MAR-750-002

Mission Sensitivity Studies for the Polar Research Vessel

U.S. Maritime Administration, Washington, D.C. April 2004

Address correspondence to:

U.S. Maritime Administration
MAR-760 - Room 8101
400 Seventh Street, SW
Washington, DC 20590

Phone: (202) 366-0006
Fax: (202) 366-7197

Contracting Officer's Technical Representative (COTR): Mr. Richard Voelker

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE April 2004	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE Mission Sensitivity Studies for the Polar Research Vessel	5. FUNDING NUMBERS
6. AUTHOR(S) James St. John, Aleksandr Iyerusalimskiy, David Karnes	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Science and Technology Corporation 10 Basil Sawyer Drive Hampton, Virginia 23666–1336	8. PERFORMING ORGANIZATION REPORT NUMBER 6000-013
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Maritime Administration Room 2109 MAR-750 400 Seventh Street, SW Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER MAR-750-002
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This Report details the results of mission sensitivity studies for the Polar Research Vessel (PRV). A design synthesis model, originally created in 2003 for the PRV feasibility design studies, was enhanced in order to use it for the mission sensitivity analyses. In addition, early efforts further developed the general arrangements of the main deck and 01 level from the 2003 feasibility design study to reflect input from the science community. This Report closes with a look at remaining issues and future activities in the PRV project.

	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

FOREWORD

The Science and Technology Corporation (STC) is pleased to submit this draft Report entitled *Mission Sensitivity 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 results of the mission sensitivity studies conducted and the synthesis model used in the process. The authors gratefully acknowledge the support and encouragement of the Contracting Officer's Technical Representative for the work, Mr. Richard Voelker, Office of Shipbuilding and Marine Technology, U.S. Maritime Administration.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

The 2004 effort on the Polar Research Vessel (PRV) picked up where the 2003 efforts left off, with a feasibility design. Work began on the next iteration of the PRV design to incorporate input from the Antarctic Research Vessel Oversight Committee (ARVOC). Deck arrangements were accordingly modified for the Main Deck and 01 Level. After progress had been made, the PRV tasking was redirected to pursue sensitivity studies of vessel construction costs for various mission requirements. This consisted of expanding and refining a synthesis model created in 2003. The 2003 model was developed to understand the effects of certain mission requirements, but did not take into account all of the aspects needed for a full understanding of ships requirements. Unlike the original model, the more complex 2004 model develops feasible vessel characteristics for any desirable mission capability. It has addiional built-in algorithms to generate the necessary information for the mission sensitivity analyses.

This Report provides an overview of the 2004 PRV efforts, including the arrangements changes from 2003 with rationale, a description of the synthesis model as it existed in 2003, the changes made to the model, a description of each module in the model, results from the current model, and remaining issues and future activities.

2. ARRANGEMENT CHANGES FROM 2003

Efforts in 2003 produced one iteration of a feasible design for the PRV. This design package included deck plans for the Main Deck and 01 Level. These drawings were modified in 2004 to incorporate input from ARVOC and the polar science community on the general arrangement of the vessel. Modifications and design rationale are outlined below.

- The moon pool size was reduced and moved aft of the Deckhouse. The 2003 moon pool and built-in drill rig occupied prime real estate in the laboratory spaces at the center of the PRV. This approach was deemed a disproportionate emphasis on the geotechnical drilling mission and Automatic Underwater Vehicle/Remote Operating Vessel (AUV/ROV) operation. The scientists had concluded that these operations would be done on some cruises, but should not detract from the science disciplines and operation more routinely done. In 2004, the moon pool size was reduced and moved outside the Deckhouse as far aft as possible while still passing through the box keel on centerline. This arrangement allows geotechnical drilling rigs to be installed temporarily when necessitated by research requirements. Keeping the moon pool on centerline is the best placement for vessel stability and minimizes the effects of ship roll on drilling and AUV/ROV operations.

- The starboard side of Deckhouse was moved inboard. In order to accommodate jumbo piston core equipment, a walkway was designed into the starboard side of the Deckhouse on the Main Deck.
- The helicopter hangar was moved to the 02 Level. Instead of installing an elevator to service the helo hangar on the Main Deck, the helo hangar was shifted to the 02 Level forward of the landing pad. As a result, the compartment layout on the aft Main Deck was modified in such a way as to provide more open deck space.
- The stern at the Science Deck was made more rectangular to maximize usable workspace and to better accommodate standard practices with respect to monitoring payload launch and recovery from the aft A-frame.
- Winch placement was modified to better service required functions.

