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Preliminary design guide for arctic equipment

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Designing equipment for arctic environments requires special considerations from the design engineer. Low temperatures and harsh environments place special demands on equipment and components. Many materials in common use will experience drastic changes in physical properties, resulting in catastrophic failure of the systems in which they are incorporated. Components may no longer meet original specifications, and instrumentation may not work properly. This design guide should familiarize the design engineer with the factors that must be considered when designing for the arctic environment. A list of environmental factors and how they may affect a design is first presented. Then, a general design procedure is presented and a detailed analysis of problems and solutions for materials, components and systems follows.

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PREFACE

This report was prepared by Michael R. Walsh, Mechanical Engineer, and James S. Morse, Electronics Engineer, Engineering and Measurement Services Branch, Technical Services Division, U.S. Army Cold Regions Research and Engineering Laboratory. The original report was produced under NCEL Project 62233 YM33F61. John Rand and Ronald Atkins of CRREL conducted the technical review of this report.

The original report was prepared for the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California, as part of their effort to support the Naval Construction Forces (SeaBees) in their mission of construction, modification, repair and maintenance of underwater facilities. The contract was originally awarded in February 1987, with the contract report sent to NCEL in January 1988. The reviewers for this version were Ronald Atkins, Chief, Technical Services Division, and Donald Garfield, Chief, Engineering and Measurement Services Branch, both of CRREL.

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Preliminary Design Guide for Arctic Equipment

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Part 1. Introduction

GENERAL

The Arctic is an environment that is hostile to both man and materiel. It is an environment of excesses: extreme cold, high winds, total daylight or total darkness, and low absolute and high relative humidity. Because of the remoteness and isolation of most arctic operations, special considerations must be given to designing equipment that can survive these adverse conditions.

This guide is broken down into two major sections. The first section examines the unique environmental problems that must be countered when designing equipment for use in the Arctic. How these environmental phenomena can affect equipment and materials is discussed. This section should be of interest to a design engineer who wishes to obtain an overview of the parameters that must be taken into account when equipment is designed for the Arctic.

The second section presents a general design guide that may be used for logical arctic design. This section also deals more specifically with materials and components that may be used in low-temperature environments. This part will be of more interest to the design engineer who is actually designing or retrofitting equipment.

This preliminary design guide also contains a bibliography and a description of how we conducted the literature search (App. A). Both of these may be of interest to the engineer who wishes to conduct more detailed research into specific areas of design.

SCOPE OF WORK

This design guide has several objectives. The first is to define the environmental factors that the design engineer will have to take into consideration when modifying existing equipment or designing new equipment for use in the arctic winter. The second objective is to describe the possible environmental effects on the equipment. The third objective is to assist the engineer who is designing new equipment or retrofitting older equipment for use in a low-temperature environment.

This report will provide design specialists with general information on cold-related design problems and then suggest solutions to these problems. It will not make arctic designers out of those who have other specialties. As such, it is intended as a supplement for designers in other fields who must now consider designs for use in arctic environments.

This design guide is necessarily limited in scope to general design procedures and considerations. Specific materials and components are not recommended. Rather, families of materials or common groups of components are considered, and their behavior in response to the arctic environment and anticipated conditions of use are described.

Part 2. Environmental Factors

INTRODUCTION

The arctic environment is a hostile environment that the design engineer must consider carefully. There are several factors that must be taken into account. The most obvious one is low temperature. Although the temperature in arctic regions may fall below -65°C on occasion, -55°C is a practical design limit. This is approximately 5°C below North America's lowest mean temperature for a month. Below this temperature, working conditions are not only difficult but extremely hazardous. Figure 1 depicts the world's cold regions.

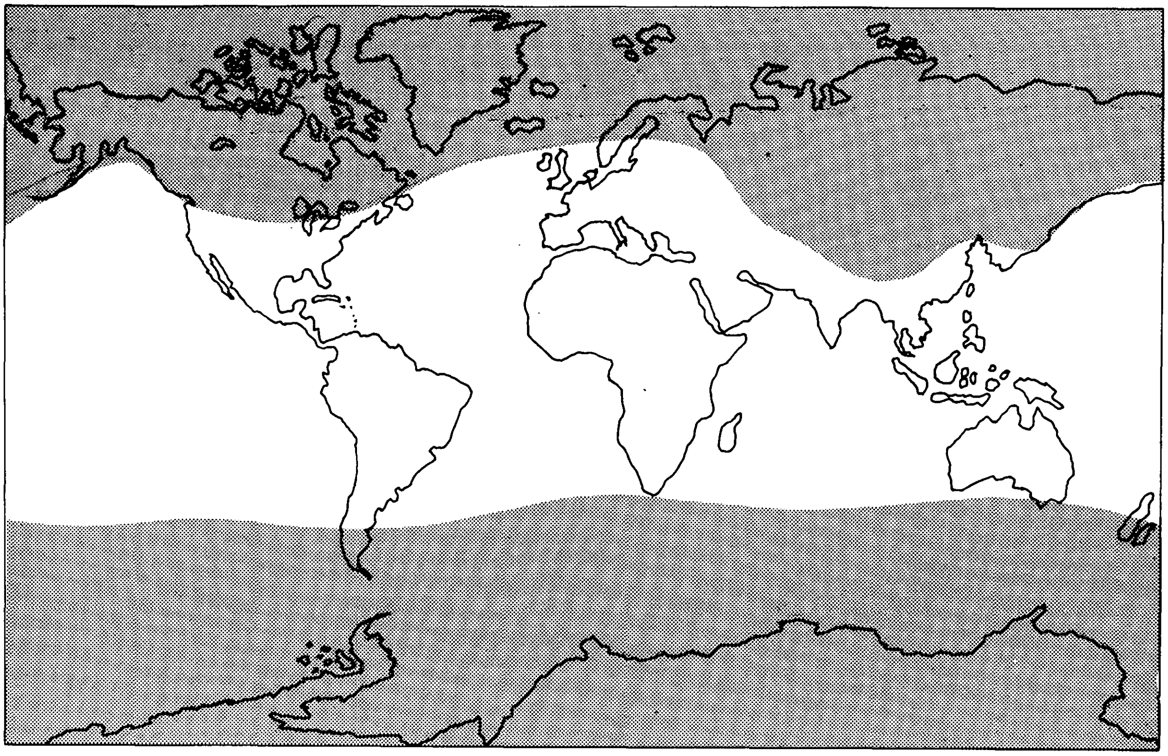


Figure 1. Cold regions within the 10°C isotherm (arctic and subarctic).

A second problem encountered in the Arctic is the winds. There are two phenomena associated with winds that will affect the performance of equipment and make operations in the North more difficult: heat loss due to convective cooling, sometimes mistakenly referred to as "wind-chill," and blowing or drifting snow. Wind will also affect offshore projects. Shifting winds and currents may cause breakup or drifting of offshore ice while operations are in progress. Wind will drive loose ice floes in open water along shorelines, restricting site access and making resupply and maintenance of equipment difficult.

The third problem to be considered is the effects of solar radiation. These can be placed into three categories. The first consideration is the visible light range, the most important aspect being the amount of sunlight in a 24-hour period and its effect on equipment operation, use and maintenance. Ultraviolet (UV) light and its effects on materials, primarily plastics, falls into the second category. In the third category is electromagnetic and radio frequency interference (EMI/RFI) and its effect on electronic equipment and communications.

The fourth and final environmental factor that needs to be considered by the design engineer is the effect on equipment of exposure to water at low temperatures. This is especially important to personnel working along the shoreline or offshore. Effects that have to be considered in design include submersion of equipment and the consequential icing and freezing that will occur upon exposure to the cold air, especially in conjunction with wind-driven convective cooling. Other problems include condensation, corrosion, fogging, rime frost accumulation and low absolute humidity.

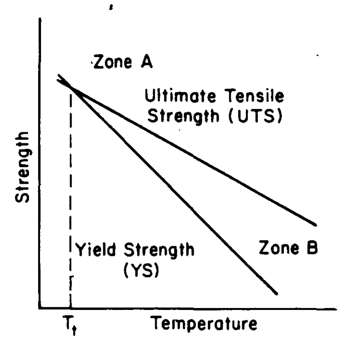
Neglecting the effects of the arctic environment on equipment can be disastrous. The failure of the Liberty ships and T-2 tankers of World War II are graphic examples of the results of not compensating for the environment. Because of fabrication problems, which were exacerbated by low temperatures, these ships literally broke in two. In Boston, around the turn of the century, a large molasses tank failed during a January cold snap, killing several people and dozens of horses. Another less well-known example was the failure of the metal buttons on the clothing of Napoleon's troops during the Russian winter campaign of 1812. It is hard to fight a battle when the temperature is -40°C and your pants are around your knees.

