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MARTIN MARIETTA

ENVIRONMENTAL REPORT

**THE USE OF EXPLOSIVES
BY THE
U.S. ANTARCTIC PROGRAM**

by

**J. T. Ensminger
T. J. Blasing**

**MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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DEPARTMENT OF ENERGY**

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U.S. ANTARCTIC PROGRAM

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Environmental Analysis and Assessment Section

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1. INTRODUCTION

This environmental report on the use of explosives in Antarctica has been prepared by the U.S. National Science Foundation (NSF) to assist principal investigators and others in complying with the National Environmental Policy Act (NEPA) and the Protocol on Environmental Protection to the Antarctic Treaty (Protocol). Implementing regulations for NEPA are found at 40 CFR 1500-1508. Environmental protection under the Antarctic Treaty is addressed in the Protocol, which was adopted by 26 countries in 1991. In the United States, responsibility for compliance with these requirements rests with the NSF Office of Polar Programs (OPP), which manages the U.S. Antarctic Program (USAP).

NEPA and its implementing regulations require that federal agencies consider the effects of major actions on the human environment before deciding to act. The vehicle for this consideration is an environmental analysis, either an environmental assessment (EA) or an environmental impact statement (EIS), depending on the expected significance of the effects. A programmatic EIS on the impacts of the USAP was published in 1980. A supplemental EIS addressing the safety, environment and health initiative undertaken by USAP was published in 1991. A new draft programmatic EIS is under preparation and will be published in mid-1995.

The Protocol designates Antarctica as "a natural reserve, devoted to peace and science" (Article 2), and identifies principles for protection of the antarctic environment (Article 3). In considering protection of the antarctic environment, the Protocol recognizes its wilderness and aesthetic values as well as its value as an area for the conduct of scientific research. Under Article 3 of the Protocol, environmental protection requires that activities in the Antarctic Treaty area be planned and conducted so as to limit adverse impacts on the antarctic environment and dependent and associated ecosystems. Environmental analysis is required, with an initial environmental evaluation (IEE) and comprehensive environmental evaluation (CEE) being essentially equivalent to the EA and EIS, respectively. Annex II of the Protocol prohibits taking¹ of or harmful interference² with

¹"Take" or "taking" means to kill, injure, capture, handle, or molest a native mammal or bird or to remove or damage such quantities of native plants that their local distribution or abundance would be significantly affected.

²Harmful interference is a prohibition not contained in the Antarctic Conservation Act, and includes activities that disturb concentrations of birds and seals, such as flying or landing helicopters, and operating vehicles in close proximity. Harmful interference also generally includes "any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant, or invertebrate."

antarctic fauna and flora except in accordance with a permit. Because most of Antarctica is essentially pristine, application of these principles means that disturbance which might be considered negligible elsewhere could be significant in Antarctica.

The continent of Antarctica (Fig. 1) includes an area of about 14.3 million km² (5.5 million miles²) and is completely surrounded by the southern oceans. About 98% of the land area is covered by ice and snow. Glacial ice of the continent forms ice shelves hundreds of meters thick in place, extending over the ocean. The USAP maintains three year-round stations on the continent to support scientific research: McMurdo Station on Ross Island, the Amundsen-Scott South Pole Station near the geographic south pole on the polar plateau, and Palmer Station on the Antarctic Peninsula (Fig. 1). Byrd Station in West Antarctica is also occupied intermittently during the austral summer. McMurdo Station is the major logistic support base for the South Pole Station and numerous scientific field camps on the continent during each austral summer.

The United States has maintained a presence and performed research in Antarctica since 1957. The operations, which were originally overseen by the U.S. Navy, are now managed by NSF. Support is provided to the USAP by the Naval Support Force Antarctica (NSFA) and a civilian contractor, Antarctic Support Associates (ASA).

Research activities and the associated support operations in Antarctica sometimes require the use of explosives. This report evaluates the potential environmental impacts associated with such activities, and possible methods for mitigating those impacts.

2. PAST AND CURRENT USES OF EXPLOSIVES

No explosives are used at the Amundsen-Scott South Pole Station. However, construction, maintenance, and operation of the facilities at McMurdo and Palmer Stations sometimes requires moving significant amounts of soil and/or rock materials. At Palmer Station, blasting is used very rarely and only for construction. At McMurdo Station, some research activities involve the use of explosives—producing holes in the sea ice for access by divers, collecting rock or fossil specimens, and more commonly, conducting seismic studies of the geologic substrata under the glacial ice. Blasting may also be used to provide fill material for roads or other construction and maintenance needs, to recontour construction site surfaces, and to remove an ice cornice that forms annually over

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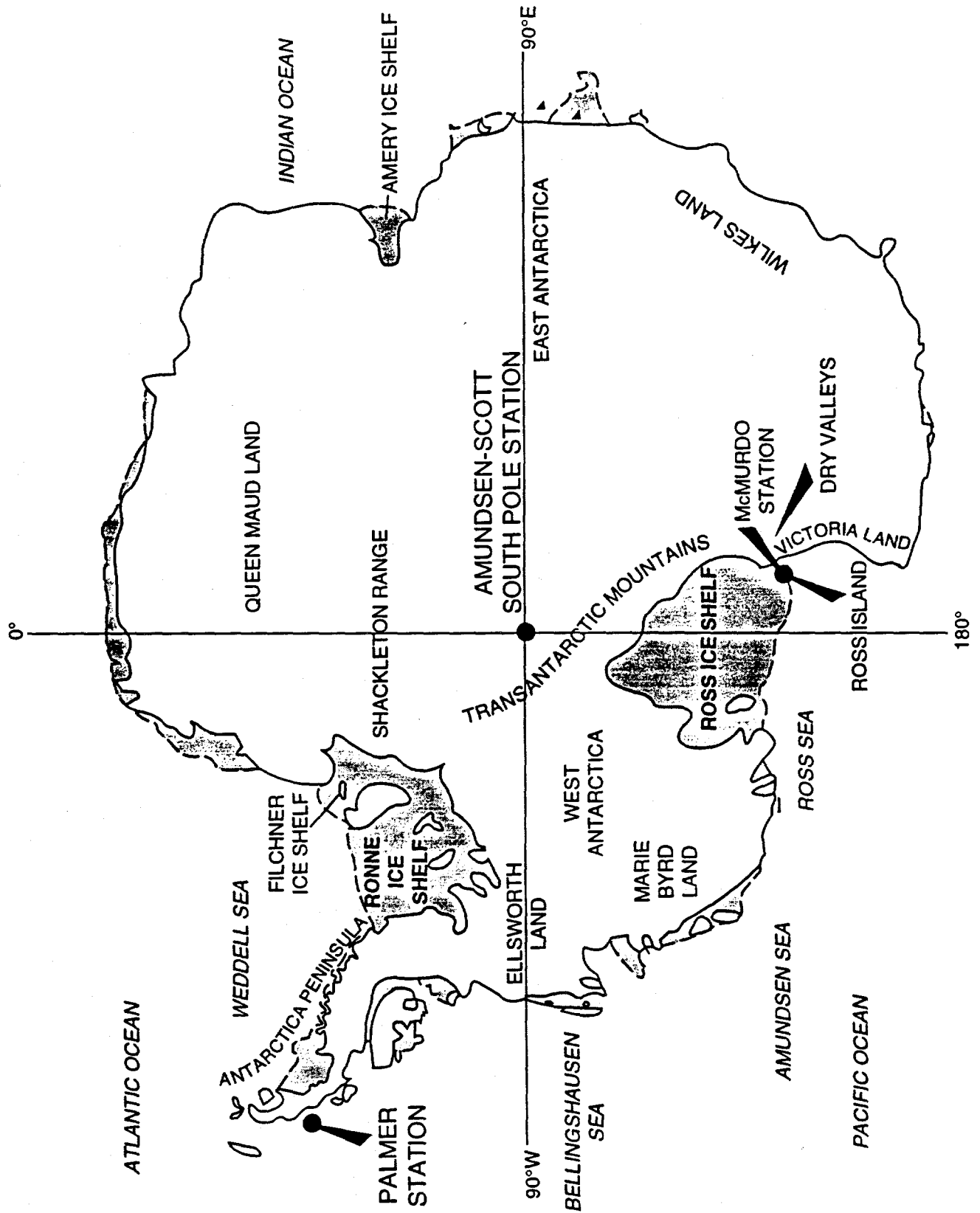


Fig. 1. Major features and location of USAP stations on the Antarctic continent.

the Williams Field Road. Blasting has rarely been used for destruction of hazardous materials. Any future activity of this type would be preceded by the preparation of specific environmental documentation.

The quantity and type of explosives used depend on a number of factors, including the purpose of the blasting, ice depth and condition, and geologic formations. Each request to use explosives is assessed by the ASA Explosives Handler to determine the best approach to be taken.

Table 1 provides a summary of explosives use for the 1991-92, 1992-93, and 1993-94 seasons. Prior to 1991-92, no records of the quantity of explosives used during each field season were kept. However, since 1991, a log has been kept in each storage magazine to record the type and quantity of explosives placed in or taken from the magazine. The magazine logs also include the intended use of the explosives checked out (e.g., science, by scientific-event number, station operations and maintenance, or construction), and whether any unused explosives were returned to the magazine (Andrews 1993).