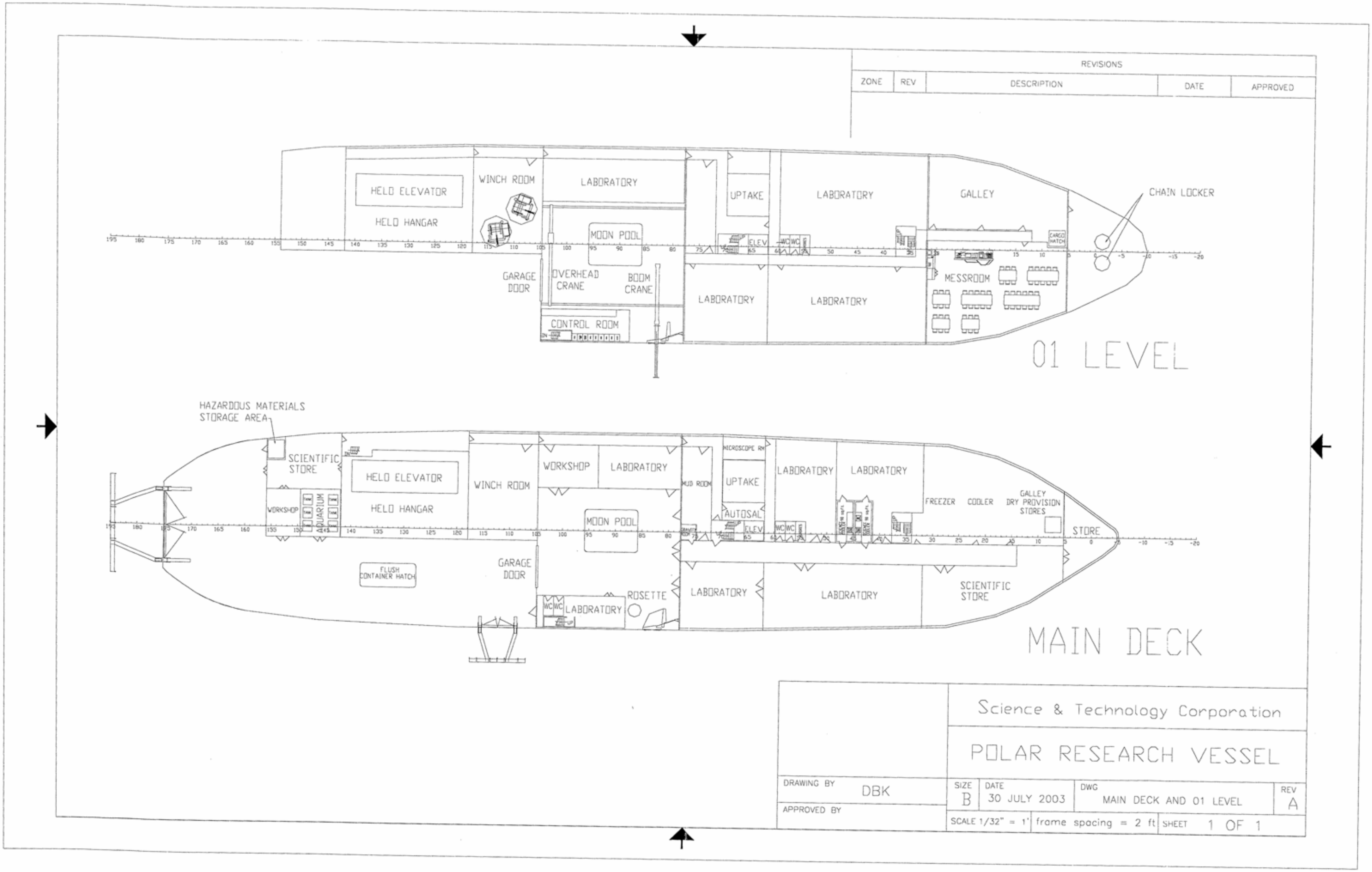

Figure 1. Main deck and 01 level for PRV - 2003 design

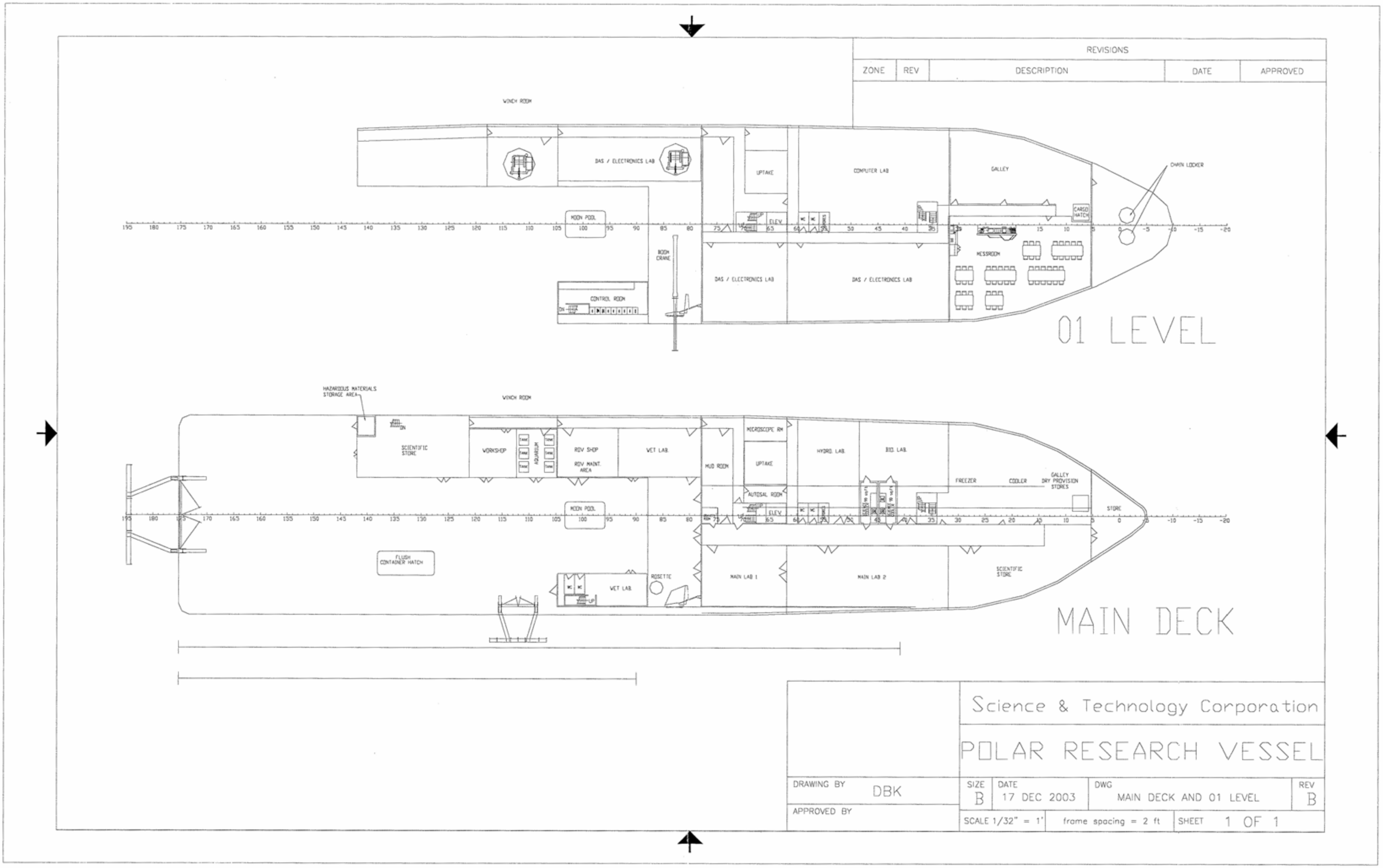

Figure 2. Main deck and 01 level for PRV – 2004 design

3. OVERVIEW OF MODEL AS IT EXISTED IN 2003

The 2003 effort on the PRV was focused on design studies to examine the feasibility of incorporating the science missions determined by ARVOC and the science community into a new ship. During those studies, STC was tasked to show what effect icebreaking capability and endurance had on ship size. Rather than developing multiple designs simultaneously to answer this question, the salient features of the design were incorporated into a design synthesis model. The effort for developing the model paid off when many design alternatives could be explored quickly by varying the required endurance and icebreaking capability. The model included open water and icebreaking resistance prediction routines, a weight estimate routine with a balance of weight and displacement, and a powering routine that selected a propeller and predicted performance. The powering routine estimated hotel load and computed fuel consumption and endurance. A simple cost algorithm was also included based on cubic number and installed horsepower taken from the prior Arctic Research Vessel studies for NSF.