TEMPERATURE EFFECTS

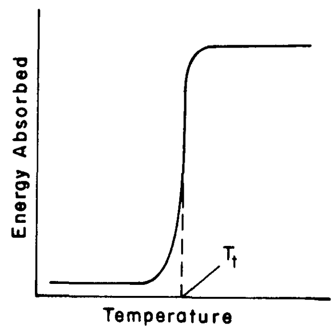
As stated previously, the first and most obvious factor that must be considered in arctic design is the temperature. The coldest regions tend to be located in elevated inland areas, such as central Greenland, the Canadian Rockies and Siberia. Temperatures as low as -63°C have been recorded in all three regions. The southern continents, with the exception of Antarctica, are about 30°C milder than those of the north. In the Arctic, the temperature can change 60°C during the span of a few days, and 24-hour temperature variations of over 55°C have been recorded. The extreme cold of the arctic winter will have many effects on materials, components and equipment in use or stored at a remote site. Temperature differentials, such as those occurring between the outside ambient and a heated enclosure, can exceed 70°C. The effects of arctic temperatures will be categorized for mechanical and electrical components, with some overlap.

Metals

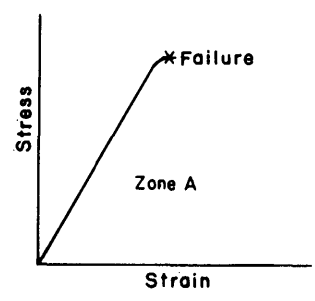
The temperature-related causes of the problems on the ships mentioned in the *Introduction* to Part 2 can be attributed to the ductile–brittle transitional behavior of some metals. This behavior is prevalent in Body-Centered Cubic (BCC) materials such as iron and its alloys, but may also occur in Hexagonal Close-Packed (HCP) materials such as zinc, titanium and beryllium. At low temperatures, the yield strength of many steels increases at a greater rate than the ultimate strength. This differential rate of change can be so large in some metals that the yield stength and ultimate tensile strength cross. This crossing point is called the ductile–brittle transition temperature or nil-ductility temperature (Fig. 2). The result is that a metal that will normally yield before failure will fail in-



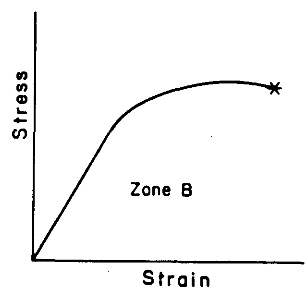
a. Ultimate tensile and yield strength vs temperature. T_t *= transition temperature (see Fig. 2c and d for zone A and B).*



b. Impact strength (energy absorbed) vs temperature.



c. Stress–strain curve for material near or below transition temperature. Failure mode is brittle fracture.



d. Stress–strain curve for material above the transition temperature. Failure mode is ductile fracture.

Figure 2. Ductile to brittle transition of BCC metals.

stead by fracture. Fracture failure is catastrophic and the lack of initial yielding can result in unexpected failure.

As temperature decreases, notch sensitivity increases along with a converse decrease of impact strength for these metals. A sharp notch or bend will have the effect of increasing the transition temperature, making the material less useful at low temperatures. The sensitivity of irons and steels to ductile–brittle transition is also affected by several factors related to process control and chemical composition, as well as to stress orientation and strain rate, so a specific type of steel may have widely varying transition points.

Another temperature-related phenomenon that affects metals is phase transformation. In tin and some of its less common alloys, the structure of the crystals changes from tetragonal to cubic, with an accompanying 21% decrease in density. The result of this change in structure is a disintegration of the metal into a powder. This is what happened with the buttons on the clothing of Napoleon's troops. Factors affecting the rate of transformation include alloying elements, type of stress and temperature. Phenomena such as phase transformation and ductile–brittle transition should be prime considerations to any engineer who is designing equipment for arctic use.

Plastics

The manner in which low temperatures affect the properties of plastics is similar to the way that they affect BCC metals. With plastics, this loss of ductility is known as the brittleness temperature. Unlike metals, where the transition zone can be very narrow, with some plastics the transition tends to be more gradual. What happens to mechanical properties, however, is the same: a marked decrease in ductility with an associated decrease in impact strength and increased notch sensitivity. The brittleness temperature varies among the different polymers, with some useless at 0°C while others are functional down to -60°C. As with metals, the chemical "alloying" of plastics and the method of manufacture will also affect low-temperature properties. Elastomer alloying has proven to be quite successful in improving low-temperature properties of plastics. As an example, the impact strength of nylon at -40°C can vary up to 400% depending on alloy content and reinforcing.

Elastomers

Elastomers and rubber compounds change in a number of ways at low temperatures. These can crystallize, lose flexibility, become increasingly stiff, experience compression set and become brittle. Lowering the temperature generally results in the gradual loss of elastic properties of the material. The consequences of this are leakage problems and increased wear on such components as seals, O-rings and wipers.

Lubricants

Lubricants are also affected by low and variable temperatures. Two important attributes of liquid lubricants that must be considered in arctic design are the cloud point and the pour point of the fluid. The temperature at which wax crystals begin to form is called the cloud point, a name derived from the increase in the fluid's opacity. Below this temperature, wax crystals begin precipitating in the fluid and eventually coagulate. These crystals will clog fine openings and cause flow problems in filters and distribution lines.

The pour point is the lowest temperature at which an oil will flow; it will stop flowing because of increased viscosity or the formation of wax crystals. Before reaching the pour point temperature, the viscosity of many synthetic oils, such as silicone and the diester-based oils, remains relatively stable at temperatures down to -70°C. Many lubricants, especially non-synthetic petroleum-based derivatives, will experience increasing viscosities with decreasing temperature. Greases show similar behavior, with silicone and diester-based greases having a much lower working temperature than petroleum-based greases. Dry lubricants such as PTFE (Teflon) and graphite are not adversely affected in the temperature range with which we are concerned.

Fuels

Wax formation and viscosity are also problems with fuels. Crude oil, which is refined into lubricants and fuels, is generally either napthanic, paraffinic, or a combination of the two. Napthanic oils, used in general lubrication applications, contain very little wax, so viscosity at low temperatures is the limiting characteristic. They can't be pumped below their pour points. With paraffinic oils, the formation of wax crystals in the fluid is the limiting factor.

For diesel fuels, which contain a high percentage of paraffinic oil, wax formation and its associated influence on pour point and cloud point must be a consideration of the design engineer. As mentioned before, the wax crystals can clog filters and distribution lines. Lowering the wax component content of the fuel will reduce filter and flow problems. However, it will also lower the cetane number, thereby adversely affecting engine starting at low temperatures. Reducing the wax content also reduces the heat content of the fuel, making it less efficient. In addition, the higher wax content of diesel fuels allows pumping below the pour point, as the wax allows easier shearing of the viscous oil. So, although viscosity can be modified through the use of pour point depressants and fuel blending, trying to modify the cloud point may not be advisable.

Antifreeze

Another fluid that has limitations in the arctic environment is antifreeze for the cooling system. Several types of antifreezes are available, the most common being the glycols. They exhibit different freezing points in pure and diluted states. Glycols lose these antifreezing capabilities as the weight percent of glycol in aqueous solution rises above about 65%. The difference in freezing points can be dramatic: about 40°C for ethylene glycol (Fig. 3).

Ethylene glycol is the most common of the commercial antifreezes. It forms a eutectic mixture with water in the range from 56 to 79% glycol by volume. Maximum antifreeze protection for this glycol is obtained by a mixture of 56% ethylene glycol by volume. It is important to remember, and it can be seen in Figure 3, that adding extra antifreeze to a solution can actually decrease the effectiveness of the mixture.

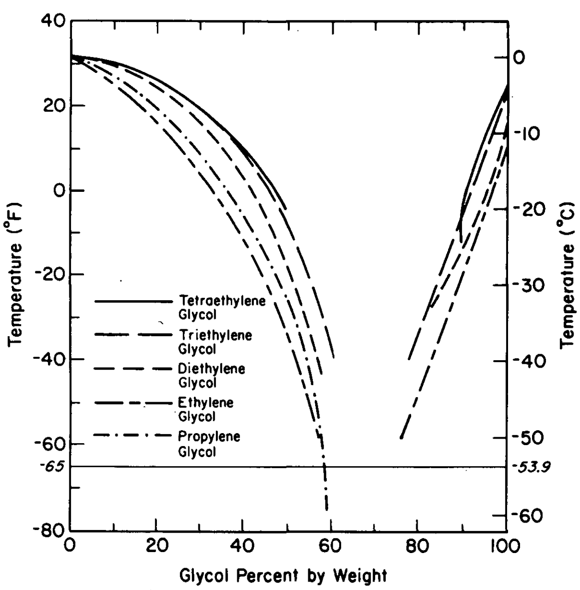


Figure 3. Comparison of freezing points of various glycols.

Electrical components

Electrical resistance and capacitance will vary with changing temperature. Electrical resistance of wire decreases with temperature. In most applications this is not a problem. However, in temperature-measuring circuits, especially those with long leads, this change in resistance should be taken into account or compensated for in some manner. In power distribution circuits, a decrease in line resistance is advantageous since line losses will decrease and systems become more efficient.

In circuit resistors, resistance may vary with temperature from a few parts per million per degree Celsius to over a thousand parts per million per degree. These resistance changes can cause unstable circuit behavior while temperatures are changing, even though the final result is a shifted but stable operating point once temperatures have reached equilibrium.