Table 1. Approximate explosives use for three working seasons in kg (lb)^a

	1991-92 ^b	1992-93 ^b	1993-94 ^c
Construction	686 (1,525)	148 (329)	331 (736)
Science and technology	400 (890)	182 (405)	1,530 (2,290)
Operations and maintenance	1,426 (3,170)	2,365 (5,258)	252 (559)
Totals	2,512 (5,585)	2,695 (5,992)	1,613 (3,585)

^aDoes not include seismic blasting which is not performed by the ASA Explosives Handler. See Sect. 2.1.1.

^bSource: Andrews 1993.

^cSource: Rhoton 1994.

2.1 SCIENTIFIC RESEARCH

A major use of explosives in Antarctica is for research purposes, particularly seismic studies and creation of holes in the sea ice for under-ice studies. Seismic studies involving the use of explosives have been conducted at various remote locations around Antarctica, including the Ross Ice Shelf, the interior of the continent, and the waters surrounding Antarctica. Measurement of the reflection and refraction of sound waves produced by detonation provides data on the nature and

geometry of constituent components of the solid earth. Seismic methods are widely used for subsurface studies that are not unique to the Antarctic. Explosives have also been used for exposing new rock for fossil exploration. Future blasting of this type will be preceded by separate site-specific environmental documentation.

McMurdo Sound provides the setting for unique research on the physical and chemical conditions of the marine environment under the annual sea ice, the flora and fauna that survive under such extreme conditions, and the impacts of man's activities on the environment. This work requires access to the under-ice environment by divers at various locations to collect samples and gather data such as water temperature, pH, and biological oxygen demand. The need for under-ice access also occurs at frozen lakes on the continent in the McMurdo vicinity—i.e., the Dry Valleys across McMurdo Sound in southern Victoria Land (Fig. 1).

The total quantity of explosives used for scientific and technical support in 1991–92 and 1992–93 was 400 kg (890 lb) and 182 kg (405 lb), respectively (Andrews 1993). The scientific and technical use of explosives for the 1993–94 season totaled 1,530 kg (2,290 lb) (Rhoton 1994). The increase in explosives usage for the 1993–94 season was principally the result of resumption of seismic blasting after a two-year hiatus.

The quantity of explosives taken to a research site typically exceeds the quantity used for blasting. To account for uncertainties and the difficulty of delivering additional explosives to a site, sufficient amounts must be transported initially to ensure that the project can be completed on the first attempt. Excess explosives are usually detonated at the site because they cannot be flown back to McMurdo with passengers, and aircraft time is not generally available for removing the remaining explosives. The quantity of excess explosives is dependent on several variables including the weather, which can significantly alter the way ice responds. Another key factor is the Explosives Handler's ability to predict the required quantity, which in turn is dependent on the amount of information provided to the Explosives Handler regarding the blasting to be done. The quantities of excess explosives that have been detonated at research sites range from a few pounds to a few hundred pounds. The remaining explosives are either detonated in one blast or a number of small blasts, depending on the surrounding environment and safety considerations (Andrews 1993).

The amount of explosives brought to a site, and therefore the amount of unused explosives remaining, could be greatly reduced by improving the amount of detailed information provided to the Explosives Handler. Such information could often be obtained by the Explosives Handler and the

researcher(s) making a reconnaissance visit prior to the date when the blasting is to occur. The blasting request should provide a clear definition of the goal of the blasting and as much detailed information as possible on the geology and/or ice conditions (Andrews 1993).

2.1.1 Seismic Research

Because antarctic geologic features are largely buried under a thick ice sheet, most of the current knowledge of the tectonic history of Antarctica is based on information from surrounding continents, ocean basins, and the margins of the antarctic continent. The subglacial geology can only be studied by remote sensing methods that are capable of penetrating the ice. These methods include radar for studying topography, the measurement of anomalies in gravity and magnetic fields, and seismic studies of the underlying geological strata. Ground and aerial radar and magnetic surveys and ground surveys of gravity have been conducted in Antarctica for approximately twenty years. Although seismic research is the principal geophysical tool in most of the world, relatively few seismic studies have been conducted on the antarctic ice because they are limited to crevasse-free areas and require substantial logistical support (ten Brink et al. 1993). Recent seismic work has been carried out through the Seismic Experiment Ross Ice Shelf (SERIS) which focuses on the Ross Ice Shelf itself, and most recently along the tectonic boundary between East and West Antarctica, in the Transantarctic Mountains (Fig. 1) (ten Brink et al. 1989; Beaudoin 1992; and ten Brink 1993).

Seismic research involves the application of acoustic signals (provided by explosives and air guns as discussed in this report) to image the structure of the solid earth. Signals are sent into the earth's crust, and reverberating sound waves are captured by strategically placed receivers. The velocity of these returning signals varies according to known characteristics of the rock through which it travels. Such research may also use passive signal generators such as earthquakes.

Standard seismic research involves two basic procedures. The first procedure, the study of the first few meters of sub-ice bedrock, involves surface detonation of Primacord. This is a trade name for fuse-like explosive material consisting of a woven fabric tube, impregnated with asphalt or wax, reinforced with a fiber or metal wrapping, and filled with a core of high explosive. The second procedure is to study the deeper crust by placing explosive charges in holes that are drilled mechanically or melted by a pressurized hot water drill into the ice to depths up to 200 meters (660 ft). Sizes of the charges vary, generally in the range of 5-55 kg (11-121 lb).

The quantity of explosives used for seismic research in the SERIS research project has ranged from 700 kg (1500 lb) to 11,000 kg (24,000 lb), with the latter occurring during the 1990-91 season. Typical amounts range in the thousands of kilograms for each seismic project; however, these explosives are used at a number of sites distributed over a large area. The SERIS project blasting is conducted by certified project personnel. The quantities and methods used are determined by consultation between the seismic researchers and the ASA Explosives Handler.

No seismic blasting occurred during the 1991-92 and 1992-93 seasons. During the 1993-94 season the SERIS project resumed, using 3,900 kg (8,700 lb) of explosives (Table 2).

Table 2. Estimated seismic research explosive usage for 1993-94

Event no.	Location	Estimate amount of explosives	Type of explosive
S-095	Wilkes Basin	8,157 lbs net wt. 3,700 kg net wt. 13,360 lbs (gross shpg) 6,012 kg (gross shpg)	ICI Geoflex 40 200 GR Detcord
S-151	Upstream-B (Outer)	500 lbs net wt. 227 kg net wt. 525 lbs (gross shpg) 238 kg (gross shpg)	ICI (Atlas) seisprime 2.25 × 1 lb

2.1.2 Creating Holes in Sea Ice

Explosives are used to create holes in the sea ice to provide access to the water column for underwater research projects where access cannot be obtained by drilling. In recent years this has included providing access for divers, a remotely operated vehicle (ROV), and other data gathering equipment. The requirement for blasting holes in the sea ice increased to twenty-one holes during the 1994-95 season (Wright 1995). This follows a decline from fourteen to six over the three previous seasons.

Creating holes in the sea ice by blasting is a highly complex process. The reaction of the ice to blasting and the amount of explosives needed are difficult to predict, and depend on such variables as unseen cracks within the ice, the age of the ice, and the depth of the ice-water interface slush layer. Therefore, a blasting process which works well in one location may not work at all 200 m

(660 ft) away on the same day (Andrews 1993). The literature on the subject of blasting in ice was reviewed for this report, and no information regarding blasting in ice thicker than one meter was found.

The process used to create an under-ice access hole consists of mechanically drilling or melting a hole approximately 12.7 cm (5 in.) in diameter down to the water/slush layer typically 4–5 m (12–15 ft). Explosive material is then placed into the hole; the depth of the explosive below the top of the ice surface depends on the site-specific conditions. After the first charge is detonated, additional shots are placed in the hole and detonated to clean out the ice. The quantity of explosives used has ranged from 5 to 55 kg (10 to 125 lb) per shot, with two to five shots needed to create an access hole.

Holes blasted through the sea ice for research purposes quickly refreeze when activities are suspended. The refrozen areas break up annually, move out to sea, and melt with the rest of the sea ice.

2.1.3 Geologic Research

Explosives have been used for geologic research to expose subsurface rock. The use of explosives for geologic studies occurs about once per season on average (personal communication from S. Stephenson, Science Projects Manager, National Science Foundation, Office of Polar Programs, to J. T. Ensminger, Oak Ridge National Laboratory, July 22, 1994). An example of geologic blasting occurred in 1990 at Oliver Bluffs, located in the Dominion Range between the Beardmore and Mill glaciers. A 60 m³ (80 yd³) section of rock was removed from an erosion scarp to expose fossils. Only 6.3 kg (14 lb) of explosive were required for this project (Andrews 1993).

The quantity of explosives used for such research has ranged from 0.2 kg (0.5 lb) to 27 kg (60 lb). The Explosives Handler discusses the detailed geology of the area with the principal investigator in order to determine the blasting approach that will best achieve the desired result. Future use of explosives for this purpose will require the preparation of site-specific environmental documentation.