The design synthesis model determines the solution, a set of design characteristics for the ship, by optimization of an objective function (minimum displacement for this model) using direct search methods starting from a set of initial conditions. Since the model is posed as a constrained non-linear optimization problem, many of the desired performance parameters are constraints, e.g. make the endurance for this ship exactly equal to the input value of 20,000 nm. There were only three main independent variables in this model; beam, icebreaking shaft rpm, and the shaft rpm at 12 kt for cruising. The hull form was assumed to be as that developed for the PRV and the length-to-beam and beam-to-draft ratios were fixed based on the *Nathaniel B. Palmer* (*NBP*). The model was run for two different endurance cases, 15,000 nm (*NBP* current capability) and 20,000 nm, and a range of level icebreaking capabilities from 3 to 5 ft. Results showed the change in ship characteristics and relative cost for a parametric variation of the endurance and icebreaking capabilities.

4. CHANGES MADE TO THE MODEL IN 2004

Since its initial development in 2003, the research vessel (RV) model had undergone substantial changes that have both refined and expanded its capabilities. The focus of the model has shifted from that of performing weight/displacement balance calculations to one of producing feasible vessel designs optimized for minimum cost to be used in sensitivity analyses. Toward this end, more detailed weights and centers have been added to the weights module. A volume check of required volume versus available volume has been added. The stability module has been added to include a check of intact stability. User ability to select specific Azipod units is a recent development. With this information, more detailed performance characteristics, weights, and centers are available.

In addition, selectable features with segregated effects were added to the RV model since 2003 to incorporate ARVOC-dictated mission requirements. These features can be turned on or off in the model via user input. They include a box keel for bottom-mapping while breaking ice, a double hull to adhere to IMO Arctic Guidelines, weight and stability allowances for geotechnical drilling capability, an expanded moon pool for deployment and recovery of ROVs and AUVs, diesel exhaust emissions reduction, and sufficient length for 50m and 80m jumbo piston coring operations. More detailed descriptions of individual modules follow.

5. DESCRIPTION OF EACH MODULE AS IT CURRENTLY EXISTS

The refined RV model optimizes feasible designs for the minimum construction cost by varying several independent quantities within a constrained range. These variable quantities include the length/beam ratio, beam/draft ratio, waterline beam, propeller rpm during open water cruising and icebreaking, and propeller diameter. The model is composed of several interrelated modules, each has an Excel worksheet in the file, that individually draw data from one another and form a summary sheet of principal characteristics. After operating on the data, they output important information to the summary sheet. The RV model modules include principal characteristics, costs, propellers, engines, pods, hull and superstructure volumes, weights and centers, icebreaking performance, open water performance, and stability. Brief descriptions follow.

The principal characteristics worksheet/module serves as a convenient output for the most important descriptive information about the vessel design and as the model's control interface. The worksheet displays a summary of the ship's principal characteristics, propulsion and performance characteristics, endurance and tankage, hull form characteristics, propeller characteristics, and manning. Its control functions take the form of user-input values for various required quantities and selected features, e.g., box keel, geotechnical drilling capability, and double hull. Additional control is designed into the model via constraints imposed on the solver function, which is run from the principal characteristics sheet. An example of the principal characteristics worksheet is presented in Table 1. The lightly shaded boxes indicate the independent variables that are manipulated during the optimization. The cost in the lower center is the optimization function (minimum). The darkened blocks are the inputs. Constraints are shown in the lower right-hand corner and there are also some of the independent variables where noted.

Table 1.Principal Characteristics Module for 3 ft Level Icebreaking Baseline Ship

Principal Characteristics					
Length Overall	306.4	ft	93.4	m	
Length Between Perpendiculars	276.0	ft	84.1	m	
Waterline Length	276.0	ft	84.1	m	
Extreme Beam	64.31	ft	19.6	m	
Waterline Beam	62.77	ft	19.1	m	
Design Draft	26.15	ft	7.97	m	
Appendage Draft	26.15	ft	7.97	m	
Depth of Hull (mn dk to keel)	37.15	ft	11.3	m	
Total Depth (to bottom of appendage)	37.15	ft	11.3	m	
Freeboard at Science Deck	11	ft	3.35	m	
Deck Height	11	ft	3.35	m	
Hull Displacement	0	LT	0	Tonne	
Appendage Displacement	0	LT	0	Tonne	
Moon Pool Displacement	0	LT	0	Tonne	
Bow Thruster Displacement	-33	LT	-33	Tonne	
Total Displacement	-33	LT	-33	Tonne	
Propulsion and Performance Characteristics					
Brake Power @ MCR	12092	HP	9021	kW	
Hotel Load	4159		3102	kW	
Brake Power for Propulsion @ MCR	7934	HP	5919	kW	
Transmission Efficiency	92%				
Shaft Power @ MCR	7299	HP	5445	kW	
Percent of MCR to Meet Icebreaking	90%				
Icebreaking Propeller Speed	110	rpm	110		250
Endurance Speed	12	kt	6.18	m/s	
Endurance Propeller Speed	138	rpm			
Maximum Speed	14.15	kt	7.28	m/s	
Maximum Ship Speed Propeller Speed	166	rpm			
Level Icebreaking Capability	3	ft	0.91	m	
Endurance and Tankage					
Endurance Time	60	days			
Endurance Range	15000	nm			
Fuel Density	7.078	lb/gal			
Fuel Margin Returning to Port	10%				
Ballast to Fuel Ratio	100%				
Double Hull	no				
Appendage	no				
Moon pool	no				
Bow Thruster	yes				
Emissions reduction	no				
SHALDRIL	no				
80 meter Jumbo piston core	no		Cost		
50 meter Jumbo piston core	no	$	72.2	M	

Hullform Characteristics					
Stem angle	21	deg			
WL entrance angle at FP	45	deg			
Flare angle at FP	68	deg			
Flare angle at station 2	52	deg			
Midships flare angle	8	deg			
Block Coefficient	0.5498				
Appendage Block Coefficient	0.2263				
Ratio of WLBeams at Pods/CL	90%				
Length/Beam Ratio	4.40				>=4.2, <=5
Beam/Draft Ratio	2.40				>=2.4, <=3
Propeller Characteristics					
PropellerDiameter	14.10	ft	4.297	m	
Propeller Maximum Diameter	15.69	ft	4.783	m	
Number of Propellers	2				
Number of Blades	4				
Relative Blade Thickness	0.09				
Expanded Area Ratio	0.85				
Pitch/Diameter Ratio	0.700				
Pod Size	13		3	index	
Pod Max Torque	79.1	LT-ft			
Towrope Pull	70.5	LT	71.7	Tonne	
Manning					
Crew Complement	22				
Science Complement	37				
Spare Space	6				
Total Complement Including Spa	65				
Constraints					
Displacement/Weight Balance	0	LT			>=0
Volume Balance	114560	ft^3			>=0
Beam Balance	10.33	ft			>=0
Icebreaking Balance	0.00	ft			=0
Endurance Balance	0.00	HP			=0
Maximum Speed Balance 1	0.00	HP			=0
Maximum Speed Balance 2	0.00	HP			=0
Pods Fit Hull	10.77	ft			>=0
Propeller Torque Limit	15.5	LT-ft			>=0
GM	2.00	ft			>=2
minimum length for Jumbo piston core	0.0	ft			<=LBP

The costs module estimates material and labor costs for steel, outfit, and machinery. Other various design and construction costs are considered, including fixed costs exclusive of base.