Capacitors have approximately the same range of variance with temperature as resistors. In addition, some capacitors may short circuit or become open circuits at extremely low temperatures. Capacitance changes may result in unstable behavior while temperatures are changing and in shifted operating points once temperatures have stabilized.

Thermal cycling

Thermal gradients and thermal expansion and contraction of mechanical components are related. As is obvious, these effects are caused by temperature differences, which can be severe in the Arctic. The results of these effects are numerous, from stress concentrations and fracture initiation to the slow loosening of bolted members. Severe thermal gradients, or thermal shock, will shatter some ceramics, plastics and metals. In structural construction and repair of machinery, close tolerance parts will not mate if temperature differences between parts are large. In addition, closely fitting sliding or rolling parts may sieze up because of differing thermal expansion rates. You must also take special care when welding to avoid stress concentrations and buckling. At low temperatures, these defects raise the transition temperature and lower the tensile strengths of BCC metals and other materials such as plastics.

Thermal gradients also have a detrimental effect on electronics. Electronic circuits should not be trusted until they have reached thermal equilibrium. Thermal gradients will cause amplifier outputs to drift. Semiconductor junctions, diodes and transistors change their voltage and current characteristics with temperature. A circuit that is well compensated for temperature may still have large error in its output if one part of the circuit is compensating for a temperature significantly different from another part of the circuit. Errors may be even greater if the temperature is changing rapidly.

Wherever two different metals are connected in a loop such that there are two junctions of the metals, and if these junctions are at different temperatures, a thermocouple is formed and a voltage will be generated that is on the order of microvolts per degree difference. Different types of metals in contact with each other occur in most electronic circuits: copper to lead or tin, brass to gold, brass to silver, phosphor-bronze to brass, copper to nickel, etc. All of these little thermocouples are very active when the temperature of electronic circuits is changing. Once temperature gradients have disappeared, the circuit may operate, but at a different offset level and with a different sensitivity to input signals.

Thermal expansion and contraction is also a problem with components and circuits. Individual components mounted to circuit boards by soldered leads are probably the least susceptible to expansion and contraction problems. The lead length from board to component will allow for differential motion and prevent component fracture or pull-out. Surface-mounted components are more susceptible to differential motion since they have no leads to act as strain relievers.

Many electronic components have glass to metal seals. These seal areas can fracture if temperature changes are too rapid, on the order of hundreds of degrees per millisecond. Rapid temperature change can destroy large encapsulated units such as power supplies. The encapsulating compound develops stress fractures that can later admit moisture or corrosive gases to the circuitry inside. Sometimes the encapsulant stress is transmitted to the components, causing their failure. For example, integrated circuits in ceramic cases are more prone to thermal shock breakage than are their plastic-encased counterparts.

Temperature-induced contraction can cause connector contact springs to disengage. Meter movements may fail completely at low temperatures because of differential contraction of the bearings and pivot shafts. Low quality plastic parts may warp so badly at low temperatures that they become unusable or even fracture.

Condensation of water vapor and the subsequent freezing of trapped moisture will also build up stress in structures and mechanisms. Water's specific property of expanding when it freezes can result in jammed and broken mechanisms. In addition, increased weight from accumulated ice may hamper the operation of certain equipment. Water freezing in hoses and lines will clog or rupture them. Fogging and rime ice buildup will also hamper operations, especially in optical equipment, gauges and equipment with small breather tubes or ventilation ports.

Condensed water vapor on an electrical circuit may destroy it since it allows leakage paths for currents that might damage sensitive devices. Condensed water on a circuit might also prove lethal to an operator for the same reason. Condensation problems can be avoided by specifying coated or encapsulated circuitry. Condensation readily occurs when you bring equipment from cold areas into warm areas. If equipment must be taken from a cold to a warm environment, it should be sealed in a deflated plastic bag first and allowed to warm up before use. If equipment is to be carried back and forth often, you need a completely sealed case. This especially applies to optical equipment.

Ice formation is a problem with electrical apparatus as it is with mechanical devices. Since moisture expands as it freezes, it is very important to keep water vapor and condensation out of connectors and component sockets. Ice can cause contacts to open and plastic parts to break. Ice is a poor conductor of electricity, but it can harm electrical equipment if it forms inside small spaces. For example, ice formed inside a transformer could cause the lamination of the core to warp enough to short some of the windings.

WIND EFFECTS

The second environmental parameter to be considered is the wind. Because of the topography of most arctic coastal regions, there is very little resistance to winds. Large barren expanses, both on and offshore, offer few obstacles to strong circumpolar winds. Wind speeds in excess of 22 m/s are common over extended periods in Greenland.

In the Arctic, wind affects equipment operation in several ways. Convective cooling, drifting and infiltration of snow, and even the lack of wind can have serious effects on a mission. Standard operating temperatures may not be obtainable because of rapid convective cooling. A derivative of this is the long warmup times and rapid cooling rates for equipment. These factors may make the continuous operation of the equipment necessary.

Blowing snow may also have adverse effects on equipment. Blowing or drifting snow will clog intakes and exhausts of stationary equipment and may necessitate either extensive site maintenance or the installation of movable protective structures when a mission is a long one. Precleaners for air intakes of power equipment may also be necessary to filter out suspended ice and snow particles. The establishment and resupply of a base, as well as equipment maintenance, are hindered by blowing snow and "white-outs."

Airborne snow particles may infiltrate an enclosure through cracks in the structure. This snow will melt upon contact with warm air and later condense and freeze on machinery and circuitry after it is shut down and cools. A lack of wind does not necessarily result in a trouble-free environment, however, as we will see in the discussion of ice fogging.

SOLAR RADIATION EFFECTS

Strong UV rays from the sun, especially in the summer, will attack certain plastic materials, affecting both their optical and mechanical properties. Crazing, crack initiation, embrittlement and fracture failure all may result. Strong EMI/RFI emissions from phenomena such as the aurora borealis will interfere with communications and sensitive electronic apparatus. Transmission and reception may be impaired during heavy aurora activity. The lack of sunlight during the arctic winter also has to be considered, especially for operations and resupply. Additional equipment and fuel will be needed to supply lighting during the long arctic nights.

AQUEOUS EXPOSURE EFFECTS

The final environmental factors that will be considered are the effects of aqueous exposure on equipment. Condensation, icing, ice fog and fogging, seepage, freeze–thaw cycling and corrosion are all factors that must be addressed when designing equipment for the Arctic. Some of these phenomena have been discussed in the previous paragraphs on temperature effects.

Fog generation is a problem that will occur when ice crystals form in the frigid air from the by-products of internal combustion engines. Another source of fog could be the precipitation of fine ice crystals from very cold air in areas of low or no wind. At -40°C, supercooled water particles will precipitate out of the air, causing the formation of a cloud of very fine ice particles. These particles can then cause problems for equipment through infiltration and ingestion via air intakes. Condensation and freezing of water vapor in breather vents of lubrication systems will cause buildup of rime ice in the tubes, which in turn will result in pressure buildup and seal failure in crankcases and gear boxes of power equipment.

Snow or ice near operating equipment can melt, causing water seepage. The resulting freeze–thaw cycling could break components, especially those that become brittle in the cold. Seepage may also affect grounding and cause short circuits in exposed electrical equipment. Preventative measures such as sealing and insulating should minimize these problems.

Corrosion is the final effect of aqueous moisture that we will consider. In waters surrounding and bordering arctic terrain, the dissolved oxygen content can be very high because water can hold more oxygen at lower temperatures. In addition, the dissolved salt content may also be high because of salt concentration from freezing water, especially in coastal lowlands. Both high dissolved oxygen and concentrated salt conditions are conducive to accelerating corrosion in metals, even some stainless steels. Exposure to water is not even necessary. The air along shorelines can contain salt that has been generated from sea spray by the wind. Equipment exposed to this air, especially over extended periods, will corrode. For example, equipment stored by CRREL in a sealed shipping container with only a small vent to the atmosphere corroded beyond use in Antarctica. This equipment was stored about 100 m from the shoreline, and during a period of six years, all ferrous, brass and aluminum surfaces were corroded beyond repair.

Table 1. Sample equipment breakdown chart.

SUBJECT: GENERATOR

ASSEMBLIES

1. Power Source
2. Starter System
3. Fuel System
4. Engine
5. Lubrication System
6. Exhaust
7. Controls
8. Gearbox/Clutch
9. Generator
10. Frame/Mount
11. Cooling System
12. Ground System

DUTY:

Continuous: Scheduled stops for maintenance.

Deployment: Stationary after set-up.

ENVIRONMENT:

Enclosed: Initial start up from cold-soaked condition.

Corrosion: Non-saline water vapor.