2.2 CONSTRUCTION AND MAINTENANCE

Construction of roads, buildings, and cargo staging areas occasionally require earthwork. Because of the nature of the rock and permafrost at McMurdo Station, it is sometimes necessary to use explosives to loosen rock which cannot be moved by heavy equipment. Construction items in the current USAP Five Year Plan that could involve the need for blasting include; the replacement of fuel tanks, a RADARSAT earthstation on Arrival Heights, a Facilities Maintenance Shop, a Science Support Services Center, a Sewage Treatment Plant, and a Hazardous Waste Facility. All such projects will also be preceded by site specific environmental review and documentation that will include the assessment of the alternative sites and excavation requirements, including the need for blasting.

Fill materials are needed for use in construction and other purposes. For example, fill materials have been collected and used in McMurdo in the construction and maintenance of the wastewater outfall and the water intake quays. Fill materials are also used for activities that occur on an annual basis such as road and ice pier maintenance. Construction of new facilities may also require explosives to move significant amounts of soil and rock during site preparation and to provide fill materials for final grading of building sites. The total construction and maintenance uses of explosives reported for the 1991-92, 1992-93, and 1993-94 seasons are presented in Table 1.

A unique situation involving the use of explosives occurred in December 1991. Potentially shock-sensitive (pyrooxidizable) laboratory chemicals that were segregated while inventorying all of the chemicals in the old biological laboratory were destroyed on the sea ice approximately 8 km (5 mi) from McMurdo Station by the detonation of explosives. The blast created a crater 12 m (40 ft) wide and 3 m (10 ft) deep in the ice. Because of the explosiveness and sensitivity of these chemicals, they could not be safely transported out of the Antarctic as hazardous wastes. Furthermore, U.S. Department of Transportation regulations prohibited their transport. The use of explosives for this purpose was a unique occurrence which, if repeated in the future, will be preceded by the preparation of an EA/IEE specific to that action.

2.2.1 Fill Material Production

To create fill material, explosives charges are placed into holes drilled mechanically into rock or permafrost. An average of 0.3 kg/m³ (0.5 lb/yd³) of explosives has been required to produce fill material at the current quarrying locations and depths. As the depth at which rock is quarried increases and reaches more solid rock, the quantity of explosives per cubic meter of fill generated may increase. The actual amount required is determined by the Explosives Handler on a case-by-case basis, taking into consideration the type and condition of the rock. Blasting early in the summer season is easier than later when the ground begins to thaw because the rock behavior during blasting is less predictable after it thaws (Andrews 1993).

Construction personnel inform the Explosives Handler of the quantity of fill material needed, and sometimes assist by drilling the holes at the quarry. The Explosives Handler performs all blasting for fill. The blast is designed for the hardest material contained in the area to be removed. For example, tight-grained basalt may be located under different types of lava flows, consolidated snow and dirt, sluff, and other layers. The percent of hard basalt versus softer rock is used to determine the quantity of explosives required.

Recognizing that fill gathering poses potential environmental and aesthetic impacts, OPP prepared an Environmental Action Memorandum in October 1990 and established a policy with the goal of minimizing such impacts. The goal is to be achieved through: (1) a system for considering, authorizing, and reporting all instances of fill gathering (including such activities as the use of explosives and grading to facilitate fill gathering); (2) evaluation and utilization of other materials, approaches or technologies that lead to minimization of fill gathering; and (3) collection and maintenance of information on the collection of fill and associated activities. At McMurdo Station, the gathering of fill is limited to specified previously disturbed areas. Authorizations are required for fill gathering activities not already addressed in a project-specific environmental impact assessment or in the USAP programmatic EIS.

2.2.2 Ice Cornice Removal

Typically, during each austral summer, it is necessary to remove an ice cornice which overhangs the Williams Field road for the safety of persons using the road. The cornice forms on the

ice bluff along the transition area where the road follows the edge of Ross Island. The roadway is closed, and the overhanging ice is "cut" using explosives and dropped alongside the roadway. During the 1992-93 and 1993-94 seasons' approximately 114 kg (254 lb) and 100 kg (222 lb) of explosives were used for this purpose (Andrews 1993, Rhoton 1994). An Environmental Action Memorandum and a report on this subject were submitted by ASA to NSF in November 1992 and December 1992, respectively.

2.2.3 Rock Removal for Construction

Construction of roads, buildings, and cargo staging areas occasionally requires earthwork. Because of the nature of the rock and permafrost at McMurdo Station it is sometimes necessary to use explosives to loosen rock which cannot be moved using heavy equipment.

A recent example occurred in January 1995. Approximately 242 kg (538 lb) of explosives were used to cut about 784 m³ (1,031 yd³) of rock for developing a new explosives storage area. Five shots with two smaller blasts produced cut outs in rock for five 2.1 × 2.1 × 6.9 m (7 × 7 × 20 ft) storage magazines (Wright 1995).

2.3 EXPLOSIVES MANAGEMENT AND SAFETY

There are a number of different safety regulations and guidance documents that relate to the transport, storage, and use of explosives. These include Occupational Safety and Health (OSHA) rules (29 CFR Section 1910.109); Department of Transportation rules (49 CFR Parts 17H77, 390-397); Bureau of Alcohol, Tobacco and Firearms rules (27 CFR Part 55, subpart h); Institute of Manufacturers of Explosives (IME) regulations; international air transport rules; naval regulations and specifications (NAVSEA OP5 Section 5-4.1.3); EPA disposal regulations (40 CFR Part 264); and Mining Safety and Health Administration rules. ASA transports, stores, and uses explosives in compliance with the applicable rules and standards.

2.3.1 Explosives Storage

The explosives storage area at McMurdo Station serves both the USAP and New Zealand Antarctic Program (NZAP). The explosive storage facilities were upgraded during the 1994-95 season. The upgrades provide for improved safety by relocating existing prefabricated explosives storage magazines to a new area. At the new location the natural topography, enhanced by the addition of berms, provides appropriately barricaded locations to assure adequate distance and buffering from public roads and inhabited buildings, consistent with explosives storage codes and regulations. The improved, barricaded locations also increase the allowable amount of explosives which can be stored at the site. Current storage capacity includes two 13,608 kg (30,000 lb) capacity magazines and three 7,258 kg (16,000 lb) capacity magazines, plus one 9,090 kg (20,000 lb) magazine to store detonators or explosives (NSF 1994). The enhanced storage facility at McMurdo complies with the "American Table of Distance for Storage of Explosives" recommended by IME (29 CFR 1910.109, Table H-21).

Additionally, the MAPCON computer inventory system is now on-line with count adjustments and complete explosives descriptive information. Explosives information concerning quantities, location, project consumption, and product specifications can be accessed through the MAPCON system.

Presently, the explosives users record take outs and returns from each magazine on a daily basis on the "use logs" which are kept inside each magazine. At the completion of a blasting event, a report is made to the MAPCON Administrator for updating the computerized inventory system.

The volume of explosives actually stored at McMurdo Station is variable. The 1993-94 inventory is shown in Table 3. Because not all the explosives used by the USAP pass through the McMurdo storage magazines, it is not currently possible to compile a complete, detailed inventory. The quantity of explosives purchased and stored on-site is a function of the science and construction needs of the following season. Additionally, the NZAP stores explosives in the McMurdo explosives storage magazines for use at their nearby facility, Scott Base. During the 1992-93 season, 765 kg (1,700 lb) of explosives were stored for use by the NZAP.

Careful planning for explosives needs coupled with judicious selection of blasting materials will reduce and stabilize the on-hand inventory at the level of actual need.

Table 3. Explosives inventory at McMurdo Station for 1993-94

Explosive	Quantity		
Magazine 1			
ICI Powerfrac 2.5" × 16"	267 cases	55# ea = 14,685 lbs	
ICI Ango	38 cases + 68 sticks	55# ea = 2,107 lbs	
	Totals	17,386 lbs	
Magazine 2			
ICI DRC's	15 ms/2264 ea	25 ms/1177 ea	
	45 ms/2699 ea	60 ms/402 ea	
0 Delay EBC's	100' leg/764 ea	30 m leg/899 ea	
	45 m leg/232 ea		
	18 m subdets/951 ea		
	(subdets are from S-095 seismic report)		
	100' leg hercules, all others ICI		
Delay EBC's	00/177 ea	02/176 ea	03/177 ea
	04/174 ea	05/179 ea	06/177 ea
	07/178 ea	08/180 ea	09/183 ea
	10/181 ea	11/182 ea	12/175 ea
	13/176 ea	14/175 ea	15/179 ea
	16/178 ea	17/184 ea	18/185 ea
Magazine 3			
ICI Detcord—Geoflex 40 200 grain (cord from 3-095 seismic project)	111 cases		
Magazine 4			
ICI Powerfrac 2.5" × 16	98 cases	55# ea = 5,390	
ICI Anzomex P	135 cases + 5 ea	1# ea = 8,105	
Magazine 5			
ICI Detcord (Redcord) 25 grains	42 cases + 2 partial rolls (344 m or 1,125 ft)		
Ensign—Bckford 400 grains	41 rolls (500 ft roll)		

Source: Rhoton 1994.