The propeller module computes propeller characteristics in icebreaking, cruising open water, and full speed open water conditions. It also estimates the weight of a propeller for a given diameter to output to the weights module. It outputs power data to the icebreaking and open water performance modules.

The engines module calculates the required engine room dimensions based upon the brake power at maximum continuous rating (MCR). It inputs the brake power at MCR from the principal characteristics sheet and outputs the minimum beam.

The pods module consists of a table of characteristics for standard Azipod units. It includes pod lengths, minimum and maximum propeller diameters, maximum power, maximum and minimum shaft speeds, and maximum torque. In addition, pod weights and centers are given. The principal characteristics and weights modules refer to this worksheet for data.

The hull and superstructure volume module performs a volume check on the design. It determines whether there is sufficient volume in the hull and superstructure for all of the required spaces. It estimates required volumes based on ship dimensions listed in the principal characteristics module. It also provides output to the principal characteristics worksheet.

The weights module computes vertical and some longitudinal moments from the lightship and deadweight categories. It draws from and outputs to the principal characteristics module as well as outputting KG to the stability module.

The icebreaking performance module draws from the principal characteristics and propeller modules to calculate the thickness of ice breakable at speeds of 2 and 3 knots. It also calculates maximum permissible power and required beam for pods. It outputs to the principal characteristics module.

The open water performance module draws information from the principal characteristics and propeller worksheets to compute fuel consumption endurance at cruising speed, fuel consumption rates, and required fuel capacities. It outputs to the weights module by way of the principal characteristics worksheet.

The stability module computes GM from appropriate vessel characteristics to check stability. GM is metacentric height, the distance between the center of gravity of a ship (G) and its metacenter (M). The GM is output to the principal characteristics module. There is a constraint in the model for the minimum allowable GM.

6. RESULTS FROM CURRENT MODEL

The RV model was run systematically for several different configurations of science features. Ships with level icebreaking capabilities of 3 feet, 4 feet, and 4.5 feet were considered. For each level, the model was run for a baseline ship that did not include any of the selectable features (box keel, double hull, moon pool, diesel emissions reduction, geotechnical drilling, accommodations for 50 scientists, 80 days endurance, and 80m jumbo piston core). The baseline ship accommodates 37 scientists and has an endurance of 60 days. In addition to the baseline cases, runs were made for vessels at each icebreaking capability with each of the individual selectable features listed above. This was done to gauge the sensitivity of vessel construction cost due to each individual feature. These results are plotted in Figure 3, Figure 4, and Figure 5.

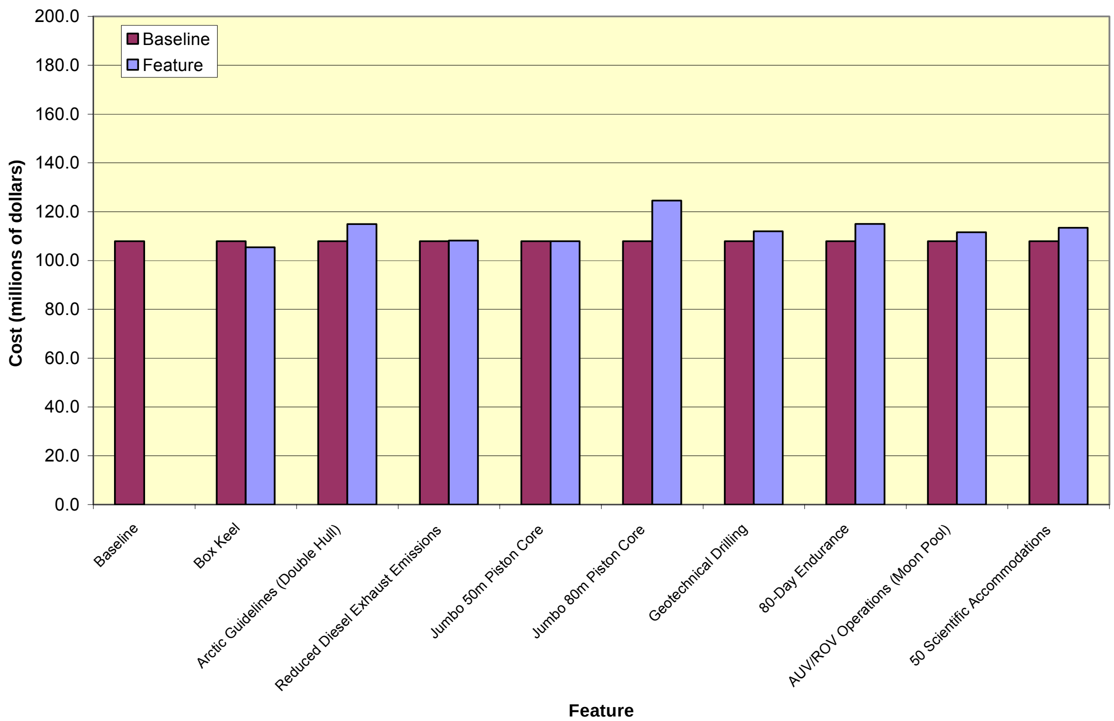

Figure 3. Sensitivity of Construction Cost Due to Individual Science Features for a Vessel with 3 Ft Level Icebreaking Capability