	MECHANICAL	ELECTRICAL	FLUID	STRUCTURAL
1)		Battery, Cables Fuse, Connector	Acid	Mount
2)	Switch Belt Bearings Throw-out mechanism	Glow plugs, Cables Fuses, Relays Alternator Voltage regulator	Lubricants	Mount
3)	Fuel Pump: O-Rings, Filter Seals, Fuel lines Bearings, Valves	Fuel pressure sensor Solenoid valves Motor	Fuel	Fuel Tank
4)	Rings, Bearings Gaskets, O-Rings Springs, Chain drive Seals, Valve guides	Glow plugs	Sealants	Engine Mounts
5)	Oil pump: Seals, O-Rings Bearings, Piping Filters, Connectors	Sensors: Pressure Level Temperature	Lubricants	
6)	Fasteners	Exhaust gas temperature Sensor		
7)	Switches Governor	Switches, Lights Meters, Wiring Connectors Voltage regulator Motor speed control		
8)	Bearings, Seals Spring, Gasket Couplings		Lubricant	
9)	Bearings, Seals Brushes, Springs Coupling	Wiring, Coil Stator, Connectors Field detector		Mounts
10)	Fasteners Bushings	Grounding strap		Frame, Anchors Mounts
11)	Coolant pump: Seals, Bearings Hoses, Fan Radiator	Wiring Temperature sensors Liquid level sensors	Coolant	Mounts
12)		Wiring, Fuses Breakers		

MATERIALS

Metals

Ferrous
- Cast Iron
- Low-Carbon Steel
- Alloy Steels
- Nickel Steels
- Stainless Steels

Non-Ferrous
- Zinc
- Copper
- Tin
- Aluminum
- Lead
- Gold
- Solder

Fluids
- Glycol-based Anti-freeze
- Low-temperature Lubricating Oils
- Low-temperature Transmission Oils
- Low-temperature Greases
- Battery Acid
- Diesel Fuel

Plastics
- Phenolics
- Fiberglas
- Wire Insulation Materials
- O-Ring Materials
- Polyethylene

Part 3. General Design Guide

GENERAL DESIGN PROCEDURE

The following procedure is suggested for either design of new equipment or redesign of existing equipment for low-temperature use.

1. Break down equipment into assemblies such as those identified for a diesel generator in Table 1.
2. Identify components of interest from assemblies and organize into classifications, such as mechanical, electrical, fluids and structural.
3. Determine environmental factors that may affect components.
4. Determine equipment use, such as stand-by or continuous operation, and who will operate it.
5. Select optimum materials.
6. Select optimum design.

Following these steps should give the designer a logical process on which to base a design concept.

CLASSIFICATION OF EQUIPMENT

In previous sections, general characteristics of the arctic environment and their possible effects on existing equipment were discussed. A general design guide has also been proposed. The objective of this section is to describe how equipment can be classified through several environmental and use categories to better assist the engineer in the design process.

In Table 1, a break-down chart is shown for a diesel generator. From looking at the chart, you can identify several sections that correspond to the general design guide. These are the assemblies that make up the piece of equipment; the components that make up the assemblies, which in turn are classified in four broad categories; the environment in which the equipment will operate; its duty cycle, including deployment; and materials that are currently being used. As this is an existing piece of equipment, optimizing design and materials is not considered on this chart. However, from this chart, a design engineer should be able to identify problem areas that need to be addressed.

The components of the various assemblies that make up the subject piece of equipment are broken down into four broad categories. In Table 1, these categories are mechanical, electrical, fluids and structural. Within these broad categories are included structural, mechanical, hydraulic, pneumatic, electrical, electronic and optical components as well as instrumentation. A different breakdown from that used on the chart may be desired, such as for more complex instrumentation. This is up to the individual designer. Our emphasis here is to identify all the various components that may be affected by the environment and then to be able to judge the environmental effects on each component and the system as a whole.

The environment in which the equipment will operate can also be divided into categories:

1. Controlled environment—equipment is operated in a heated enclosure.
2. Unheated enclosure—used for nonessential equipment and for storage.
3. Field work (surface)—where equipment is subjected to the elements but is not immersed.
4. Field work (immersed)—includes most diving equipment.

Duty cycles include:

1. Continuous duty—includes equipment used for communications and power generation.
2. Standby—backup equipment that must be available and operable on short notice.
3. Intermittent-daily—equipment used for field work.
4. Very intermittent—equipment used once or twice a week.

These classifications should help the designer better define the parameters that must be considered for effective arctic design.

MAJOR EQUIPMENT COMPONENTS

Table 2 presents groups of components, divided into categories, that are or may be used in the Arctic. Along with the components, attributes that must be addressed and the effect that low temperatures will have on that particular component are listed. Finally, some solutions to functional problems at low temperatures are suggested.

MATERIALS

Metals, plastics and elastomers

The number of materials that can be used in the Arctic is large but limited. Some of the most commonly used metals are unsuitable for low-temperature use, while others actually have improved mechanical properties. Alloying materials and altering manufacturing methods can often significantly improve the performance of certain materials that

Table 2. Major equipment components.

Component	*Attribute*	*Low-temperature effects*	*Suggested solutions*
		a. Component Class: Electrical	
Batteries:			
Lead–acid	Energy output	Falls to 20% or less of nominal.	Size battery so that 20% is enough at low temperature. Keep warm.
Nickel–cadmium	Energy output	Falls to 20% or less of nominal.	See Mazda (1983, p. 20/19).
Lithium	Energy output	Falls to 20% or less of nominal.	
Zinc–air	Energy output	Falls to 20% or less of nominal.	
Capacitors	Capacitance	10 ppm/°C to 2000 ppm/°C.	Maintain at constant temperature.
	Leakage		Select lowest temp coefficient.
	Resistance	Neg temp co 0 to −1500 ppm/°C.	Provide dynamic compensation.
Circuit boards	Dimensions	Shrink with lowering temp.	Use temperature-stable boards such as glass/resin laminate.
	Flatness	Bend or curl.	
Circuit breakers:			
Thermal	Trip point	Trip point increases with lower temp.	Use temperature-compensated type, keep warm.
Magnetic	Trip point	Trip point not affected by temp, mechanical operation may fail due to lubrication stiffening.	Low-temperature lubrication. Keep warm.
Connectors	Contact reliability	Contact is broken.	Better spring material in contact.
	Insertion ease	Difficulty in mating.	Select materials for dimensional stability of contact holder. Select seals for low-temp use.
	Environmental seals	Loss of seal.	
Crystals	Frequency	Changes ±200 ppm/°C.	Provide thermal stabilization. Select special cut. Temperature compensate. Select crystals with low-temperature coefficients.
Displays:			
Analog meter	Meter movement	May stick.	Keep warm, use low-temperature lube, select for low-temperature use. Take anti-static measures.
	Needle position	Seems to follow operator fingers.	
Electro-mechanical devices	Movement of wheels	May stick.	Use low-temperature lube, keep warm, select low-temperature model, use low friction materials.
Liquid crystal	Response time	Response time slows.	Keep warm, select low-temperature version; make allowances. Use display heaters.
Electronic inductors	Coupling efficiency	Efficiency should improve.	Keep cool and well ventilated. Keep dry. Keep dimensionally stable.
Fuses	Current carrying capacity	Current carrying capacity increases up to 120% with lowering temperature.	Keep warm, make allowances.
	Melt point current		
Insulation: Wire	Flexibility	Becomes stiff or brittle.	Keep warm. Select especially for low temperature. (Silicone, Teflon, olyethylene.)
Integrated circuits:			
Analog	Input offset voltage	Changes ± with temperature.	Provide dynamic compensation.
	Input offset current	Changes ± with temperature.	Provide stable temperature.
			Provide design allowances.
	Input bias current	Changes ± with temperature.	Use Mil. spec. components.
Digital	Turn on and turn off time	Turn on time increases.	Allow variance in design.
		Turn off time decreases.	Select low-temperature component. Warm.
Measurement systems and instruments	Accuracy	Decrease in accuracy.	Select for temperature range of interest.
	Temperature coefficient		Use compensation, calibrate at temperature, provide artificial environment.
Motors	Rotation	May fail to start turning. Excessive torque required to start.	Heat bearings, low-temperature lubrication, warm gear reducers.
Plugs	Make contact	May be harder to mate plug and receptacle.	Handle carefully to avoid overstressing.
Relays:			
Electromechanical	Contact closure	May fail to move at low temperature, mercury wetted surfaces may freeze ($T < -39$°C).	Warm, use low-temperature lube, select low-temperature version. Improve low-temperature clearances.
Solid state	Turn on and off times	Turn on time may increase.	Warm, select specifications for low-temperature use.
	Case integrity	Rapid temperature change could crack plastic cases.	

Table 2 (cont'd).

