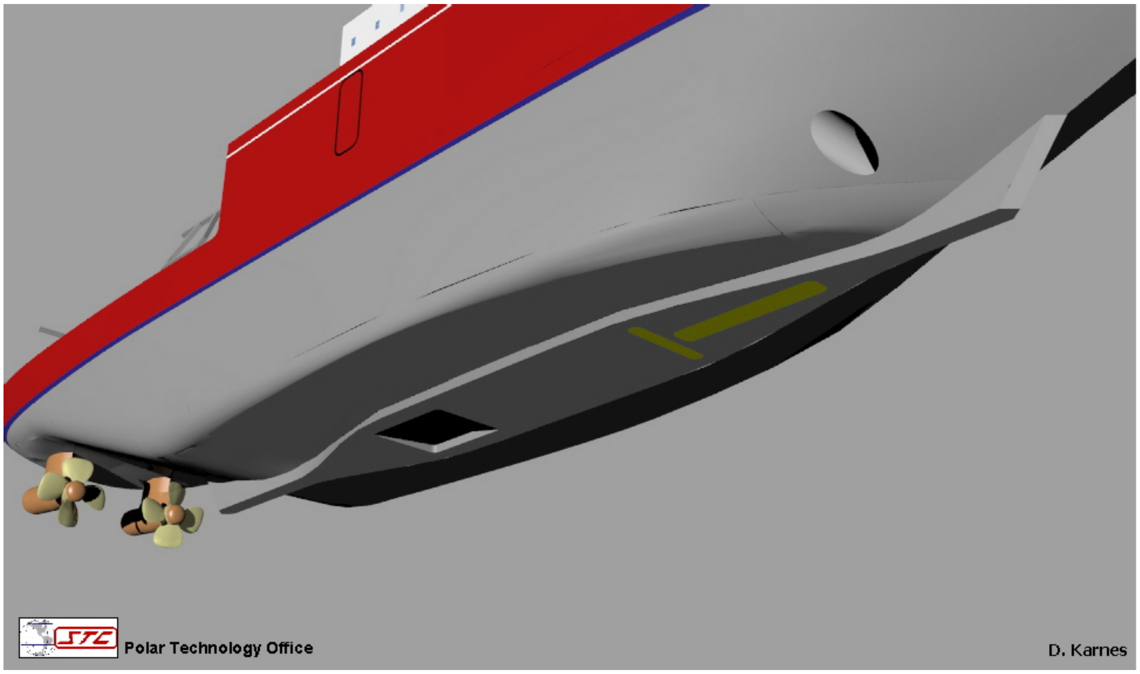

Figure 17. Underwater view of box keel

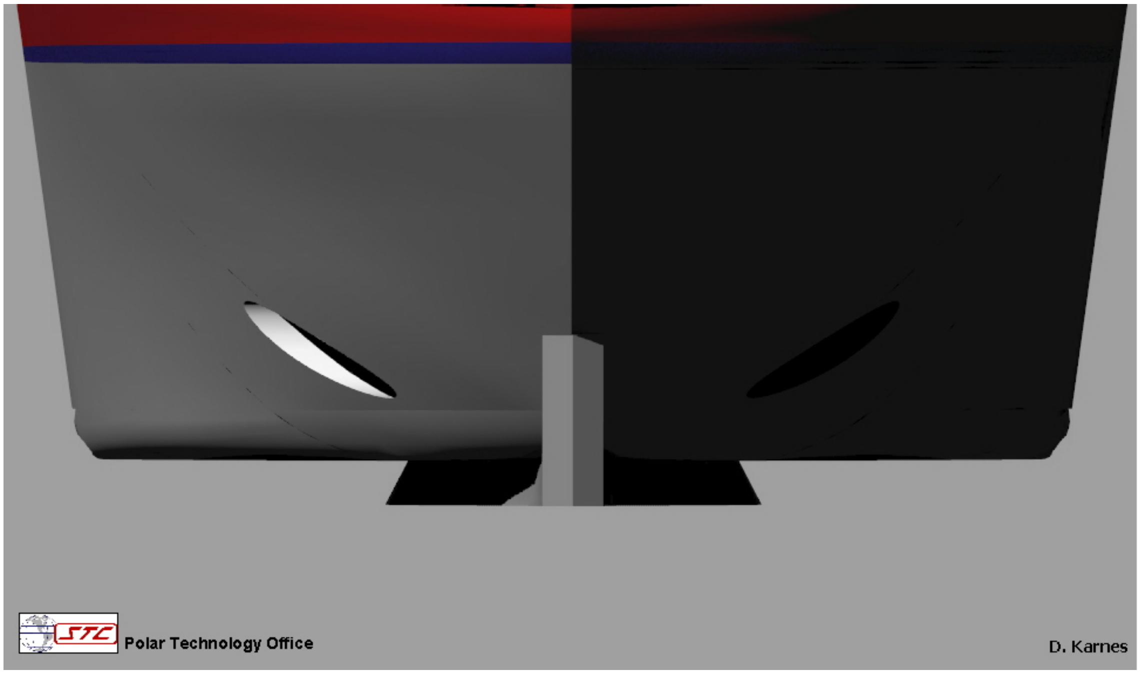

Figure 18. Head-on view of box keel

6.6 FEATURES OF MAIN DECK & 01 LEVEL

As shown in Figure 10, the deck plan in Attachment 2, the main deck and 01 level house a combined moon pool and Baltic room with a 22 ft deck height. A control room overlooks both the moon pool and the boom crane. In that same compartment, the removable lower section of the geotechnical drilling rig is located above the moon pool. Above the 02 level, the drill rig is permanently installed. Extending forward from the moon pool/Baltic room, an 8 ft-wide corridor connects the laboratory spaces, as shown in the deck plan in Attachment 2. At the aft end of the compartment, a garage door connects the Baltic room with the starboard side deck. Winches on the 01 level service the moon pool, the starboard A-frame, and the boom crane. Space for a dedicated microscope room has also been designated on the main deck.

6.7 COMPARISON OF LABORATORY SPACES BETWEEN PRV & NBP

The PRV has significantly greater laboratory spaces than the NBP. This was partially driven by the increased complement of researchers, although much of the added space lab space was provided because the larger ship allowed it. A comparison of lab spaces aboard NBP and PRV is shown in Table 6.

Table 6. Comparison of laboratory spaces aboard NBP and PRV

Laboratory Space	NBP (ft^2)	PRV (ft^2)	% increase
Dry Lab (main)	1,121	2,234	99%
Data Acquisition System / Electronics Lab	1,261	3,520	179%
Hydro Lab	445	792	78%
Bio Lab	524	885	69%
Computer Lab / LAN office / electronic storage	883	1,936	119%
Wet Lab	380	763	101%
Baltic Room / Moonpool	660	2,424	267%
Aquarium Lab	288	270	-6%
Science Refrigerator / Coolers	152	224	47%
Science storage	505	1,548	207%
Workshop	142	231	63%
Open workdeck	4,062	5,411	33%

As can be seen from the table, all areas increased from NBP to PRV except for the aquarium lab. The design of PRV's aquarium lab is thought to be of greater utility, more closely resembling that aboard the *Laurence M. Gould* than that of the NBP. It should be noted that at this early stage of design, these laboratory spaces would undergo changes with greater refinement of science requirements.