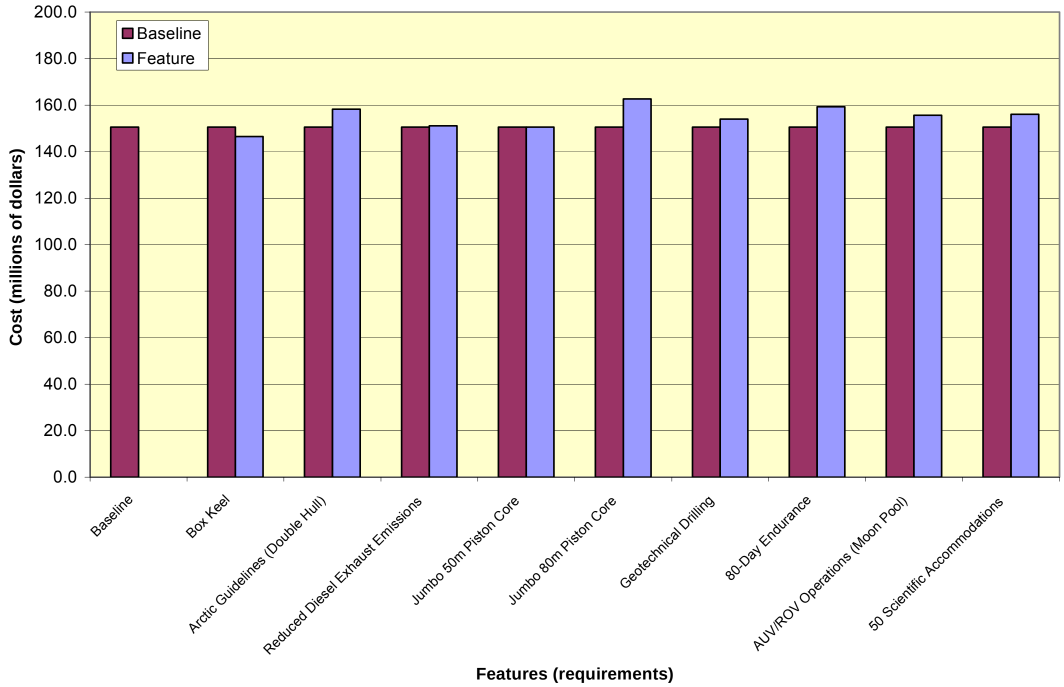

Figure 4. Sensitivity of Construction Cost Due to Individual Science Features for a Vessel with 4 Ft Level Icebreaking Capability

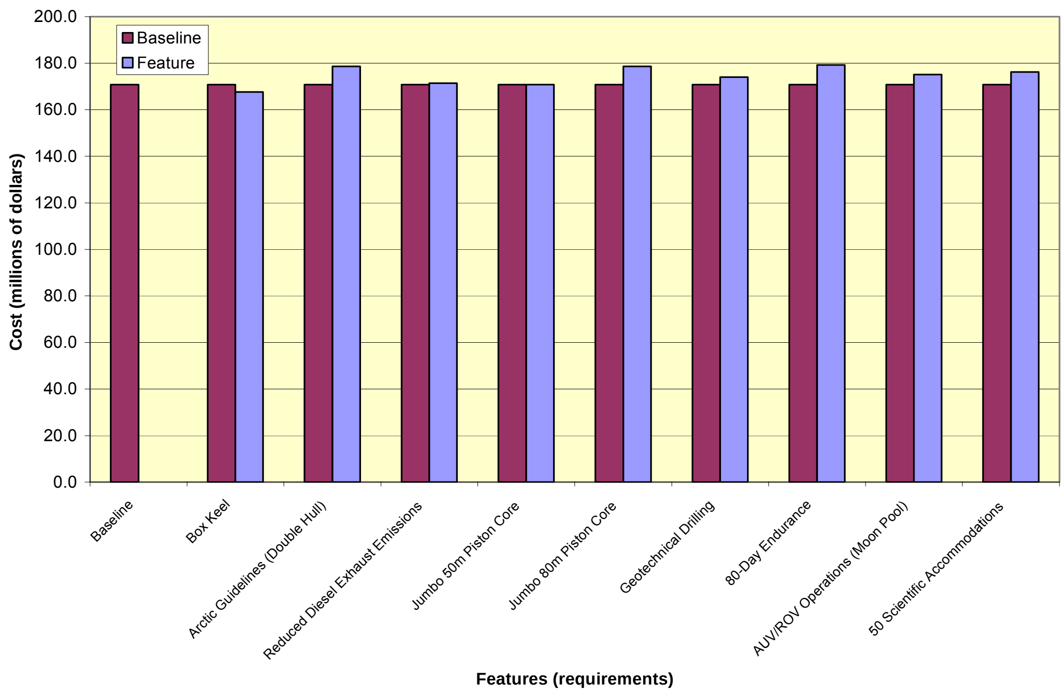

Figure 5. Sensitivity of Construction Cost Due to Individual Science Features for a Vessel with 4.5 Ft Level Icebreaking Capability

Besides the baseline and individual feature cases, the model was run for various combinations of features. These runs for 3 ft level icebreaking capability are summarized in Table 2. Similar combinations for icebreaking capabilities of 4 ft and 4.5 ft were run as well. The construction costs for each of these variations were compared with the baseline of that icebreaking capability and also the 3 ft baseline. These data are presented in Table 3, Table 4, and Table 5.

Table 2.
Combinations of Features Run for Vessel with 3 ft Level Icebreaking Capability

	Level icebreaking	Box keel	Reduced diesel emissions	Length for 50 m jumbo piston core	50 science accommodations	80 days endurance	SHALDRIL capable	Expanded moon pool	Double hull	Length for 80 m jumbo piston core
baseline	3 ft	○	○	○	○	○	○	○	○	○
	3 ft	●	●	●	○	○	○	○	○	○
	3 ft	●	●	●	●	○	○	○	○	○
	3 ft	●	●	●	○	●	○	○	○	○
	3 ft	●	●	●	○	○	●	○	○	○
	3 ft	●	●	●	○	○	○	●	○	○
	3 ft	●	●	●	○	○	○	○	●	○
	3 ft	●	●	●	●	●	○	○	○	○
	3 ft	●	●	●	●	●	●	○	○	○
	3 ft	●	●	●	●	●	●	●	○	○
	3 ft	●	●	●	●	●	●	●	●	○
	3 ft	●	●	●	●	●	●	●	●	●

○ = feature not selected ● = feature selected

Table 3.
Relative Construction Costs of Various Vessel Configurations with 3 ft Level Icebreaking Capability

	Level icebreaking	Box keel	Reduced diesel emissions	Length for 50 m jumbo piston core	50 science accommodations	80 days endurance	SHALDRIL capable	Expanded moon pool	Double hull	Length for 80 m jumbo piston core	Cost ($M)	% of baseline cost	% of 3 ft baseline cost
baseline	3 ft	○	○	○	○	○	○	○	○	○	107.9	100%	100%
	3 ft	●	●	●	○	○	○	○	○	○	105.7	98%	98%
	3 ft	●	●	●	●	○	○	○	○	○	111.4	103%	103%
	3 ft	●	●	●	○	●	○	○	○	○	113.0	105%	105%
	3 ft	●	●	●	○	○	●	○	○	○	109.8	102%	102%
	3 ft	●	●	●	○	○	○	●	○	○	109.8	102%	102%
	3 ft	●	●	●	○	○	○	○	●	○	112.5	104%	104%
	3 ft	●	●	●	●	●	○	○	○	○	118.8	110%	110%
	3 ft	●	●	●	●	●	●	○	○	○	122.6	114%	114%
	3 ft	●	●	●	●	●	●	●	○	○	126.8	117%	117%
	3 ft	●	●	●	●	●	●	●	●	○	135.0	125%	125%
	3 ft	●	●	●	●	●	●	●	●	●	136.9	127%	127%