2.3.2 Explosives Transport

Department of Transportation regulations (49 CFR) are used as a guide for transportation of explosives, as well as NAVSEA OP5 and IME regulations and recommendations. A blasting cap box which exceeds the IME-22 design standards has been used to allow caps and dynamite to be flown on the same plane. Use of the box is reviewed and approved by NSFA each year to obtain the necessary waiver. Generally, explosives cannot be flown with passengers (AFR 71-4).

Most explosives are purchased from a New Zealand vendor and delivered to McMurdo Station by air. Explosives purchased in the continental U.S. (CONUS) are sent to New Zealand via military aircraft. Transporting explosives via surface vessel would increase the number of times the explosives are handled, in addition to increasing the cost due to insurance and ship crew salary increases required for carrying explosives. Air transport from CONUS and New Zealand to McMurdo Station is managed to meet military (NAVSEA OPE and AirPac) and civilian (IATA) requirements.

3. ANTARCTIC ENVIRONMENT

This section is based on an extensive baseline description of the antarctic environment developed by the Ohio State University Institute of Polar Studies (1977) for an environmental assessment of potential mineral resource development in Antarctica that has been summarized in *The U.S. Antarctic Program Final Environmental Impact Statement* (1980, reprinted 1984).

3.1 GEOLOGY AND SOILS

Approximately 98 percent of the antarctic land area is buried under ice and snow. The small portions of the continent that are intermittently ice- and snow-free are either rugged mountains or coastal areas. As additional snow falls on the interior of the continent, the accumulated snow and ice spreads very slowly outward toward the coasts (Fig. 2). In some areas the spreading ice sheet coalesces into large floating shelves such as the Ross, Filchner, and Amery Ice Shelves.

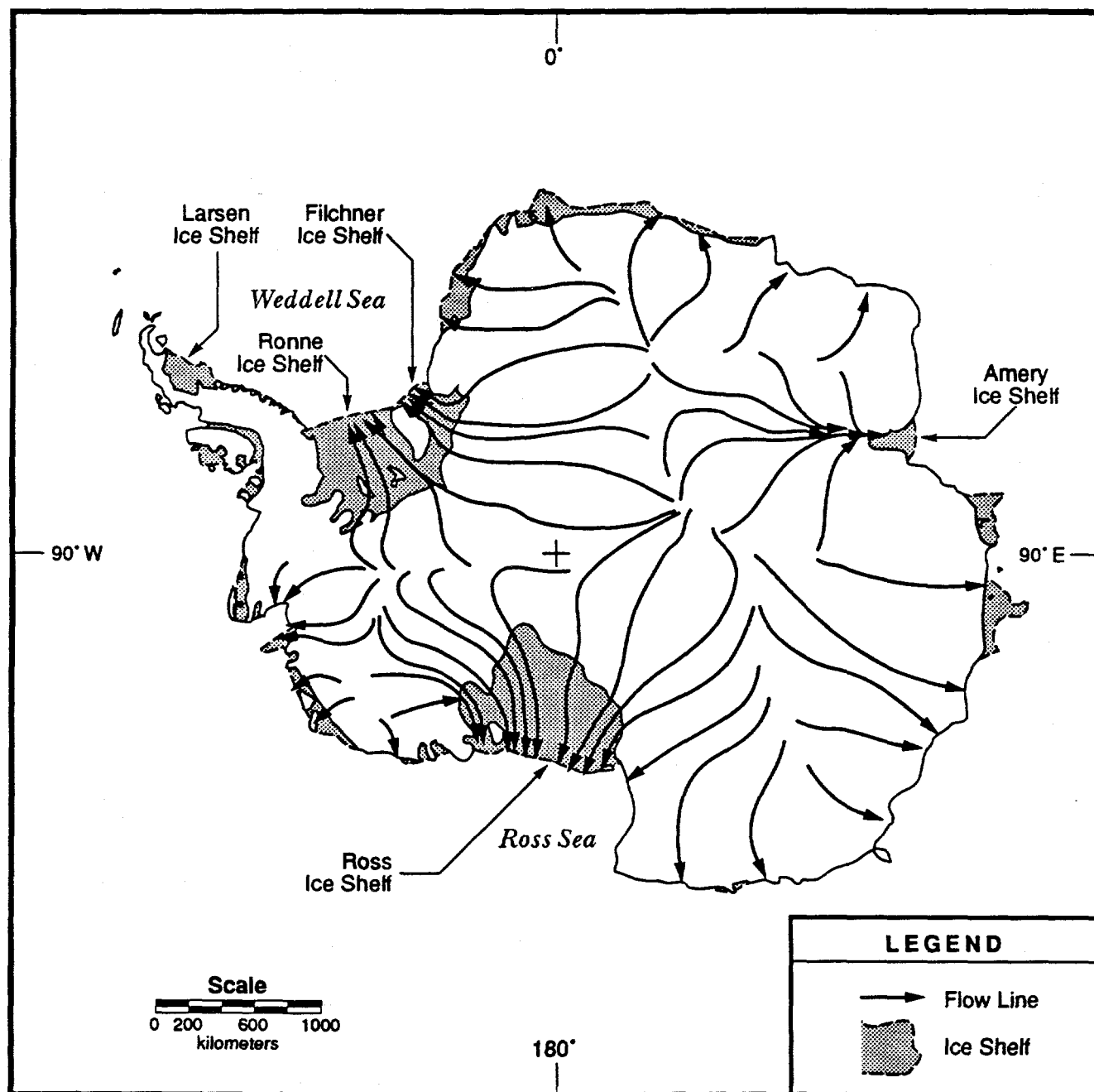


Fig. 2. Direction of ice movement on the Antarctic continent.

Antarctica can be divided into three geologically distinct regions; East Antarctica, West Antarctica, and the Antarctic Peninsula (Fig. 1). Geological studies have shown that East Antarctica is distinct geologically from West Antarctica and the Antarctic Peninsula. East Antarctica is a shield area comprised of ancient Precambrian rocks, some more than 3 billion years old overlain by Mesozoic and younger rocks. West Antarctica and the Antarctic Peninsula are comprised of deformed Paleozoic and younger rocks. Copper minerals have been identified on the Peninsula, and coal occurs south of the Weddell Sea.

East Antarctica is separated from West Antarctica by the Transantarctic Mountains. In East Antarctica, the polar ice plateau is generally more than 3,000 m (10,000 ft) thick. Without its thick ice cover, this part of Antarctica would be a lowland with bordering mountain ranges. With the thick layer of snow and ice, the polar plateau rises to elevations exceeding 4,000 m (13,000 ft) in some areas.

Several ice-free valleys occur in East Antarctica. The best known are the Dry Valleys of southern Victoria Land (Fig. 1). Such valleys are characterized by an extremely dry climate and internal drainage. Several contain ice-covered saline lakes.

In West Antarctica and on the Antarctic Peninsula, the thickness of the ice sheet is generally less than in East Antarctica. These areas are more mountainous than East Antarctica, but the mountain peaks are generally lower, with few exceeding 3,500 m (11,500 ft). However, the highest peak on the continent, at 5,140 m (16,690 ft) is in the Ellsworth Mountains of West Antarctica.

On continental Antarctica, both precipitation and mean temperature are so low that chemical and biological activity are inhibited. Mechanical weathering is strongly dominant. As a result, the soils are predominantly gravelly or sandy, containing only small amounts of fine material and very little moisture. Most of the soils are alkaline. Unless they are located under or near bird rookeries, they are deficient in nutrients such as nitrogen and phosphorus, due to the lack of moisture and low microbial activity. In some of the very old soils, especially in the Dry Valleys, a zone only a few inches below the surface is cemented by salt.

The soils of the Antarctic Peninsula are somewhat better developed than those of continental Antarctica because the climate is warmer and more moisture is available. They are also predominantly acidic. Proximity to the sea leads to enrichment in potassium and sodium. Like the continental soils, however, they are generally deficient in available nitrogen and phosphorus.

Permafrost is defined as soil or rock in which temperatures below 0°C (32°F) persist continuously for two or more years (Ferrians et al. 1969). It may be either dry permafrost (in which the ice content is less than the pore volume, so that excess water does not form upon thawing), or ice-rich permafrost (in which there is more ice than pore space). The ice-rich permafrost does not allow drainage of fluids and thawing may cause earthslides or mudslides.

3.2 INLAND WATER RESOURCES

Near the coasts in summer, meltwaters from ice and snow, and occasional rain, saturate the soil and form numerous puddles and ponds. These water bodies range widely in their physical and chemical characteristics. Streams and lakes are locally important and groundwater is found sporadically above the permafrost level.

In the continental interior, only the Dry Valleys have surface streams of glacial meltwater that flow during most of the summer. Some of these valleys, in southern Victoria Land, contain lakes of highly saline stratified water, the result of the characteristic internal drainage of the valleys, the loss of water by evaporation, and the ensuing concentration of salts. Some of these lakes have permanently frozen surfaces.

3.3 BIOTA

3.3.1 Terrestrial Biota

The antarctic environment is the least favorable for terrestrial life of any on earth. Lack of moisture, low temperatures, and salt accumulations inhibit growth. Distinct differences exist between the extremely sparse ecosystems of the continent and the somewhat more varied biota of the Antarctic Peninsula.