Component	*Attribute*	*Low-temperature effects*	*Suggested solutions*
Resistors	Resistance	Changes from < ±1 to > ±1200 ppm/°C.	Maintain at constant temperature. Select highest tolerance acceptable for a given function.
Semiconductors	Forward voltage drop	Neg temp coefficient. -2 mV/°C	Maintain constant temperature. Provide dynamic compensation.
	Reverse leakage current	Pos temp coefficient -3 mV/°C	Provide thermistors in circuit.
Sensors and transducers	Output	All have a temperature coefficient and specific temperature ranges in which they may be used.	Select carefully for anticipated temperature range. Use compensated models, calibrate at usage temperature. Provide heated environment.
Test equipment: Digital multimeter, signal generators, signal analyzers, etc.		All have a temperature coefficient and range of operation.	Select for temperature range. Calibrate at temperature. Design with low-temperature components. Artificial environments.
Transformers: Power distribution	Insulation Leakage	Seals may leak. Insulating oil may freeze.	Keep clean and dry. Warm before use. Specify for low-temperature operation.
Wire	Resistance	Decreases with temperature.	Not usually a problem.
		b. Component class: Hydraulics, pneumatics and fluids	
Accumulators	Pressurization Flexibility Volume	Pressure loss due to decreased gas volume. Loss of bladder flexibility. Decreased volume due to lower charge volume.	Charge accumulator in ambient. *Caution*—Lower charge before shipping—overcharged bladder may extrude and become damaged. Use bladder material such as EPDM or silicone. Use piston-type accumulator with low-temperature seals.
Antifreezes	Fluidity Clarity Volume	Freezes. Silicate gelation, causing filter and pump failure. Coolant loss.	Make sure antifreeze content is in 60% to 65% range with respect to total volume. Use ethylene or propylene glycol. Use antifreeze with lower silicate content. Use hoses designed for low temperatures (see Hose).
Diaphragms	Flexibility	Brittleness. Stiffness.	Use material with low ductile-brittle transition temperature such as stainless steel. Use elastomer or silicone.
Filters	Flow	Clogging due to ice partaicles. Reduced flow due to increased fluid viscosity.	Preheat fuel or coolant before filtering. Provide bypass to avoid catastrophic failure due to reduced coolant or lube flow.
	Condensation	Formation of ice in bowl.	Keep filter above -18°C. Drain off any water before leaving heated enclosure and right after shutdown.
Fittings	Tightness Leakage	Loosening due to thermal cycling. Leakage due to differential expansion, loss of tightness.	Use O-ring fittings and thread-lock or Teflon pipe sealant. Weld fittings on tubing if necessary.
Fuel	Cloud point Pour point Water content Viscosity	Increased viscosity. Formation of ice crystals. Formation and coagulation of wax crystals.	Remove paraffinic portion of fuel to improve cloud point (not a good solution due to loss of heat value). Blend fuel or use additives for lowering pour point. Use only very dry fuel, and siphon off any standing water. Use fuel specifically designed for low-temperature use, such as DF-A diesel fuel, JP-5 or Jet A-1 turbine fuel, or JP-10 missle fuel. Preheat fuel.
Hose	Flexibility Strength Length	Stiffening. Embrittlement. Contraction.	Use special hose designed for low-temperature use, such as low-temperature Buna-N or polyester reinforced urethane, polyallomer or polyester elastomer. Allow sufficient length for contraction (~10^{-5} in./in. per °F). Do not allow long, unsupported lengths of hose.
Lubricants	Viscosity Pour point Wax point	Viscosity change. High viscosity. Wax formation.	Preheat system. Idle at low rpm or power to warm up oils. Investigate synthetic oils. Use napthanic rather than paraffinic base oil.

Table 2 (cont'd). Major equipment components.

Component	*Attribute*	*Low-temperature effects*	*Suggested solutions*
	Stiffness Dissolved water	Increased stiffness. Ice formation.	Design in high-pressure bypass around filter to avoid lube loss. Add pour point suppressors to napthanic oils. Use lithium soap thickened, silicone oil-based greases. Use dry, cryogenic lubricants containing TFE, MoS_2, or graphite. Investigate synthetic, thermally stable lubricants such as polyethers, silicate esters, and perfluoroalkylpolyether (PFPE-2).
O-rings	Flexibility Seal	Stiffening. Breakage. Leakage.	Use low-temperature elastomers. Use backup rings. Use spring-actuated seals.
Pistons	Flow of medium Drag Bypass	Increased viscosity of fluid. Increased seal drag. Leakage of seals due to increased stiffness.	Use a low-temperature synthetic fluid. See O-rings. Insulate exposed pistons.
Pumps	Efficiency Sealing Cavitation	Increased fluid viscosity with associated decreased efficiency (oils). Increased friction. Stiffening of seals. Air entrainment due to increase of fluid viscosity. Increased suction effort.	Use low-temperature hydraulic fluid. Heat supply side. Use low-temperature seals, such as spring reinforced silicone seals. Don't run pump at full power until warmed up. Add baffles to reservoir to increase time oil spends to deaerate. Use a tank heater.
Quick-disconnects	Leakage O-ring failure Connectability	See O-rings. O-ring embrittlement. Freezing of moisture.	See O-rings. Replace O-ring with low-temperature elastomer such as silicone or polyurethane, depending on application. Hermetically seal connector.
Regulators	Sealing Control Condensation	Stiffening of O-rings. Formation of frost.	Use low-temperature O-rings. Keep unit above −23 °C (−10 °F).
Rotary actuators	See Pistons Flow of medium	Stiffening of O-rings. Increased viscosity of fluid.	See O-rings. Use a low-temperature synthetic fluid.
Rotary unions	Sealing Friction	Stiffening of O-rings.	See O-rings.
Sealants	Flexibility Integrity	Brittle point. Cracking.	Use low-temperature sealants such as silicone or EPDM-based sealant. Apply at room temperature to avoid gaps. Use TFE braid for joint sealant.
Valves (see also O-rings)	Flow Spool shuttle	Increased viscosity of fluid medium resulting in decreased flow. Freezeup.	Increase orifice sizes. Heat valve. Make sure parts have similar coefficients of thermal expansion. Make sure air is dry when using air valves. You may want to monitor spool position electrically. Use diaphragm valves.
		c. Component class: Mechanical	
Bearings:			
Ball, roller and needle	Lubrication	Stiffening or loss of lubrication. Drag, high starting torque.	Use low-temperature lubricant such as synthetic-based oils and greases containing silicones or diesters.
	Seals	Seal stiffening and cracking. Gap formation.	Spring seals, compound seals.
	Change of preload	Loss or excessive preload due to differential coefficients of expansion.	Match materials, spring-load bearings.
Belts:			
Cog, V-belt, O-ring, timing	Tension	Low-temperature set, especially during storage.	Relieve tension when not operating. Change belting material, specify low-temperature belting.
	Flexibility	Backing stiffens and cracks. Belt becomes stiff. Tensile strength decreases.	Keep drive in operation to generate internal heat.

Table 2 (cont'd).

Component	*Attribute*	*Low-temperature effects*	*Suggested solutions*
Clutches and brakes	Oil viscosity	Increased viscosity.	Use lower viscosity or synthetic oil. Check with manufacturer.
	Engagement	Freezing of plates.	Disengage during storage.
	Spring integrity	Material embrittlement.	Use non-BCC spring material.
Chains and sprockets	Lubrication	Increased wear and friction. Stiff chain. Loss of lubrication.	See Bearings.
	Integrity	Embrittlement.	Use low-temperature steels or different material.
Gaskets	Sealing	Stiffening, cracking.	Use materials such as Teflon.
Gears	Lubrication	See Bearings.	See Bearings.
	Impact	Embrittlement of teeth.	Use non-BCC metals or plastics.
	Ventilation	Freezing of breather tubes.	Insulate or heat tubes.
	Fit to shaft	Loss of fit.	Use similar materials, use key.
Push-pull cables	Lubrication	See Bearings.	See Bearings.
	Elasticity	Stiffening of parts, brittle fracture.	Use materials such as stainless steel.
Retainers	Integrity	Material embrittlement.	Use non-BCC material or stainless steel.
Seals:			
Rotary, linear, static, excl O-rings	Sealing	See Bearings.	See Bearings; also investigate alternative materials such as silicone, fluorosilicone, polyurethane, etc.
	Fit	See Bearings; also increased drag.	
Sleeves and journal bearings	Slippage	See above.	See Bearings. Key in sleeves.
	Lubrication	Loss of impact strength.	Reinforced low-temperature plastics or non-BCC metals.
	Resistance to impact		
Springs	Spring integrity	Material embrittlement.	Use non-BCC spring material.
		d. Component class: Structural	
Adhesives	Strength	Change in shear strength.	Use adhesives such as methacrylates and anaerobics that have good low-temperature strength. Apply to clean, warmed surfaces. Design joints to minimize shear stress (compound lap joints, etc.).
	Flexibility	Embrittlement.	
Framing members	Strength	Increased strength, decreased ductility.	Use materials with low ductile-brittle transition temperatures.
	Ductility		
	Thermal stability	Shrinkage-expansion. Stress concentrations. Loosening of fastened joints.	Use materials with lower coefficients of thermal expansion. Slot fastener holes. Use lock washers.
Hardware	Strength, ductility, thermal stability.	See above.	See above. Use larger fasteners in critical locations. Avoid stress risers, such as small holes and sharp edges.
Pressure vessels	Strength	Embrittlement	Use material not susceptible to ductile-brittle transition phenomenon, such as high nickel steels or nonferrous metals.
	Impact resistance	Decreased impact strength.	
Vibration isolators	Stiffness	Increased stiffness. Change in damped frequency.	Use adjustable dampers, such as air springs, to change preloads or damping characteristics. Heat enclosure.

would otherwise be unacceptable at low temperatures.