○ = feature not selected ● = feature selected

Table 4.
Relative Construction Costs of Various Vessel Configurations with 4 ft Level Icebreaking Capability

	Level icebreaking	Box keel	Reduced diesel emissions	Length for 50 m jumbo piston core	50 science accommodations	80 days endurance	SHALDRIL capable	Expanded moon pool	Double hull	Length for 80 m jumbo piston core	Cost ($M)	% of baseline cost	% of 3 ft baseline cost
baseline	4 ft	○	○	○	○	○	○	○	○	○	150.6	100%	140%
	4 ft	●	●	●	○	○	○	○	○	○	147.0	98%	136%
	4 ft	●	●	●	●	○	○	○	○	○	152.5	101%	141%
	4 ft	●	●	●	○	●	○	○	○	○	155.7	103%	144%
	4 ft	●	●	●	○	○	●	○	○	○	150.4	100%	139%
	4 ft	●	●	●	○	○	○	●	○	○	152.5	101%	141%
	4 ft	●	●	●	○	○	○	○	●	○	154.5	103%	143%
	4 ft	●	●	●	●	●	○	○	○	○	161.3	107%	149%
	4 ft	●	●	●	●	●	●	○	○	○	164.8	109%	153%
	4 ft	●	●	●	●	●	●	●	○	○	170.1	113%	158%
	4 ft	●	●	●	●	●	●	●	●	○	178.9	119%	166%
	4 ft	●	●	●	●	●	●	●	●	●	178.9	119%	166%

○ = feature not selected ● = feature selected

Table 5.
Relative Construction Costs of Various Vessel Configurations with 4.5 Ft Level Icebreaking Capability

	Level icebreaking	Box keel	Reduced diesel emissions	Length for 50 m jumbo piston core	50 science accommodations	80 days endurance	SHALDRIL capable	Expanded moon pool	Double hull	Length for 80 m jumbo piston core	Cost ($M)	% of baseline cost	% of 3 ft baseline cost		
baseline	4.5 ft	○	○	○	○	○	○	○	○	○	170.8	100%	158%		
	4.5 ft	●	●	●	○	○	○	○	○	○	168.3	99%	156%		
	4.5 ft	●	●	●	●	○	○	○	○	○	173.8	102%	161%		
	4.5 ft	●	●	●	○	●	○	○	○	○	176.6	103%	164%		
	4.5 ft	●	●	●	○	○	●	○	○	○	171.6	100%	159%		
	4.5 ft	●	●	●	○	○	○	●	○	○	173.1	101%	160%		
	4.5 ft	●	●	●	○	○	○	○	●	○	176.0	103%	163%		
	4.5 ft	●	●	●	●	●	○	○	○	○	182.2	107%	169%		
	4.5 ft	●	●	●	●	●	●	○	○	○	185.5	109%	172%		
	4.5 ft	●	●	●	●	●	●	●	○	○	190.2	111%	176%		
	4.5 ft	●	●	●	●	●	●	●	●	○	199.1	117%	184%		
	4.5 ftTable 4. Relative Construction Costs for Various Vessel Configurations with 4 Ft Level Icebreaking									●	●	●	●	●	●

○ = feature not selected ● = feature selected

Of these various vessel configurations, four of each icebreaking capability were selected for more detailed comparison. These configurations are presented in Table 6.

Table 6. Various Vessel Configurations for Further Comparison

	Level icebreaking	Box keel	Reduced diesel emissions	Length for 50 m jumbo piston core	50 science accommodations	80 days endurance	SHALDRIL capable	Expanded moon pool	Double hull	Length for 80 m jumbo piston core	Cost ($M)	% of baseline cost	% of 3 ft baseline cost
3 ft baseline	3 ft	○	○	○	○	○	○	○	○	○	107.9	100%	100%
3 ft option 2	3 ft	●	●	●	○	○	●	○	○	○	109.8	102%	102%
3 ft option 3	3 ft	●	●	●	●	●	●	○	○	○	122.6	114%	114%
3 ft option 4	3 ft	●	●	●	●	●	●	●	●	●	136.9	127%	127%
4 ft baseline	4 ft	○	○	○	○	○	○	○	○	○	150.6	100%	140%
4 ft option 2	4 ft	●	●	●	○	○	●	○	○	○	150.4	100%	139%
4 ft option 3	4 ft	●	●	●	●	●	●	○	○	○	164.8	109%	153%
4 ft option 4	4 ft	●	●	●	●	●	●	●	●	●	178.9	119%	166%
4.5 ft baseline	4.5 ft	○	○	○	○	○	○	○	○	○	170.8	100%	158%
4.5 ft option 2	4.5 ft	●	●	●	○	○	●	○	○	○	171.6	100%	159%
4.5 ft option 3	4.5 ft	●	●	●	●	●	●	○	○	○	185.5	109%	172%
4.5 ft option 4	4.5 ft	●	●	●	●	●	●	●	●	●	199.1	117%	184%

○ = feature not selected ● = feature selected

The vessel configurations in Table 6 were selected to cover a range of mission capabilities. For each icebreaking level, the baseline ship (no extra features) and the ship with all added mission capabilities were chosen. The other two options were selected as logical breakpoints in the increase of cost versus capability. Construction costs of these vessels are plotted against level icebreaking capability in Figure 6. More detailed characteristics of these selected vessel designs and those of the *NBP* are presented in Table 7.