6.8 ADDITIONAL VIEWS OF PRV

Figure 19. Starboard stern quarter

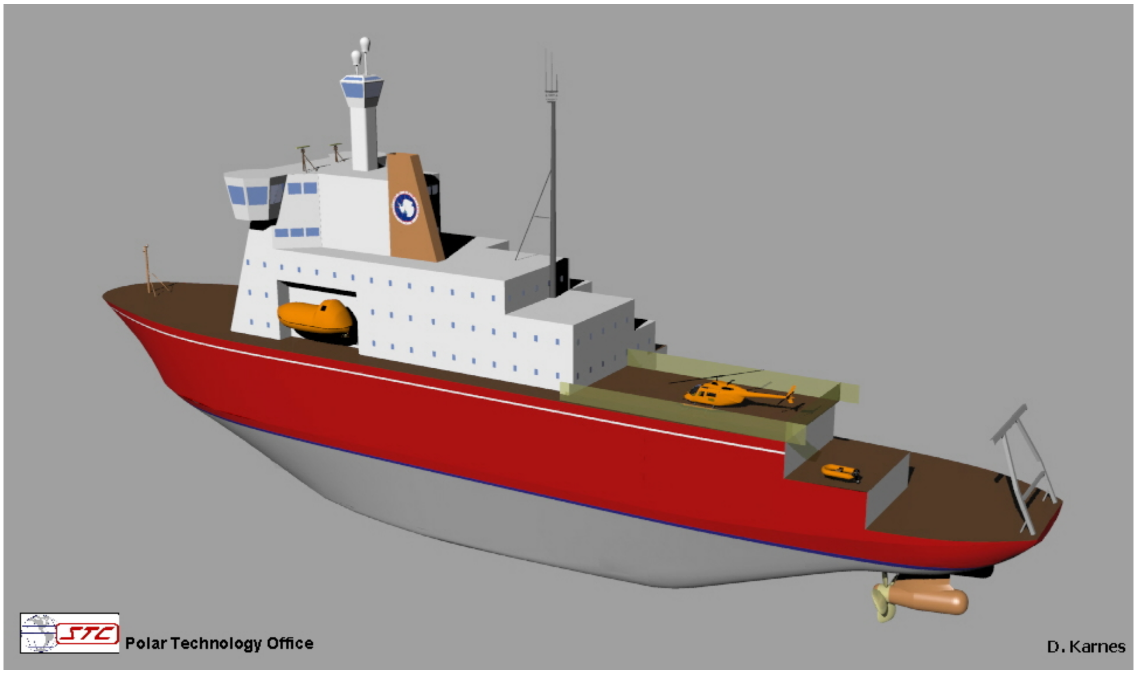

Figure 20. Port stern quarter

7. COST ESTIMATE

7.1 APPROACH TO COST ESTIMATING

The vessel cost estimate is a typically challenging task for so early a stage of design. Since the manufacturers of the propulsion system, ship's outfit and the list of major science equipment are not determined yet, any direct cost calculation based on labor, cost of material and cost of equipment can not be done. Some other methods need to be applied.

The general approach was to perform the cost estimate for NBP in currentdollars as a reference data point and estimate the cost for PRV. Comparison of costs of NBP to PRV would enable analysis of the effect of increasing endurance and icebreaking capability on ship cost.

7.2 COST ESTIMATING PROCEDURES

No universal method for estimating vessel cost at the initial design stage is known. Therefore, several alternative methods were used in the current study.

- Initial weight estimates for different weight groups for cost per ton multipliers for materials and labor
- Glosten Associates cost formulation based on regression of research vessels incorporating cubic number and horsepower (developed for ARV)

- Initial weight estimates for different weight groups and cost per ton multipliers for those groups developed by STC based on average data for previously designed vessels fitted with diesel-electric fixed shaft and podded propulsion plant

7.3 COST ESTIMATE FOR NBP TODAY

There was no comprehensive information on the cost of construction of NBP versus actual ship price. The only data available were the cost of NBP obtained from ECO in 1992 dollars and estimated at $44 million.

Cost of NBP based on Glosten Associates formulation for the ARV from a regression of vessel costs was $80 million for the 1992. This cost was used for further analysis because ECO cost estimate was conducted using different method unavailable for this study.

The cost escalation factor from 1992 to 2003 is 1.238 and is based on 11 years of producer price index for shipbuilding and repair industry. Using the above factor the cost of NBP in 2003 dollars would reach $55 million based on ECO estimate or $99 million based on Glosten Associates formulation estimate.

7.4 COST ESTIMATE FOR PRV

The cost estimate has been developed independently by Science and Technology Corporation and the U.S. Maritime Administration for a vessel that is at an initial design stage

The range of cost is projected to be $155 - $179 million based on 2003 dollars based on calculations by Science and Technology Corporation and the U.S. Maritime Administration

7.5 COMPARISON OF COSTS OF NBP TO PRV

Comparison of costs of NBP to PRV is presented in Figure 21. As one can see from the plot in Figure 22 the cost difference is almost 69%. However, the new vessel is quite different in size, mission capabilities and science features. This is illustrated in Table 7.