There are several mechanisms by which materials lose strength at lower temperatures. In metals, the most common phenomenon is the ductile-brittle transition temperature. The transition temperature is most common in BCC (Body-Centered Cubic) metals, such as the irons and steels, although it occurs to a lesser degree in HCP (Hexagonal Close-Packed) materials. The transition takes place because of rising yield strength without a proportional rise in ultimate tensile strength (Fig. 2). The result is a tendency towards brittle fracture rather than ductile failure. Impact toughness decreases while notch sensitivity increases. Structures and mechanisms susceptible to this phenomenon are more prone to catastrophic failure, especially when impacted.

There are several solutions to the problem of an unacceptable ductile–brittle transition temperature. The most obvious is to use a material that does not have this problem in the temperature range being considered. Examples of these materials are non-BCC metals such as copper and aluminum. These materials exhibit good ductility at low temperatures and some even increase in strength. Most stainless steels work well at low temperatures. Among stainless steels, the austenitic grades have a lower transition temperature than ferritic grades. Processing and alloying of steels will also affect the transition temperature. Deoxidizing or "killing" steels with silicon and aluminum increases their impact properties. Small-grained steel is also more desirable, with the many grain boundaries acting as an impediment to rapid crack growth during fracture. Alloying the steel with small amounts of nickel and manganese also lowers the brittleness temperature.

Irons and steels are not the only problem metals. Zinc and tin also can be troublesome at low temperatures. Zinc can lose up to 90% of its impact strength between 21 and -40°C. As many die-cast parts, such as carburetors, small pump bodies and some controls, are made of zinc, you should be careful when designing or specifying components for machines. When equipment is air-dropped, thin-walled cast zinc components may fail. Tin, as previously mentioned, can go through a phase change at low temperatures resulting in loss of all mechanical properties. Alloying with other metals will alleviate this problem.

Plastics and elastomers suffer from problems similar to those of steels. Low temperatures bring loss of ductility, increased notch sensitivity and change in elastic properties. The solutions to these problems are similar to those for steels: alloying, different manufacturing processes or different materials. The addition of plasticizers, impact modifiers and fiber reinforcement will all have positive effects on certain low-temperature properties such as elasticity and impact resistance. Thermoplastic Elastomers (TPEs) generally exhibit very good low-temperature strength. Thermoplastics and thermosets generally are not as good at low temperatures, becoming brittle in the 0 to -40°C range. Again, different alloys of the same material will have vastly different low-temperature properties.

There are several tests used to derive mechanical properties of plastics: impact, tensile and brittleness tests. The most common are the notched and unnotched izod impact tests and the tensile test, which are also commonly used with metals, and the Gardner impact, tensile impact and brittleness tests, which are more specific to plastic. The values from these tests are good for comparisons, especially if results can be found for the temperature range of interest. Most tests are done at room temperature (23°C), the freezing point of water and -40°C. Some plastics that perform well at low temperatures may be tested below -40°C.

Materials for seals and O-rings are of special concern to the designer. Loss of flexibility, increased friction and loss of sealability may all result when the wrong elastomer is used. Silicones, urethanes and fluoroelastomers, as well as natural rubber, are all able to withstand low temperatures without loss of sealability. However, stiffness and friction will increase, and chemical inertness varies between materials, so all properties must be considered. Hardness is usually a trade-off when you are trying to assure low-temperature flexibility. A solution to this dilemma is to use spring-loaded seals employing a low-temperature material such as TFE, PTFE or other fluoropolymers in conjunction with a stainless steel spring. This allows a controlled sealing force with a resilient seal.

Finally, let's look at fabrics. Weatherproof fabrics should be used for lift bags, tool bags, covers and tarps. They should be both waterproof and flexible at low temperatures. A coated fabric is therefore necessary, such as a silicone rubber or Viton-coated Nomex, Dacron or nylon fabric. Another possibility is a fabric such as Gore-Tex, which incorporates PTFE. You should also consider abrasion resistance, low-temperature flexibility, oil and chemical resistance and tear strength.

Oils and greases

The most obvious problem with oils and greases in cold regions is that they tend to become more viscous and lose their ability to properly coat the surfaces that they are supposed to protect as temperature falls. There are, however, several options for the designer. Synthetic-based oils and greases should be a prime consideration. These have been in wide use in the aerospace industry for over 10 years. The most common synthetic oils are silicone-based. These oils generally exhibit good lubricating properties down to the -40 to -50°C range. In addition, synthetic hydrocarbon oils, fluorinated ether-based oils, as well as other fluorinated oils, diester-based fluids and halogenated silicones should also be considered (Table 3). These synthetic fluids exhibit many desirable qualities for low-temperature use, including low pour points, nonflammability, good extreme pressure

Table 3. Viscosity and temperature properties of oils (after Booser 1986). All oils 20 cSt at 40°C and 0.1 MPa.

Lubricant type	*Viscosity index*	*Viscosity (cSt)*	
		-40°C	*100°C*
Fluorolube	-132	500,000	2.9
Hydrocarbon	0	50,000	3.4
Hydrocarbon	100	14,000	3.9
Phosphate base	164	8,000	4.6
Polyglycol ether	164	7,000	4.6
Ester	151	3,000	4.4
Ester base	197	1,000	6.3
Silicone	195	150	9.5

and antiwear properties, and good stickiness. Most will also perform well at high temperatures. The major problem with these fluids is seal compatibility—the base oil is often a solvent for low-temperature seals. Viscosity versus starting torque should also be investigated, especially for instrument applications.

Greases can be considered in much the same manner as oils. Synthetic-based greases tend to have better low-temperature properties than regular greases. Silicone, diester, synthetic hydrocarbon and TFE-based oils in combination with lithium, arylurea or gel grease thickeners are common low-temperature blends for greases, which have many of the same attributes as low-temperature oils. In many applications, such as low-temperature bearing lubrication, greases will out-perform oils. One additional benefit of grease is its water resistance, an important consideration in wet or underwater projects (Table 4).

Grease and oil additives should also be considered. Some of the thermoplastic elastomers mentioned in the previous section on materials can be used as modifiers for oils. These additives can be used as viscosity modifiers, extending the useful range of common motor oils. In addition, they also tend to increase the anti-friction properties of the oils, improving system efficiency. Oil additives containing PTFE have been tested in equipment in cold regions and have improved equipment performance, especially during cold starts.

In addition to oils and greases, you should consider dry lubricants, PTFE, MoS_2 and graphite being most common. These materials can be used as the primary or backup lubricant for a device. With dry, bonded lubricants, the bonding agent is usually the determining factor for temperature range. Polyimide resin binders have the best low-temperature limit.

When designing lubricating systems for arctic equipment, you should realize that the loss of lubrication is one of the prime causes of equipment failure in the field. Some precautions are therefore necessary. Consider oil heaters on larger pieces of equipment. By-pass circuits for clogged filters may also be a good idea. A backup lubricant, such as the dry film mentioned previously, would be useful in critical bearings. Finally, a strict maintenance schedule should be developed to assure proper lubrication of the various critical components.

Fuels

Fuel problems have been discussed in Part 2. As mentioned, there are some solutions to the problems of pour point and wax point. Additives to modify viscosity are available, but little can be done to change the cloud point of the fuel without decreasing its wax content and thereby adversely affecting other properties, such as heat content, cold starting ability and pumpability.

There are several fuels available for low-temperature use. Commercial no. 1-D diesel fuel is recommended by equipment manufacturers for use below 5°C. For lower temperatures, down to -55 °C, DF-A, Jet A-1, JP-5 and Type II distillate fuels should be considered. DF-A fuel (Diesel Fuel-

Table 4. Characteristics of military greases (after Booser 1986).

Military specification	*Temperature range (°C)*	*Common oil type*	*Common thickner*
MIL-G-81322	-54 to 177	Synthetic hydrocarbon	Clay
MIL-G-4343	-54 to 121	Diester/silicone	Lithium
MIL-G-21164 (5% MoS_2)	-73 to 121	Diester	Lithium soap or clay
MIL-G-23827	-73 to 121	Diester	Lithium soap or clay
MIL-G-25013	-73 to 232	Silicone	Non-soap
MIL-G-83261	-73 to 232	Fluorinated polysiloxane	F&P or PTFE

Table 5. Properties of fuels (after GSA 1954, Coordinating Research Council, Inc. 1984).

Fuel type	*Cloud point (°C)*	*Pour point (°C)*	*Kinematic viscosity (cSt)*	
			-50°C	*38°C*
DF-2	-17	-23	450	1.8-6.0
DF-1	-31	-37	100	1.4-4.0
JP-10	—	-79	36	2.2-2.7
DF-A	-46	-57	30	1.4-4.0
Jet A-1	—	-47	17	1.2-1.3
JP-5	—	-46	17	1.2-1.3
JP-4	—	-58	5	0.75-0.8

Note: Values vary widely between sources. Do not use this table for anything other than general comparison.