The vegetation of the antarctic continent consists of only a few of the smaller and more primitive forms of plant life—algae, fungi, lichens, mosses, and rare liverworts. The animals that consume these plants and are sheltered by them are all very small invertebrates, the largest being less

than 4 mm (0.16 in.) long. The major animal groups that have been identified among the low-growing antarctic vegetation include one-celled protozoans, several kinds of flatworms, and roundworms, rotifers, tardigrades, insects, springtails, and mites. About half of the terrestrial arthropods (insects and mites) are actually parasitic on birds or seals. Both birds and seals can be found on land, particularly during the breeding season; however, they depend on the ocean for their food. With the exception of those few birds that prey on other birds' eggs and young, most bird and seal species spend the majority of their time either on the sea ice or in the water. During the breeding season, it is not unusual for bird rookeries to take up all snow-free level ground in many coastal areas.

The vegetation of the Antarctic Peninsula and its associated islands is subject to a less extreme temperature range and receives more moisture. As a result, vegetation is more widespread and more varied than that in continental Antarctica. Generally, the species diversity is higher and the communities are more complex. In addition to algae, fungi, lichens, mosses, and liverworts, a few flowering plants and mushroom forming fungi can be found in the tundra-like vegetation of the Antarctic Peninsula and islands. Land animals include the same types of small invertebrates found on the continent. Birds and seals may be found on coastal lands in abundance during the breeding season.

3.3.2 Aquatic Biota

Along the coasts in summer, meltwaters often form puddles, ponds, and lakes which vary widely in their physical and chemical characteristics and provide diverse ecosystems. These water bodies usually contain algae, bacteria, fungi, protozoa, and a few invertebrates. In lakes that freeze solid in winter, the algae tend to form spherical clumps. Lakes that do not freeze completely contain planktonic algae, as well as dense growths of blue-green algae lining the bottom.

Some of the large lakes in the Dry Valleys of southern Victoria Land contain several types of algae under their frozen surfaces, including planktonic algae and periphyton. Associated organisms include bacteria, fungi, protozoa, rotifers, nematodes, and tardigrades.

3.3.3 Marine Biota

Algal blooms in the nutrient-rich oceans around Antarctica provide food for zooplankton such as copepods and krill. The krill, frequently found in great swarms, are a major food source for squid,

whales, seals, and certain birds, particularly penguins. Benthic invertebrates such as sponges, clams, and starfish are widespread. Fish such as antarctic cod, although present, are less abundant than in other oceanic ecosystems.

About 50 species of birds, of which penguins are the dominant group, feed on marine life but breed on the coasts of Antarctica and its offshore islands. Adelie and emperor penguins breed in antarctic regions only. Adelie penguins breed on ice-free pebble beaches during the short antarctic summer. In winter they stay near the edge of the pack ice, where their main food supply of krill is abundant. Emperor penguins generally breed on ice shelves attached to land. The chicks hatch during the winter and become independent in early summer when their food supply is most abundant.

Four seal species are associated with the antarctic pack ice—the crabeater, Weddell, leopard, and Ross seals. In the vicinity of McMurdo Station, Weddell seals predominate. Weddell pups are born on the pack ice in October and early November. Both cows and their pups remain on the ice until weaning occurs approximately eight weeks later. Temperatures normally increase enough by February to cause the pack ice to melt, break up and float away. Killer whales which feed on seals and penguins then enter McMurdo Sound until the temperature decreases and the Sound refreezes.

3.4 CLIMATE AND AIR QUALITY

On the antarctic continent, mean temperatures in the coldest months range from -20 to -30°C (-4 to -22°F) on the coast; means may be as low as -70°C (-94°F) on the polar plateau. In the warmest months temperature means are about 0°C (32°F) on the coast and -35°C (-31°F) on the polar plateau. Temperatures on the Antarctic Peninsula reflect the maritime climate, averaging about 0°C (32°F) in summer and about -10°C (14°F) in winter.

On the high polar plateau, the skies are relatively cloudless and winds of medium intensity blow most of the time. The coastal regions, however, experience frequent violent storms. These may be caused either by cold air flowing down from the polar plateau (katabatic winds) or from cyclonic centers (storms) out at sea. The katabatic winds are often of furious intensity and may exceed 130 km (70 knots) per hour for many hours. Cyclonic centers are frequently generated in a belt between approximately 70 and 60°S , especially in three major centers of generation: over the Amundsen and

Bellingshausen seas, off the coast of Wilkes Land, and east of the Weddell Sea. These centers often bring blizzard conditions.

The cold air of Antarctica is relatively unpolluted. Around the coasts of the continent, the air contains low levels of artificial pollutants. The air of the central portions of the polar plateau has especially low concentrations of contaminants; therefore, it is an excellent area for establishing bench-mark data on global air pollution levels and to follow long-term buildups if they occur.

Localized areas of pollutant buildup have been detected around major stations and along vehicle trails and flight paths. Increased concentrations of fluorocarbons, bromine, chlorine, lead, and anthropogenic particulates from lower latitudes have also been noted. The main sources of local pollution are refuse burning, which has been discontinued at McMurdo Station, and the burning of fossil fuels for heating, power generation, and transportation. Estimated emissions rates for these activities at McMurdo Station, as presented in the Supplemental Environmental Impact Statement for the U.S. Antarctic Program (NSF 1991), are shown in Table 4.

4. ENVIRONMENTAL CONSEQUENCES

4.1 GEOLOGY, SOILS AND ICE

Wherever construction and maintenance work involves the use of explosives and/or heavy equipment, the potential exists for environmental impacts to geologic, soil, and ice resources. The impacts on the affected site will be essentially the same whichever method is used. In such instances, particular attention should be paid to site selection and alternative building technologies to limit to the extent possible the necessity for earth moving and the associated potential for environmental and aesthetic impacts.

Impacts of blasting for fill material have been mitigated by the identification of specific sites for the collection of fill and gravel at McMurdo Station. The areas identified have been previously disturbed and have been historically used for these types of activities. As stated in Section 2.2.1, each future fill-gathering operation must go through an environmental authorization process if it has not been addressed in a project-specific environmental assessment or in the USAP Programmatic Environmental Impact Statement.

Some "foreign substances" may be introduced to the ice, rock, or soil by the use of explosives. These may include charred carbonaceous materials and minute pieces of metal shrapnel from blasting caps. The residues depend on the type of explosives used and whether the explosives container (waxed cardboard box) is detonated as well. DOT regulations require that explosives containers be destroyed on site. The chemical makeup of dynamite is stated on the Material Safety Data Sheet supplied by the manufacturer. Most dynamite contains essentially the same chemicals in different packaging. In the above cases, the residues are rapidly distributed and diluted through additional movement of the loosened material by heavy equipment and by Antarctic meteorological forces to the point that their effects are considered less than minor or transitory. Any easily visible debris remaining after completion of blasting for construction or maintenance purposes will be cleaned up for retrograde as solid waste. Any explosives residues remaining after blasting activities on the sea ice will move out to sea with the ice as it melts and breaks up each year.

The only type of blasting that would occur on the polar plateau would be for seismic research. Although the numbers of detonations for seismic studies may run into the hundreds, the charges are placed in or on the snow or ice and present no potential impacts to the soil or geological substrata. The disturbance of a small area of the snow surface can be considered less than minor or transitory when viewed in relation to the vast Antarctic environment, and the fact that it is quickly erased by antarctic winds and new snow accumulations. The detonation of explosives deep within an ice shelf or in ice over land would likely result in residues being sequestered in the ice cap and gradually moved toward the ocean, as are other solid wastes currently buried in the ice. There are no plans for direct seismic blasting of rock.

According to an NSF rule published in the Federal Register (Vol. 57, No. 172, September 3, 1992), small-scale detonation of explosives for seismic research, such as that described above, performed in remote areas of the continent where there is no potential for impacts on plants or animals is excluded from the requirement for environmental assessment because impacts are defined as less than minor or transitory. Any detonation that exceeds the "small-scale" criterion will require separate site-specific environmental documentation.

Although some seismic blasting has occurred historically in antarctic coastal waters, explosives are no longer used for seismic work in oceans around Antarctica. They have been replaced by air and water guns (personal communication from J. I. Holik, Antarctic Support Associates, to P. Karasik, NSF Office of Polar Programs).

4.2 INLAND WATER RESOURCES

Because of the unique research opportunities provided by the highly stratified saline lakes in the Dry Valleys region of southern Victoria Land, blasting holes in the ice of the frozen surfaces has not been practiced and is not under consideration for future use. Methods that produce less turbulence such as melting with heated glycol in copper tubing preserve the unique chemical stratification of the water under the ice for scientific study.

4.3 BIOTA

4.3.1 Terrestrial Biota

Any blasting taking place on land not covered by snow and ice (i.e., construction, fill gathering, fossil exploration) will be preceded by the preparation of site-specific environmental documentation. Thus, the types and amounts of vegetation, if any, located within the blasting area will be identified. The documentation will include an assessment of the potential impacts to the populations identified with respect to the amounts of explosives to be used and the size of the affected area.

The greatest potential for significant impacts to terrestrial biota involves the effects of blasting on sensitive bird and mammal populations. Both penguins and seals can be found on land, particularly during the breeding season.