7.6 EFFECT OF INCREASING ENDURANCE AND ICEBREAKING CAPABILITY ON SHIP COST

The effect of increasing endurance and icebreaking capability on ship cost was investigated using the developed synthesis design model. In other words, several ships were designed with icebreaking capability ranging from 3 ft to 5 ft at 3 kt speed. Two endurance levels, 15,000 nm and 20,000 nm were used for each variation of icebreaking capability. The cost sensitivity to those features is presented in Figure 22. PRV cost sensitivity analysis. This analysis has shown clearly that icebreaking capability has the most significant effect on ship cost because it significantly drives the shaft power and the size of the vessel.

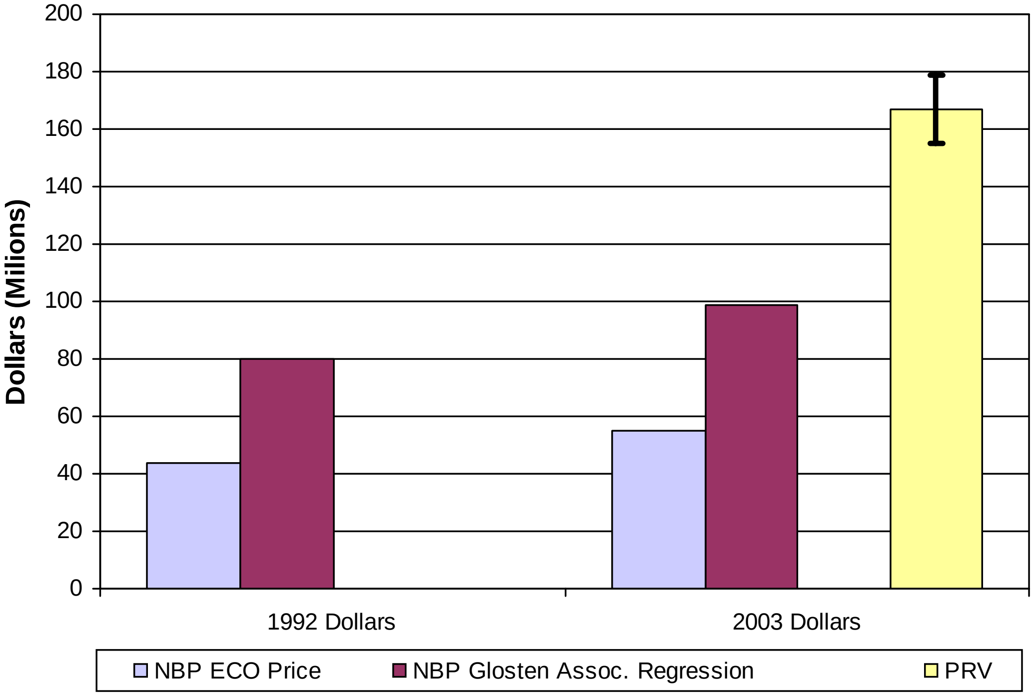

Figure 21. Cost of PRV and Nathaniel B. Palmer in 2003 dollars.

Table 7. Some Comparisons of NBP to PRV

	NBP	PRV	Increase
Displacement (LT)	**6,800**	**11,000**	**62%**
Shaft Power (HP)	**12,600**	**22,500**	**79%**
Icebreaking capability (ft)	**3**	**4.5**	**50%**
Total lab space (sq ft)	**5,714**	**13,048**	**128%**
Accommodations for scientists	**38**	**50**	**32%**
Endurance (NM)	**15,000**	**20,000**	**33%**
Cost ($ millions)	**99**	**167**	**69%**