Arctic) is currently in widespread use in Greenland. Other fuels that may be worth considering are JP-4 and JP-10, with freezing points of -58 and -79°C respectively. Jet A, JP-4, and JP-5 fuel worked well in equipment on the Alaska pipeline project. Fuel heaters are also available (Table 5).

Gases

Some problems may also be encountered with gaseous substances. Bottled propane gas, such as that used in heating and soldering, will not gassify properly at low temperatures. Gas cylinders left out in the relatively mild northern New England winter, with temperatures only around -30°C, are troublesome. It is best if they are left in a heated enclosure if they are to be used. An alternative would be a plasma torch cutting unit for operations out of water, which can run off 0.28-MPa air and 60-Hz/1220-V power.

HYDRAULIC AND PNEUMATIC SYSTEMS

Understanding the effects of low temperatures on hydraulic fluids and components such as hoses, seals, reservoirs, valves and bladders is a first step in designing and operating hydraulic systems. Nearly all of the operating problems result from not considering fluids and elastomers.

Petroleum-based hydraulic fluids must have pour points at least 3°C below the minimum temperature to which the fluid will be subjected. Most pump and motor manufacturers specify the maximum fluid viscosity acceptable for startup, as well as for continuous operation. Sometimes a fluid can be selected that has a viscosity index (change of fluid viscosity with temperature) that will meet both criteria. If a system is operated continuously for extended periods, the viscosity for continuous operation is of primary importance. However, the startup condition cannot be ignored. In these circumstances, it is often advisable to either make provisions for intermittent operation during startup or to incorporate fluid heaters into the system. See Table 6 for a summary of properties of common hydraulic and gear oils.

Where intermittent startup procedures may be required, it is better to include a clutch between the prime mover and the hydraulic pump, and to disengage the clutch while leaving the prime mover running. Specifying a startup routine may also be necessary to ensure proper oil flow to critical elements such as bearings, gears and sliding contact mechanisms.

Fluid heaters may be built into the hydraulic fluid reservoirs, possibly eliminating the need for complex intermittent startup procedures. Heaters should be designed to raise the temperature of the fluid in the reservoir about 6°C in one hour. Heater watt densities should not exceed about 65 W/cm². Thermostats should also be provided to prevent overheating of the fluid. Heaters should be located near the bottom of a reservoir to enhance convective circulation, but should be far enough from the bottom so sludge accumulations will not contact them. Caution is advisable when designing oil heaters into hydraulic systems. Overheating of oil near the heater because of poor circulation or excessive heat generation can break down or ignite the oil.

Table 6. Properties of hydraulic and gear oils (after AMC 1971).

Oil type	*Pour point (°C)*	*Viscosity (cSt)*		
		-54°C	*-40°C*	*38°C*
Hydraulic oil				
MIL-H-6083C	-60	3,500	800	10*
MIL-S-81087A	-73	3,500	—	50
MIL-H-5606B	-60	3,000	500	10*
MIS-10150	-68	800	200	5*
Gear oil				
90	—	—	>1,000,000	250
75 W-90	-51	800,000	70,000	121
Synthetic hydrocarbon	-60	21,300	6,600	19.6

Note: Conflicting values can be found for viscosities. Use these numbers for general comparisons only.
* Viscosity at 54°C.

Hydraulic oil filtration is another problem that needs to be considered in designs. A suction filter should be provided on the inlet side of the pump. However, to avoid pump cavitation, this should be a relatively coarse strainer. Fine particles should be filtered out on the outlet side of the pump. This latter filter must be equipped with a bypass relief valve to prevent filter damage. Also, the filter case must be designed to withstand system operating pressures. Clear plastics are often used on in-line filters, but these tend to become brittle in the cold. An aluminum shell would be better. An indicator to let the operator know when fluid is bypassing the filter is useful.

You should follow the manufacturer's recommendations when selecting the proper hydraulic hose for temperature and fluid compatibility. Hose materials such as urethane, polyallomer or polyester elastomers reinforced with polyester or stainless steel can be used in ambients down to -49°C. Recommended minimum bend radii should be observed. Provisions should be made for hose contraction and expansion because of temperature and internal pressure changes. Hose flexing should be kept to a minimum, especially during low-temperature startups. On hoses that must flex, such as where pivoting pistons are used or at hinged joints, provisions should be made to prevent "S" bends or kinks during flexing. In these cases, the hose should be positioned so that the bend opens and closes like a hinge. It is important to minimize the stresses on hydraulic hoses. Failure caused by stress cracking of hose covers is common with underdesigned hydraulic hose in low ambient temperatures. Avoid long runs of unsupported hose. These could be damaged during shipment of the equipment that they are mounted on. For hose that is exposed and may be abraded, several manufacturers offer teflon hoses with braided stainless steel covers that are functional down to -54°C.

Selection of seal materials is described in the *Materials* section. Materials for such components as accumulator bladders must remain flexible at the lowest temperatures encountered, and be compatible with the hydraulic fluid. Suppliers should be questioned to assure that materials meet all requirements.

Air entrainment in reservoirs of larger hydraulic systems is another problem exacerbated by low temperatures. Because of the increased viscosity of the fluid, air is more likely to stay entrained in the fluid. This leads to pump cavitation, loss of system efficiency, degradation of cylinder performance, and may result in pump failure. Ice will also form in hydraulic systems, sometimes staying suspended in the oil and clogging filters. As mentioned in the section on fluids, heating the hydraulic oil and proper baffling of the reservoir will help eliminate these problems.

Operating at low temperatures and with cold operating fluids, valves may become sluggish or stick. It may be necessary to monitor valve spool position on remotely operated valves with Hall-effect position sensors. Care should be taken to ensure proper seals are incorporated into the valve to avoid leakage or seal failure. Materials with similar coefficients of thermal expansion should be specified for critical clearance parts of the valve to ensure that there is no sticking. On hand-operated valves, such as shut-offs, the handle must be of a material that will not become brittle in the cold. It should also be large enough to be operated with mittens on.

With seawater and high water-based fluid hydraulic systems operating in the Arctic, you need to be able to do at least one of the following:

1. Drain the system completely and dry internal parts.
2. Keep above-water portions of the system heated at all times.
3. Flush the entire system with an antifreeze solution before shutdown.

It is important to assure the proper ratio of the antifreeze solution if that option is used. The wrong ratio will result in freezeup, as can be seen in Figure 3.

Pneumatic systems also have potential problems when operating in arctic environments. Air leaving the compressor is quite warm, and therefore capable of holding more water vapor than the cold ambient air. When this compressed air cools upon expansion and contact with a cold surface, the water vapor condenses and freezes on this surface. This ice can clog filters, jam valves and stick vanes in air motors. Commercial deicing devices and fluids are available specifically for use in pneumatic systems.

ELECTRICAL SYSTEMS

Wire

Electrical wire, as opposed to electronic wire, is used to distribute power at 120/240 Vac. Fixed wiring, i.e., having solid conductors and not normally used to feed portable equipment, is usually done with a PVC jacketed wire. PVC is nominally

Table 7. Typical characteristics of insulation and jacket compounds (after Belden Wire and Cable Co. 1987).

	Low temperature flexibility	*Weather/sun resistance*	*Abrasion resistance*	*Electrical properties*	*Water resistance*	*Normal low temperature (°C)*	*Special low temperature (°C)*	*Fuel, gas and kerosone resistance*
Rubber	G	F	E	E	G	-30	-55	P
Neoprene	F-G	G	G-E	P	E	-20	-55	G
Hypalon	F	E	G	G	G-E	-20	-40	F
EPDM	G-E	E	G	E	G-E	-55	—	P
Silicone	O	O	P	O	G-E	-80	—	P-F
PVC	P-G	G-E	F-G	F-G	E	-20	-55	P
LDPE	G-E	E	F-G	E	E	-60	—	P-F
CPE	E	E	E	E	E	-60	—	P-F
HDPE	E	E	E	E	E	-60	—	P-F
PP	P	E	F-G	E	E	-40	—	P-F
CPP	P	E	F-G	E	E	-40	—	P
PU	G	G	O	P	P-G	—	—	P-G
Nylon	G	E	E	P	P-F	—	—	G
Teflon	O	O	E	E	E	-70	—	E

Note: Any given property can usually be improved by selective compounding.

Key: P = Poor; F = Fair; G = Good; E = Excellent; O = Outstanding.

Hypalon = Chlorosulphonated polyethylene
EPDM = Ethylene-propylene-diene monomer
PVC = Polyvinyl chloride
LDPE = Low-density polyethylene
CPE = Cellular polyethylene
HDPE = High-density polyethylene
PP = Polypropylene
CPP = Cellular polypropylene
PU = Polyurethane

rated for use to -20°C. However, special low-temperature versions are available that are rated for use to -55°C. Polyethylene is a good insulation for use down to -60°C, and extruded Teflon is also good for low temperature use, although it is very expensive.