Any blasting in terrestrial environments, unless permitted under the terms of the Protocol on Environmental Protection, will be carried out in such a way as to ensure that it will not result in "taking" (killing or injuring) or in "harmful interference" (disturbing) a native bird or animal. Furthermore, any attempts to remove the animals from a proposed blasting area, unless authorized under a specific permit, also constitute harmful interference.

4.3.2 Aquatic Biota

Blasting is unlikely to occur in the puddles and ponds that are formed in summer by meltwaters. However, if such environments were to be affected, a survey of the affected pool would be required to determine whether any unique organisms might be present.

As previously explained, no blasting is to be done in the fragile, stratified, aquatic environments of the Dry Valleys lakes of southern Victoria Land.

4.3.3 Marine Biota

Squid, whales, fish, seals, and penguins inhabit the oceans around Antarctica and feed on the swarms of krill that frequently occur. Killer whales enter the coastal environments when the pack ice melts in summer to feed on penguins and seals. Fish such as antarctic cod are present, but less abundant than in other oceanic ecosystems. Benthic invertebrates are widespread.

Obviously, the use of explosives by the USAP on the sea ice around Antarctica has the potential to adversely impact populations of animals that inhabit the coastal environments. Where colonies of birds or seals are present on the ice surface, the Protocol rules for terrestrial biota concerning "taking" and "harmful interference" apply.

A more difficult situation in which to protect the marine biota of Antarctica involves the under-ice environment. Research involving the under-ice environment requires that holes be made through the sea ice for access by divers and for data gathering. In some locations, blasting is the method of choice for logistical reasons (see Sect. 2.1.2). In such circumstances, it is virtually impossible to ensure that the water under the ice is free of animals such as penguins and seals. The latter (particularly Weddell Seals) are known for their ability to remain submerged for extremely long periods of time allowing them to travel long distances. Furthermore, seals can use breathing holes as small as six inches in diameter. Both seals and penguins are curious animals and may be attracted by the noise produced when the initial holes are being drilled into the ice for placement of the charges. Fish have also been observed to be attracted to blasting sites to feed on other killed or injured fish. This behavior would expose them to any subsequent blasting activities. Recent research concerning the effects of explosives on mammals and birds is very limited with the most extensive studies having been conducted in the 70s and early 80s.

Fish with air bladders are usually injured or killed when exposed to the shock wave from an explosion. The most prevalent mechanism of fish mortality is rupture of the air bladder. Bottom dwelling fish that do not possess air bladders have been demonstrated to be less susceptible to explosive shock waves (Aplin 1947). Although free-swimming fish species are highly vulnerable to the blasting shock waves because of the fragility of their air bladders, it is unlikely that the few localized sea-ice blasting operations in Antarctica would produce a noticeable decrease in their populations.

With regard to mammals and birds, Yelverton et al. (1973), in experiments with land animals (sheep, dogs, and monkeys), determined that air- or gas-containing organs such as the lungs, the gastrointestinal tract, and the ear are most likely to be damaged by explosions in water. In a companion study, Yelverton also used the duck as a model to represent diving birds exposed to explosions under water. The results of these studies were used to formulate underwater blast criteria for marine mammals and diving birds. These criteria, the shock wave impulse levels causing varying degrees of damage to the animals, are shown in Tables 4 and 5. Although a high peak overpressure is necessary to cause injury to marine animals, Yelverton's experimental evidence demonstrated that the impulse (an integration of pressure over time) of the shock wave provides the best indicator of the extent of injury. Detailed discussions of the calculation of shock wave impulse can be found in Yelverton (1973), Hill (1978), and Wright (1982).

Yelverton's data were developed using small dynamite charges in the range of 0.2–3.6 kg (0.5–8.0 lb) near the surface. The 3.6 kg (8.0 lb) charge produced a shock wave impulse level of 40 psi/msec at a distance of 15.6 m (52 ft). The 5–55 kg (10–125 lb) charges used to produce holes in the ice would obviously produce stronger impulses at greater distances. Data on the effects of overlying ice on shock wave impulses were not found.

The criteria developed by Yelverton were shown to be fairly consistent for animals in the 5–40 kg (11–88 lb) weight range. Thus, under no circumstances should explosives be used in the vicinity of seal pups, which weigh approximately 13.5–18 kg (30–40 lb) at birth, or penguins, which are also within the vulnerable weight range. However, the adult marine mammals of Antarctica are much larger, generally weighing a minimum of 360 kg (800 lb). Because of their size and several

Table 4. Underwater-blast criteria for mammals diving beneath the water surface

Impulse, psi/msec	Criteria
40	No mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should recover on their own.
20	High incidence of slight blast injuries including eardrum rupture. Animals would recover on their own.
10	Low incidence of trivial blast injuries. No eardrum ruptures.
5	Safe level. No injuries.

Table 5. Underwater-blast criteria for birds diving beneath the water surface

Impulse, psi/msec	Criteria
45	Fifty percent mortality. Survivors seriously injured and might not survive on their own.
36	Mortality threshold (LD_{50}). Most survivors; moderate blast injuries and should survive on their own.
20	No mortality. Slight blast injuries and a low probability of eardrum rupture.
10	Low probability of trivial lung injuries and no eardrum rupture.
6	Safe level. No injuries.

psi/msec = pounds per square inch per millisecond

Source: Yelverton 1973.

adaptations for diving (discussed below), adult marine mammals are probably less vulnerable to explosive shock waves than the test animals used by Yelverton.

Hill (1978) states that several adaptations of marine mammals for deep diving may provide some protection from explosive shock waves. First, the lung structures of seals may collapse during deep dives. Their flexible thorax would allow the lungs to collapse against the dorsal side of the thoracic cavity. Weddell seals also have incomplete, flattened, cartilaginous rings which support the trachea and would allow collapse of the trachea under intense compression. Additionally, seals exhale before diving or during the initial part of the dive, removing most of the air volume in the lungs. The flexibility of the pulmonary system and the reduced amount of air in the lungs may result in the seal respiratory system being less vulnerable to shock waves.

Second, the air spaces located in the ears of seals and whales are surrounded by bone or cartilage and lined with cavernous tissues which are believed to fill with blood, expand, and fill the spaces during deep dives. Furthermore, the seal's external ear is closed while diving. Therefore, diving seals at depths of 150 m (500 ft) would probably be less vulnerable to hearing loss than those close to the surface (Hill 1978).

Finally, large marine mammals are generally less vulnerable to shock wave damage than smaller animals. This is probably related to the thicker body walls which include a layer of blubber. It has been shown that the blubber/muscle interface is an excellent shock wave reflector. Furthermore, the unwettable skin and fur of seals provides an additional layer of shock wave insulation between the water and the animal's body (Hill 1978).

The above factors may provide some protection for marine mammals against injury from explosive shock waves, however, they do not prevent injury or death under conditions that expose them to sufficiently severe impulses. Instances of marine mammal deaths from underwater explosions have been reported. Fitch and Young (1948) reported three instances in which sea-lions were killed by seismic explosions. However, California grey whales in the area were not frightened away. Also Hanson (1954) reported that fur seals were killed by 11 kg (25 lb) dynamite charges exploded 23 m (75 ft) away. In a laboratory environment, Wright (1971) showed that sea otters would be injured by an explosive overpressure of 100 psi and killed by 300 psi. The overpressures were produced by firing 20 mm cartridges through an expansion chamber into a pressure vessel.

Bohne et al. (1985) reported that noise sources, particularly explosions in the McMurdo Sound vicinity, may have caused hearing damage to marine mammals, and noted from personal communication with researchers that two deaf Weddell seals had been found in McMurdo Sound in 1982. Seal researchers also reported in 1992 that they had identified several seals that gave no response to loud noises when approached from behind, thus they were assumed to be deaf (personal communication from J. W. Testa, University of Alaska-Fairbanks to J. T. Ensminger, Oak Ridge National Laboratory, November 1992).

About 80 explosions were detonated in McMurdo Sound for scientific purposes during the 1984-85 season. Twenty-five Weddell seals were subsequently taken from McMurdo Sound by NZAP researchers in January 1985. The seals were sacrificed by gunshot to the head. American researchers (Bohne et al. 1986) obtained the heads of the animals, although they were severely damaged by the method of sacrifice, and presented the results of a study of 11 intact cochleas removed from this

sample. Five of the ten cochleas that were subsequently determined to be useable for the study had "clear evidence of previous damage," ranging from scattered loss of hair cells to degeneration of an entire portion of the organ of Corti and its replacement by squamous epithelium. The exact cause of the damage to the seal's ears could not be definitely determined. However, explosive noises that were present in the McMurdo Sound environment were identified as a possibility.

Virtually no research has been done specifically concerning the injuries caused by shockwave impulse levels on marine animals in an under-ice environment such as that of Antarctica. However, based on the weights of the charges used for blasting holes, it can be assumed that under some circumstances, injuries could be incurred by marine animals out to distances of 100–200 m (330–660 ft). The Protocol prohibits not only activities that injure or kill antarctic animals, but also those that result in harmful interference with the normal activities of antarctic animal life. Based on the Protocol requirements to avoid injury to animals or harmful interference with their activities, the use of explosives within a kilometer (0.6 mi) of any mammals or birds is prohibited.