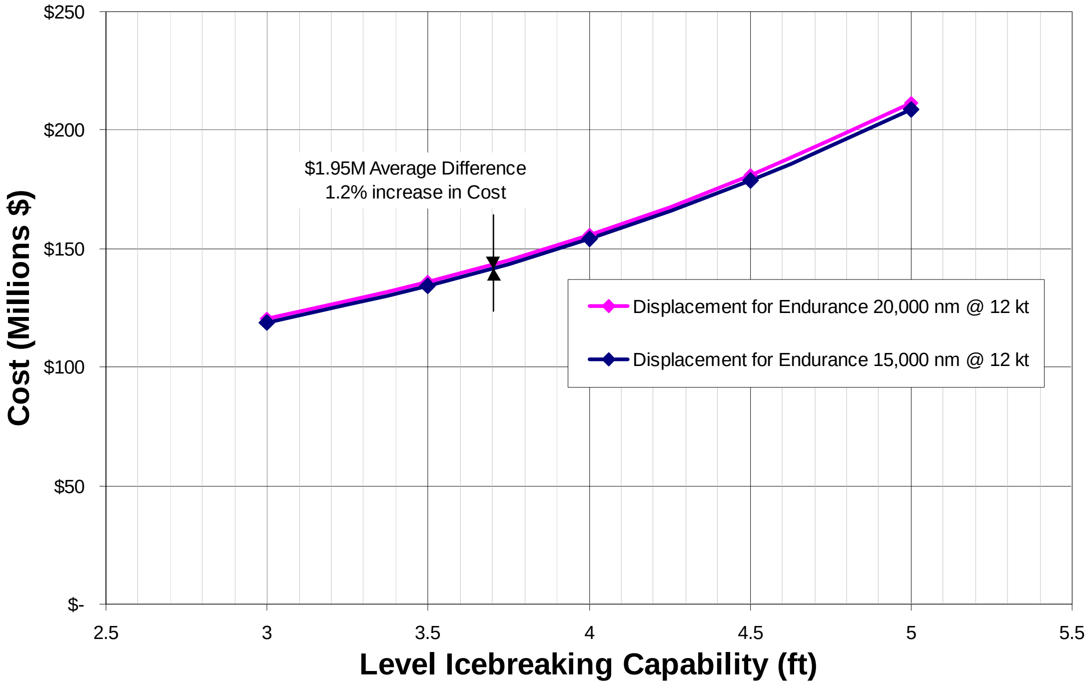

Figure 22. PRV cost sensitivity analysis.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The performed special studies and PRV design efforts enable us to draw two groups of conclusions. The conclusions from the special design studies were:

- Clearing the ship's track remains a technical challenge. A combination of azimuthal thrusters and stern arrangements may result in safer and more reliable towing in ice.
- Bubble sweepdown is a bigger problem for bathymetry than are ice pieces and can be handled with a box keel with reverse flared sides. Deep draft is an advantage for both bubble sweepdown and ice. Proper bow form and stern form can guide ice around arrays to some extent.
- The most efficient propulsion machinery which meets both icebreaking requirements and station-keeping requirements for geotechnical drilling is an azimuthal propulsion system based on diesel-electric integrated power plant.

The main conclusions from the PRV design were:

- Icebreaking capability has a major impact on ship's size, power and cost.
- In order to meet initial operational requirements the new vessel must be significantly bigger (over 60%) than *Nathaniel B. Palmer*.
- At the increased size of the vessel it is feasible to deploy all required science capability and substantially increase the laboratory space and work deck area on the ship.
- The moon-pool size and required operations through the moon-pool dictate the vessel main arrangements.

The performed feasibility design studies were based on the initial operational requirements provided for the design team. At the current design level the efforts were focused on those most critical for ship design set of requirements. As a result of the special studies and design efforts it was confirmed that a new vessel can be designed to meet those requirements. However, since the design cycle could not be completed at this stage (stability, weight estimate, etc.), additional design efforts should be conducted to confirm that the new ship is feasible.

8.2 RECOMMENDATIONS

The following recommendations can be given for the next design stages.

Clarify Science and Operational Requirements. The most important issues are as follows

- Icebreaking capability
- Operational requirement for geotechnical drilling
- Number of boats, size, seaworthiness, method of launch and recovery
- Requirements for moon pool including size, associated support space and equipment
- Endurance
- Seakeeping requirements
- Acoustically quietness requirements

Continue special technical studies

- Propulsion and machinery study to select the propulsion units, diesel-generator manufacturer and entire propulsion plant vendor
- Geotechnical drilling
- Methods to reduce the noise

Complete feasibility study and refine the cost estimate

Develop the multi-year project plan

9. REFERENCES

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