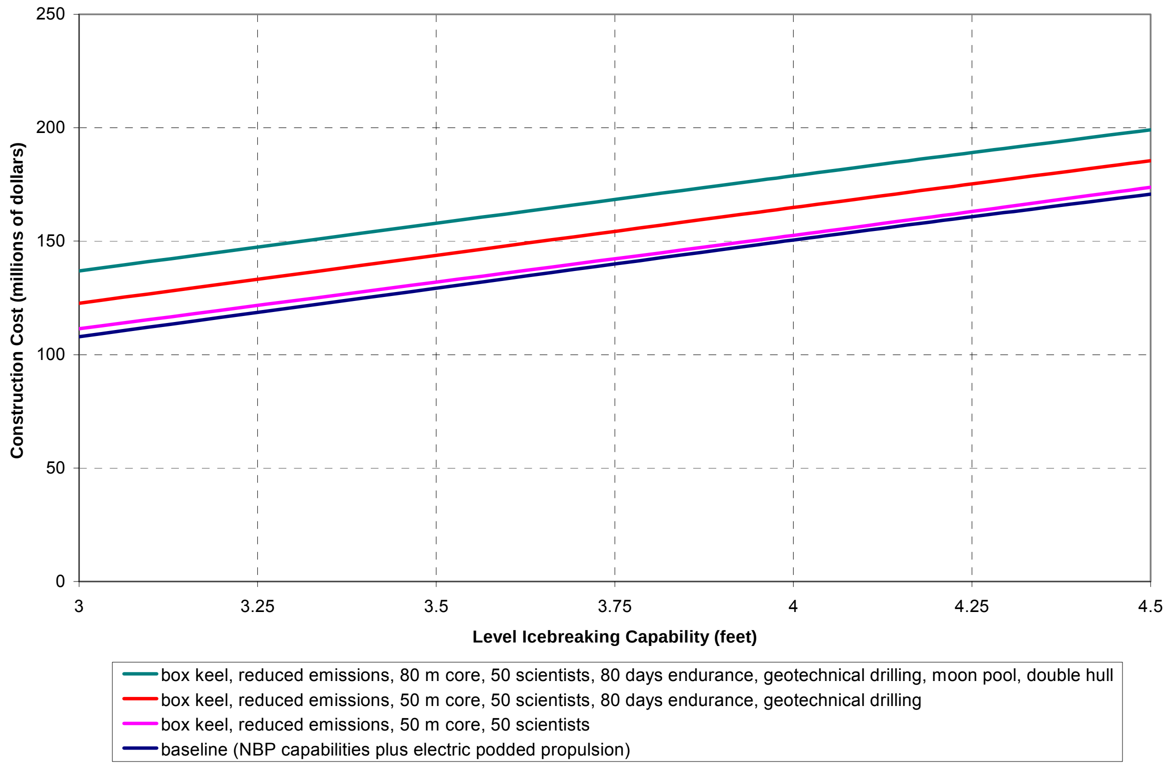

Figure 6. Construction Costs for Selected Vessel Configurations as a Function of Level Icebreaking Capability

Note that in Figure 6, the increased cost for an additional capability is independent of the icebreaking capability, but icebreaking capability has a large effect on cost.

Table 7. Detailed Characteristics of Selected Vessel Configurations

	NBP	3' baseline	3' option 2	3' option 3	3' option 4	4' baseline	4' option 2	4' option 3	4' option 4	4.5' baseline	4.5' option 2	4.5' option 3	4.5' option 4
Principal Characteristics													
Length Overall (ft)	308.5	306.4	309.6	352.9	378.4	320.9	320.5	357.3	378.4	330.0	329.9	376.4	394.5
Length Between Perpendiculars (ft)	288.0	276.0	278.9	317.9	340.9	289.1	288.8	321.9	340.9	297.3	297.2	339.1	355.4
Waterline Length (ft)	279.8	276.0	278.9	317.9	340.9	289.1	288.8	321.9	340.9	297.3	297.2	339.1	355.4
Extreme Beam (ft)	60.0	64.3	64.5	65.1	69.7	70.4	70.3	71.6	74.1	72.3	72.3	72.1	74.7
Waterline Beam (ft)	60.0	62.8	62.9	63.6	68.2	68.8	68.8	70.0	72.6	70.8	70.8	70.5	73.2
Design Draft (ft)	22.5	26.2	26.2	26.5	26.9	28.7	28.6	29.2	30.2	29.5	29.5	29.4	30.5
Appendage Draft (ft)	22.5	26.2	29.2	29.5	29.9	28.7	31.6	32.2	33.2	29.5	32.5	32.4	33.5
Depth of Hull (mn dk to keel) (ft)	31.0	37.2	37.2	37.5	37.9	39.7	39.6	40.2	41.2	40.5	40.5	40.4	41.5
Total Depth (to bottom of appendage) (ft)	31.0	37.2	40.2	40.5	40.9	39.7	42.6	43.2	44.2	40.5	43.5	43.4	44.5
Freeboard at Science Deck (ft)	8.5	11	11	11	11	11	11	11	11	11	11	11	11
Deck Height (ft)	9	11	11	11	11	11	11	11	11	11	11	11	11
Total Displacement (LT)	6,800	7,831	7,952	9,258	10,788	9,862	9,830	11,372	12,927	10,731	10,716	12,145	13,716
Propulsion and Performance Characteristics													
Brake Power @ MCR (HP)	18,800	12,092	11,961	12,997	13,262	21,343	20,800	22,014	22,397	25,926	25,589	26,788	26,999
Hotel Load (HP)	5,600	4,159	4,159	5,118	5,118	4,159	4,159	5,118	5,118	4,159	4,159	5,118	5,118
Brake Power for Propulsion @ MCR (HP)	13,200	7,934	7,803	7,879	8,144	17,184	16,641	16,896	17,279	21,768	21,430	21,669	21,881
Shaft Power @ MCR (HP)	12,700	7,299	7,179	7,249	7,493	15,809	15,310	15,544	15,896	20,026	19,716	19,936	20,131
Percent of MCR to Meet Icebreaking	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Icebreaking Propeller Speed (rpm)	156	110	110	110	110	124	120	121	124.18	110	110	110	110
Endurance Speed (kt)	12	12	12	12	12	12	12	12	12	12	12	12	12
Endurance Propeller Speed (rpm)	130	138	140	137	136	126	125	124	126	108	109	106	107
Maximum Speed (kt)	15.0	14.1	14.0	14.4	14.6	16.1	15.9	16.4	16.5	16.9	16.7	17.5	17.6
Maximum Ship Speed Propeller Speed (rpm)	141	166	165	167	168	181	176	180	183	164	164	167	167
Level Icebreaking Capability (ft)	3	3	3	3	3	4	4	4	4	4.5	4.5	4.5	4.5
Endurance and Tankage													
Endurance Time (days)	60	60	60	80	80	60	60	80	80	60	60	80	80
Endurance Range (nm)	15,000	15,000	15,000	20,000	20,000	15,000	15,000	20,000	20,000	15,000	15,000	20,000	20,000
Fuel Margin Returning to Port	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Ballast to Fuel Ratio	56%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Propeller Characteristics													
PropellerDiameter (ft)	13.12	14.10	14.05	14.08	14.17	15.35	15.55	15.46	15.32	17.25	17.20	17.24	17.27
Number of Propellers	2	2	2	2	2	2	2	2	2	2	2	2	2
Number of Blades	4	4	4	4	4	4	4	4	4	4	4	4	4
Pod Size	nozzle	13	13	13	13	15	15	15	15	16	16	16	16
Towrope Pull (LT)	117.9	70.5	69.6	70.1	72.0	125.0	123.4	124.1	125.2	158.1	156.2	157.6	158.8
Manning													
Crew Complement	22	22	22	22	22	22	22	22	22	22	22	22	22
Science Complement	37	37	37	50	50	37	37	50	50	37	37	50	50
Spare Space	8	6	6	8	8	6	6	8	8	6	6	8	8
Total Complement Including Spares	67	65	65	80	80	65	65	80	80	65	65	80	80
Options													
Double Hull	no	no	no	no	yes	no	no	no	yes	no	no	no	yes
Appendage	no	no	yes	yes	yes	no	yes	yes	yes	no	yes	yes	yes
Large moon pool	no	no	no	no	yes	no	no	no	yes	no	no	no	yes
Emissions reduction	no	no	yes	yes	yes	no	yes	yes	yes	no	yes	yes	yes
SHALDRIL	no	no	yes	yes	yes	no	yes	yes	yes	no	yes	yes	yes
80 meter Jumbo piston core	no	no	no	no	yes	no	no	no	yes	no	no	no	yes
50 meter Jumbo piston core	no	no	yes	yes	no	no	yes	yes	yes	no	yes	yes	no
Cost (millions of dollars)	99.0	107.9	109.8	122.6	136.9	150.6	150.4	164.8	178.87	170.8	171.6	185.5	199.1