No studies or documented evidence of impacts to benthic organisms caused by the use of explosives in waters or on sea ice surrounding Antarctica have been found. Aplin (1947) concluded that lobsters are apparently very resistant to concussion and unlikely to be injured by seismic survey work. Trasky (1976) stated more generally that available test information indicates that most invertebrates are fairly resistant to high pressures, and that damage would require exposure to an intense shock wave close to the blast. Although blasting in or over shallow [less than 30 m (100 ft) deep] water could significantly affect the benthic environment, the impacts would be very localized and transitory. The majority of the blasting operations performed in marine environments around Antarctica are in greater depths of water and would result in less than minor or transitory impacts to the benthos.

It may be possible to cause seals and penguins to leave the under-ice area of a planned explosion. One possible method is by broadcasting killer whale sounds. Use of this technique to keep sea otters and other animals away from oil spills is being researched. The feasibility of using such a method for seals in Antarctica is unknown. The additional equipment, labor, and transport requirements must be considered.

An additional mitigation measure would be the use of sonar devices for identifying schools of fish or other marine animals under the ice before blasting. The sonar transducer could be lowered through a small hole drilled into the ice prior to placement of the explosives. The identification of

nearby animals under the ice would result in delaying the detonation until the animals leave the area. This preliminary check might not guarantee the absence of animals within hazardous distance of the detonation, particularly the larger 55 kg (125 lb) charges, but would at least indicate whether any are in the immediate vicinity. It would be a significant improvement over blasting with no information concerning the under-ice situation.

In the absence of methods for ensuring that the under-ice environment is free of marine animal life, blasting in the waters or on the sea ice around Antarctica should be minimized to the extent possible. Current USAP policy is to limit the use of explosives to locations greater than 1 km (0.6 mile) distant from known concentrations of marine mammals and birds (personal communication from R. S. Cunningham, Environmental Policy Manager, National Science Foundation, Officer of Polar Programs to J. T. Enslinger, Oak Ridge National Laboratory, April 20, 1995).

4.4 AIR QUALITY

Some pollutants are released into the antarctic atmosphere as a result of shallow or surface blasting in ice, soil, and rock. These could include particulates, NO_x , SO_x , CO, and hydrocarbons. In the urban areas of the world, the potential health effects of pollutants such as CO and SO_x are primary concerns. However, in the vast, unpopulated environment of Antarctica, the emphasis is on the protection of the relatively clear condition of the atmosphere and the unique opportunities that it provides for atmospheric and astronomical research. The amounts of pollutants released from relatively short-term explosive events are minor in comparison to those currently released by the combustion of fossil fuels for heating, power generation and transportation (see Table 6). Air pollutants released by explosions are also transitory in that they are quickly dispersed by the antarctic coastal winds.

Because of the short-term duration of blasting activities, the levels of emissions produced by explosives may, in some cases, be lower than the levels of pollution that are produced by the longer term operation of heavy equipment to accomplish a job. However, this is a complex issue that depends upon several variables including the type and amount of material to be loosened, the type and amount of explosive, and the type of equipment that might be used. For example, if it is assumed that 0.225 kg (0.5 lb) of trinitrotoluene (TNT) is needed to move 1 m³ (1.3 yd³) of

Table 6. Estimated annual air pollutant emissions at McMurdo Station

Source category	Annual emissions basis		Pollutant emissions rate (tons/yr)				
	Units	Quantity	SO ₂	NO ₂	PM-10	HC	CO
Aircraft operations							
LC-130 and C-130	LTOs ^b	328	0.6	2.9	0.4	8.9	14
C-141	LTOs	25	0.04	0.2	0.01	1.8	2.2
C-5B	LTOs	5 ^c	0.01	0.1	neg.	0.2	0.5
All			0.7	3.2	0.4	11	17
Internal combustion engines							
Diesel (stationary and mobile)	1000 gal ^d	1500	23	350	25	28	77
Gasoline (mobile)	1000 gal	150	0.4	7.7	0.5	15 ^e	300
External combustion							
Boilers, furnaces, etc.	1000 gal	1300	4.6	13	1.6 ^f	1.6 ^f	3.3
Storage tanks (evap.)							
JP-8						0.2	
Gasoline						7.2	
Total			29	377	28	74	414

^aOne ton equals 0.907 metric tons. English units are used in this table because regulatory emission limits and USEPA emission factors are given in English units. Metric units are used in the text of this document.

^bLanding take-off cycles.

^cOnly two C-5B flights to McMurdo were reported for the 1989-90 summer season, but up to five flights per season would be typical.

^dOne gallon equals 3.785 liters.

^eSum of exhaust, evaporative, and crankcase emissions.

^fUsed emission factors for residential furnaces.

earth at McMurdo Station, then 225 kg (495 lb) is required to move 1000 m³ (1300 yd³). According to Environmental Protection Agency (EPA) Compilation of Air Pollutant Emission Factors, AP-42 (1985), the detonation of 225 kg (495 lb) of TNT can be expected to emit 90 kg (198 lb) of CO to the atmosphere. Data on the amount of nitrogen oxides (NO_x) emitted to the atmosphere by the detonation of TNT are not provided. However, for dynamite gelatin containing 20–100% nitroglycerin, the emission factor given in EPA AP-42 is 26 kg (57.2 lb) of NO_x per 1,000 kg (2,200 lb) of explosive. If TNT is conservatively assumed to produce about the same amount of NO_x, then the detonation of 225 kg (495 lb) of TNT yields about 5.9 kg (13 lb) of NO_x.

No specific data are presented in EPA AP-42 concerning the amounts of particulate material (PM) emitted to the air during explosions. Therefore, for purposes of this comparison, it is assumed that the amount of PM emitted by an explosion that loosens 1000 m³ (1300 yd³) of earth approximates that of a batch drop of 1000 m³ (1300 yd³) of earth. According to EPA AP-42, the amount of PM [diameter less than 0.0003 cm (0.0001 in)] that is emitted by such a process is in the range of 0.005–0.020 kg (0.01–0.04 lb) PM per 1,000 kg (2,200 lb), depending on wind speed, moisture content, and silt content. Assuming a density of 1,500 kg/m³ (2,500 lb/yd³) for the material in question, the emission of PM to the atmosphere by the use of explosives to loosen 1000 m³ (1300 yd³) of earth is approximately 0.0075–0.030 kg/m³ (0.0127–0.051 lb/yd³), or 7.5–30 kg (16.5–66 lb).

For heavy equipment, the amount of excavating effort may be expressed in terms of machine hours operated. The equipment is assumed to be a large diesel dozer or scraper. According to EPA AP-42, CO emissions are about 1 kg/hr (2.2 lb/hr) for heavy diesel powered equipment in good operating condition. Thus, approximately 90 machine hours are required to equal the amount of CO produced by the detonation of 225 kg (495 lb) of TNT. However, A large diesel machine can be expected to emit NO_x in the range of 0.57–1.74 kg/hr (1.3–3.8 lb/hr). If 1 kg/hr (2.2 lb/hr) is taken as the typical amount, then the equipment produces about the same amount as the detonation of 225 kg (495 lb) of TNT in approximately 6 machine hours.

Total emissions of PM per hour by heavy diesel equipment during an excavation project reaches about 3 kg/hr (6 lb/hr). This includes PM from the engine exhaust, SO₂ which is assumed to be completely oxidized to SO₄ particles, and fugitive dust from moderately dry soil (EPA AP-42). Thus, the operation of heavy equipment to loosen the 1000 m³ (1,300 yd³) of earth can potentially exceed the production of PM by 225 kg (495 lb) of explosives in 3–6 hours of operation.

This example shows that the use of explosives to loosen earth is likely to produce more CO than the use of heavy equipment. However, there is also strong potential for the heavy equipment to produce more NO_x and PM than the use of explosives in performing the same job. Furthermore, NO_x and PM emissions have the potential to affect the clarity of the antarctic air while CO does not. Excavation projects should be evaluated for the use of explosives or heavy equipment on a case-by-case basis.

4.5 CUMULATIVE IMPACTS

It is unlikely that significant cumulative impacts will occur from the use of explosives by the USAP for construction and maintenance operations. The small levels of air emissions, dusts, chemical residues, and wastes that would be produced in the vicinity of McMurdo Station would be minor in relation to those resulting from other activities, particularly air and ground transportation. The major potential cumulative impacts would be associated with the construction and maintenance projects themselves, regardless of the methods used, and would be evaluated in the project specific environmental documentation or fill gathering approval process.

There is also very low probability of cumulative impacts from the use of explosives for seismic research purposes. This type of blasting generally takes place in remote areas, away from other sources of pollution, is of relatively short duration, and results in low levels of emissions.

Other forms of research blasting (i.e., for the creation of holes in the ice and for geological investigations of exposed rock) have a somewhat increased (but still remote) probability of cumulative impacts. The risk of harm to marine biota would increase with the numbers of explosions detonated in McMurdo Sound, and the risk of interference with future research would increase with the amount of alteration of a given geological formation by blasting. Cumulative impacts of explosives use can be mitigated by the preparation and approval of project-specific environmental documentation prior to initiation of geologic work, and the use of alternative methods to blasting for research on the sea ice.

Other countries also use explosives for research, construction, and maintenance in Antarctica. The uses are intermittent and widely dispersed, therefore, it is unlikely that they would result in cumulative impacts, especially inland. However, record keeping and communication of blasting information between nations and installations, will mitigate environmental and safety concerns. This is

particularly important where installations are in close proximity such as the NZAP Scott Base and the USAP McMurdo Station, and in the coastal regions where there is potential to affect populations of biota.

5. ALTERNATIVES TO THE USE OF EXPLOSIVES

5.1 CONSTRUCTION MAINTENANCE

Ongoing support of the USAP research activities in Antarctica will require continuing maintenance of existing facilities and roads as well as construction of new facilities to replace those that have become outdated. Construction will also be needed to provide necessary facilities for new activities approved for Antarctica, along with the associated research and support staff. Some use of explosives will continue to be required.

Antarctica presents unique problems for carrying out construction and maintenance operations. At only a few centimeters below the surface, the ground consists of approximately 33% permanently frozen water, creating a concrete-hard layer of frozen soil. According to engineers, the most efficient way to make a major cut in the frozen soil layer is by blasting. In the case of fill gathering, blasting facilitates localized collection of fill material and therefore results in the disturbance of less surface area than would occur through the use of heavy equipment. Due to the extremely hard, frozen subsurface, bulldozers would need to scrape a substantially larger surface area to produce the equivalent amount of fill material. Heavy equipment would also use fuel and could release more air emissions (see Sect. 4.4).

For construction projects, the best alternatives to blasting for site preparation lie in the selection of the building site and the building methods to be used. Through the selection process, sites can be chosen that have been previously disturbed and/or that require minimum recontouring. Furthermore, construction methods can be selected that utilize the existing contours and minimize the earth and rock moving requirements. Building site selection and construction methods need to be addressed specifically in the environmental documentation for each new construction project.

5.2 RESEARCH

Methods, other than blasting, that are used for producing holes in the ice for research activities include drilling with a hand auger or mobile power drill and melting with pressurized heated water or heated glycol in copper tubing. The potential impacts of the various technologies used for drilling holes in the soil, rock, and ice are assessed in a separate environmental document titled "The Use of Drilling by the U.S. Antarctic Program" completed by NSF in August 1994.

In frozen inland lakes such as those found in the Dry Valleys area of southern Victoria Land (Fig. 1), ice is melted almost exclusively with heated glycol circulated in closed loop copper tubing. This method helps maintain the special chemistry and stratification of the water for research purposes (see Sect. 4.2).

On the sea ice around McMurdo Station, the most commonly used alternative to blasting for providing under-ice access by divers is mobile power drilling. The largest auger currently available at McMurdo Station produces a 1.2 m (4 ft) diameter hole which is suitable for most activities. Generally, drilling is logistically simpler, more environmentally benign, and faster than the use of explosives. This is because of required compliance with extensive regulations and safety precautions for blasting, and because blasting generates a significant amount of unconsolidated ice bits that must be managed by detonation of additional blasts.

When circumstances require larger holes in the ice, when the site is more than 19–24 km (12–15 mi) from McMurdo Station, or when major physical obstacles to the movement of the drill rig are encountered (such as pressure ridges in the ice), blasting becomes the method of choice. In the antarctic environment, at remote locations, distance and physical obstacles are the deciding factors in the choice of blasting for producing holes in the ice.

An alternative measure would be to provide drilling equipment that could be easily transported by helicopter. The one-time costs of such equipment should be compared to the current annual costs of purchasing, transporting, and storing the necessary explosives for this task. Most importantly it would delete the need for blasting holes in the sea ice and the associated safety and environmental concerns.

Seismic research comprises a major portion of the operations using explosives in Antarctica. An alternative method for seismic studies has been investigated in an experiment comparing seismic research methods used on the Antarctic Peninsula (King et al. 1993). In this study, the required sound

waves were produced by firing an airgun above the snow surface. The results were compared with those produced by explosives. The airgun produced a clear reading of the ice/bedrock interface 300 m (990 ft) beneath the surface, while the results of the blasting method required filtration before being read. The airgun technique was also determined to have potential for profiling ice shelf thickness and seabed depth.

Hill (1978) noted that air guns have been demonstrated to be relatively harmless to marine animals when used for seismic exploration in marine environments. Although this technique would not completely replace the use of explosives for seismic research, its use could reduce the amount of explosives and the number of detonations currently required for such research in Antarctica.

Modified blasting techniques have also proven to have reduced environmental impacts, where their use is required in marine environments. AQUAFLEX charges [8 m (26 ft) lengths, 8.5 g/m (0.1 oz/ft)] were identified by Hill (1978) as being virtually harmless to marine mammals because of their linear shape and small quantity of explosive. Conversely, point source charges as small as 0.2 kg (0.44 lb) were shown to be damaging out to a distance of 10 m (33 ft). It was also noted that marine mammals would probably not incur gross physical damage from charges of less than 5 kg (11 lb) at distances greater than 60 m (198 ft). However, damage to hearing could occur at greater distances.

6. CONCLUSIONS

Support for scientific research comprises the most significant use of explosives in Antarctica. The greatest single use of explosives, and the only type of blasting that will occur on the Polar Plateau (an exception is the rare use of explosives to cave in dangerous ice for safety reasons), is for seismic surveys. Although the detonations for seismic studies may number in the hundreds, the charges are small-scale, are placed in or on the snow or ice, are distributed linearly over long distances, and present no potential impacts to soil or geological substrata. The impacts that might result from this type of testing, such as short-term air emissions, production of small amounts of solid waste, and contamination of snow or ice with explosive residues, would be less than minor or transitory. NSF regulations eliminate the need for environmental assessment of small-scale detonations of explosives for seismic research in remote areas where there is no potential for impacts to plants or animals.

Point source explosives are no longer used as acoustic sources for seismic research in the coastal waters of Antarctica. Research has shown that the use of alternative methods such as airguns and linear charges greatly reduce the potential for impacts to marine animals, possibly to less than minor or transitory levels.

Other uses of explosives for research in marine environments present the potential for environmental impacts. The blasting of holes in the sea ice for under-ice access may have resulted in the apparent auditory damage detected in several Weddell seals in McMurdo Sound. However, because some sites are inaccessible for currently available drilling equipment, blasting holes in the ice is necessary in some locations. It is impossible to ensure that the under-ice environment is free of marine vertebrates, particularly seals which are capable of traveling very long distances under the ice. Therefore, maximum use should be made of other less damage producing methods for producing holes in the ice. Wherever possible, drilling by auger or melting will avoid the possibility of injuring under-ice biota. If blasting is necessary, the minimum charges that will effectively provide the size opening needed will reduce the risk of injuring seals or penguins. When marine animals are visible, the Madrid Protocol prohibits any unpermitted "taking" of antarctic animals or "harmful interference" with their natural activities. Current USAP policy states that blasting will not occur less than 1 km (0.6 mile) from known populations of antarctic animals.

Additional mitigation measures include the use of sonar devices to detect any animals in the immediate vicinity prior to placement of explosives in the drilled hole. The acquisition and use of new, easily transportable drilling equipment would delete the need for blasting access holes in the ice.

Planning and consultation with the ASA Explosives Handler will result in the most efficient use of explosives for research and will also reduce the storage inventory. Researchers should work closely with the ASA Explosives Handler prior to and after their arrival in Antarctica to develop the most accurate estimates of explosive needs and plans for their use.

The use of explosives for geologic research, such as providing access to fossil containing strata, also has the potential for significant environmental impacts. In this case particular care must be taken to avoid activities that could significantly reduce the potential for other future geological research in the same area. Because the extent of impacts are specific to the location and the proposed project plan, site-specific environmental documentation describing the need for explosives and assessing potential environmental impacts will be required before the project is initiated.

The use of explosives is also a necessary part of the USAP construction and maintenance operations in Antarctica, which at times require moving significant amounts of soil and rock. Circumstances may dictate the use of explosives over the use of heavy equipment, as in the case of removing an extensive rock formation from a construction site, or gathering fill material from deep in the concrete-hard permafrost. However, in such cases, the majority of the potential environmental impacts would be related to the proposed action itself, regardless of the method (explosives and/or heavy equipment) used to move the material. Any impacts resulting directly from the use of explosives for these purposes, such as short term air emissions, production of solid waste, or contamination of soil, rock, or ice with explosive residues are likely to be less than minor or transitory. Additionally, site-specific environmental documentation that would be prepared for proposed new construction projects would include any expected uses of explosives. The situation would be similar for other types of operations activities that take place only rarely, such as removal of the ice cornice along the Williams Field Road and the destruction of hazardous materials that cannot be retrograded. OPP policy requires that fill be collected only at specified sites and that documentation be prepared for authorization of fill gathering operations prior to the initiation of work.

The need for the use of explosives in construction can be reduced by careful site selection that will minimize the need for recontouring, and by the use of building techniques that make maximum use of the existing contours. Such efforts will also assist in reducing the inventory of stored explosives and the associated stockpiling of outdated explosives at McMurdo Station.

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