The sensitivity study for the PRV revealed that some of the mission requirements are associated with no significant construction cost increase. For example, all of the designs have sufficient length for the 50 m jumbo piston coring operations. Not counting its equipment cost or the impact its weight has on stability (they were not considered in this model) there is no added cost for including the 50m jumbo piston core requirement. Likewise, reducing diesel emissions adds relatively little to construction cost for all designs. Including a box keel actually reduces the vessel construction cost by effectively providing displacement without much accompanying structural weight.

In contrast, other mission requirements always have a significant associated construction cost increase. The most significant of these is level icebreaking capability. The thicker the ice a ship must break, the more expensive is its construction cost. Other mission requirements such as weight allowances for geotechnical drilling capability, inclusion of a double hull, and an expanded moon pool contribute less to the vessel cost. In some cases, a mission requirement can either affect the vessel construction cost significantly or not at all. The 80 m jumbo piston core (JPC) is the primary example of this. For a 3 ft icebreaking baseline ship, adding only the 80 m JPC requirement greatly affects the cost because the ship must get significantly longer to accommodate the capability. However, a larger ship, e.g. one with 4.5 ft icebreaking capability, already has the length required for the 80 m JPC. Thus including the mission requirement in this case has no affect on construction cost.

As a check of the 2004 model, it is useful to compare the 2003 PRV design with the 4.5 ft level icebreaking capable ship that includes all of the mission requirements selected. These are compared in Table 8. As shown in Table 8, the 2004 all-up ship is larger in displacement than the 2003 PRV. This increase is due to a refined definition of the hull shape and weight of the hull, a weight margin added to the estimate of weight, inclusion of the double hull weight and the increase in both ship size and weight to achieve a weight balance with displacement. The new all-up ship represents a second iteration of the design spiral and, therefore, a refined design. The installed power is less on the all-up ship than on the PRV full-scale results of podded propulsor icebreaking ships have shown a 10 percent increase in thrust at slow speed. This factor was added to the model in 2004 and results in the lower power for the same beam and icebreaking capability.

Table 8. Comparison of 2003 PRV Design and All-Up Ship from 2004 Design Study

	PRV	All-Up Ship
Principal Characteristics		
Length Overall (ft)	378.4	394.5
Length Between Perpendiculars (ft)	340.9	355.4
Extreme Beam (ft)	74.5	74.7
Waterline Beam (ft)	73.0	73.2
Draft (ft)	26.6	30.5
Appendage Draft (ft)	29.6	33.5
Freeboard (ft)	11.0	11.0
Displacement (LT)	11,000.0	13,716.0
Propulsion and Performance Characteristics		
Total Installed Power (HP)	29,500.0	26,999.0
Shaft Power (HP)	22,500.0	20,131.0
Propeller Diameter (ft)	17.8	17.3
Level Icebreaking Capability @ 3 kt (ft)	4.5	4.5
Shaft Speed for Icebreaking (rpm)	112	110
Maximum Open Water Speed (kt)	18.5	17.6
Endurance Speed (kt)	12.0	12.0
Endurance		
Endurance @ 12 kt (nmi)	20,000.0	20,000.0
Endurance (days)	80.0	80.0
Manning		
Crew Complement	22	22
Scientist Complement	50	50
Spare Space	8	8
Total Complement Including Spares	80	80
Options		
Double Hull	Yes	Yes
Box Keel	Yes	Yes
Large Moon Pool	Yes	Yes
Diesel Emissions Reduction	Yes	Yes
Geotechnical Drilling	Yes	Yes
80m Jumbo Piston Core	Yes	Yes
50m Jumbo Piston Core	Yes	Yes
Cost (Millions of Dollars)	$167	$199

7. REMAINING ISSUES AND FUTURE ACTIVITIES

The results of the sensitivity analysis have demonstrated that some of the science requirements may have a significant impact on the ship size and overall construction cost. It should be noted also that the design synthesis model used in the study was set up for podded-type propulsion system only. This type of propulsion system was selected in 2003 as a result of analysis of the initial set of requirements and conducted technical studies. However, in the case of removing certain requirements (e.g., large moon pool), alternative propulsion systems such as a traditional diesel-electric one or diesel-direct with controllable pitch propellers power train may become feasible. Propulsion system alternatives were not studied in this project and, therefore, were not included in the sensitivity analysis. It will require further efforts to update the model in order to make it capable of designing the PRV fitted with various propulsion systems.

After completion of the 2003 feasibility design efforts, ARVOC and the science community expressed some concerns about potential acoustic and electromagnetic noise generated by the electric motors of the azimuthal thrusters. This issue was not addressed in the current study. The alternative solution providing most of the podded propulsors advantages could be Z-drive type azimuthal thrusters with or without nozzles. It is not clear at this moment what noise level a Z-drive system will produce compared to podded drives.

The performed sensitivity study enables one to proceed with the PRV concept design and performance specification development subject to refined science requirements. However, the scope of future activities and the focus of the next stage technical efforts will greatly depend on the selected approach to the procurement. The above technical issues need to be addressed before compiling the specification for the new ship regardless of what kind of procurement and schedule will be implemented. If the concept design is included in the RFP as guidance, however, the design efforts will grow more significantly and schedule issues will become more critical. Therefore, future steps should include both further technical studies and planning studies intended to develop a procurement plan and overall acquisition project schedule.