Copper wire has a positive temperature coefficient. At lower temperatures, line resistance is decreased. For example, number 12 wire has a resistance at 20°C of 5.37 Ω/1 km. At -40°C the resistance decreases to 4.09 Ω/1 km. Line loss therefore decreases with temperature.

For flexible wiring such as extension cords, power tools or any appliance that experiences flexure, a stranded conductor cable should be used. Stranded wire with the smallest strands should be used where maximum flexibility is required, i.e., a 65-strand 12-gauge wire is more flexible than a 16-strand 12-gauge wire. The greatest problem with wire and cable at low temperature is the brittleness of the insulation material. Cable insulation must be flexible to the lowest expected temperature. Silicone rubber insulation is available that will remain flexible down to -80°C. Teflon is rated flexible to -70°C. Some polyethylenes have also good to excellent low-temperature flexibility.

Insulation properties of prime importance for arctic work are low-temperature flexibility (as mentioned above), sun resistance, maintenance of electrical properties (high resistance and breakdown voltage) and water resistance.

Any wiring that can be done in a warm environment should be completed before Arctic deployment. Fixed wiring may be done with less robust insulation but must be protected from physical abuse at low temperatures. Avoid sharp bends, contact with sharp corners, or other circumstances that will mechanically stress the wire jacketing. Wire and cable that must remain flexible at low temperatures must have carefully selected insulation and jacketing materials. Table 7 lists properties of some common insulating materials.

Connectors

Connectors should probably be called connector assemblies, since they are made up from many individual parts. Connectors are composed of parts from the following list: electrical contacts, dielectric (insulating) contact housing, a shell to hold everything together, seals front and rear, and strain relief for the wires (Table 8).

Contacts are most commonly made from cartridge brass, which is composed of 70% copper and 30% zinc. Brass is usually plated with a more corrosion-resistant material, such as tin, silver, gold or nickel, to prolong its useful life. Another fairly common contact material is phosphor bronze. Phosphor bronze has mechanical proper-

Table 8. Connector parts and materials.

Component	*Material*
Contacts:	Cartridge brass (plated) Beryllium copper, alumel chromel Phosphur bronze, constantan Platinum, steel, iron
Insulator:	Nylon Glass-filled Nylon Thermoplastic Glass-filled thermoplastic Compression glass Ceramic Elastomeric material Diallyl phthalate Glass-filled diallyl phthalate Teflon, phenolic, glass-filled phenolic Polychloroprene Epoxy Glass-filled epoxy Melamine
Shell:	Stainless steel, steel, iconel, monel Aluminum alloy, titanium Brass (plated)

ties superior to brass but is slightly less conductive.

Insulators range from very soft elastomeric materials to extremely brittle glass. The most common material used in quality connectors is diallyl phthalate and glass-fiber-filled diallyl phthalate. Diallyl phthalate is used because it has exceptional dimensional stability and excellent resistance to heat, acids, alkalies and solvents, and also has very low water absorption qualities.

Shell materials range from aluminum to brass to stainless steel and titanium. Aluminum seems to be the most popular and is available painted, plated or anodized. Shell material should be selected for robustness and environmental resistance. Connectors are available in fine thread, coarse thread and half twist bayonet latch styles, as well as straight push-together latching. Selection is determined by the application.

Seals are generally a soft elastomeric material. Face seals are usually manufactured by potting the rear of the connector shell with either a removable or permanent compound.

Waterproof connectors in general employ a soft elastomeric material as the insulator around the contacts. When mated properly the two connectors will compress this material slightly for an effective seal. O-rings are also used in some connectors in the mating parts. The rear area of the connector is sealed by O-rings, compression fittings and by using potting compound. Compression seals may be on each wire or on the whole cable. It is important to use a seal material such as low-temperature elastomers that will not take on a low-temperature compression set. For Teflon wire a compression seal is best since potting compounds will not stick to Teflon unless the Teflon has been chemically etched. Chemical etching of Teflon is not easy or safe under arctic field conditions.

For arctic use, connectors with crimp-on electrical contacts are easier to repair in the field. However, this requires a special crimping tool and a contact insertion and removal tool for each type of connector in the system. It therefore is advantageous to standardize connectors for as many systems as possible.

Strain reliefs are available as two halves clamping together, clamping to one side, and circumferential gland-type compression clamping. Strain relief is necessary to prevent the wires from being pulled out of the rear of the contact pins. Table 8 contains a list of the parts that make up connectors and their common materials.

Resistors

All resistors have a temperature coefficient, which means resistance will vary with temperature. The temperature coefficient can be either positive or negative and has the units of ppm/°C (parts per million per degree Celsius). Any circuit designed for use at low temperatures must be analyzed for the effects that resistance change with temperature will cause. Some typical circuit changes that occur are: amplifer gain changes, voltage reference point changes, voltage divider ratio changes, constant current source drift and oscillator frequency drift. Resistor temperature coefficients can vary from greater than ±1200 ppm/°C to less than 1 ppm/°C. Circuit analysis is essential to make sure that money is wisely spent on the best resistor for a specific function in a circuit. Resistor costs can vary from a few cents to several dollars apiece.

A secondary problem may occur in the physical mounting of resistors to circuit boards and other mounting strips. Resistors should be mounted to minimize strain transmission into their bodies. This usually means allowing an extra bend in the leads.

Table 9 contains temperature-related drift data for various resistors and resistor configurations. From it, the best resistor for the accuracy necessary in an application can be specified.

Table 9. Temperature coefficients for common resistors.

Resistor type	Temperature coefficient range (ppm/°C)
Standard	
Carbon composition	±1200
Cracked carbon	−200 to −1000
Wire wound (general)	±200
Precision	±1 or less
Film	
Metal (thick film)	±50
Metal (thin film)	±5
Carbon	−500
Oxide	±500
Potentiometers	
Wire wound	±10
Cermet	0 to +100
Carbon	±100 to ±250
Conductive plastic	±300

Table 10. Thermal capacitance drift for common capacitors.

Capacitor type	Temperature coefficient range (ppm/°C)
Impregnated papem	+100 to +200
Metallized paper	+150 to +200
Mica-stacked	±200
Metallized	±60
Ceramic	
Low permittivity	+80 to +120
Medium permittivity	−600 to −800*
High permittivity	too variable to specify
Glass	+150
Glass vitreous enamel	+120 (−55 to +200°C)
Plastic	
Polyethylene terephthalate	−150 ±75
Polycarbonate	±150
Polystyrene	−150 ±50
Polypropylene	−50 to −300
Electrolytes (aluminum)	±1000 to 2000
Tantalum (pellet)	+100 to +200
Tantalum (foil)	+500
Variable capacitors	
Air dielectric	+10
Ceramic rotary and tubular	−750 to +100

* Used for temperature compensation.

Capacitors

Capacitors are grouped by the type of dielectric used. All are sensitive to temperature, frequency effect and age. Both insulation resistance and capacitance vary with temperature, so circuits must be carefully analyzed to determine what the capacitance change will do. Some typical circuit changes are: power supply ripple increases with a drop in temperature, tuned circuits become untuned, time constants change, wave shapes change and circuits become noisy from loss of filtering. Table 10 gives general capacitance drift as related to temperature. Again, specify the capacitor with the necessary accuracy for the job.

Displays

Electrical displays may be one of three types: analog meter, electromechanical or digital. Analog meters are susceptible to lubrication stiffening problems and to differential expansion problems in their meter movement bearings. Analog meters are commonly enclosed in plastic cases. Under arctic conditions of low humidity, plastic meter faces may build up a large static electricity charge. This static charge can cause very erratic behavior of the pointer inside the meter. Antistatic spray may be of some help in relieving this problem. Meters should be specified for low-temperature use.

Electromechanical displays commonly have rotating disks with numbers on the edge. Rotation is controlled by a motor or ratcheting mechanism. Typically, this is a complicated mechanical device with many lubricated parts. Lubrication must be rated for expected temperature range or the unit must be warmed.

Digital display characteristics are described in Table 11. An important factor to consider is readability under arctic lighting conditions, such as sunlight reflecting off the snow surface. Light-emitting diodes (LEDs) fade under bright light so a shield or hood may be needed over the display to ensure that it can be read. At -40°C, liquid crystal displays (LCDs) will be very slow responding, taking as many as three seconds to change a digit. To solve this problem, some LCDs are available with heaters. Heaters may also be applied to many other standard LCDs. The drawbacks to this solution are greater power consumption and an increase in circuitry. Some ambient light is also necessary for proper operation of LCDs.

Relays

Mechanical relays must either be specified for

Table 11. Characteristics of displays in electronic equipment (after Graf 1983).

Display technology	*Relative brighness*	*Typical operating temperature (°C)*	*Durability*
Light-emitting diodes	Medium bright. Washout in sunlight.	-40 to 85	Rugged, no breakable parts.
Liquid crystal displays	High contrast. No luminance.	-40 to 65	Mechanical damage possible (glass construction.)
Gas discharge	Bright.	0 to 70	Rugged.
Incandescent	Very bright.	-55 to 100	Mechanical damage possible (glass and filaments).
Vacuum fluorescent	Bright.	-10 to 55	Mechanical damage possible (vacuum tube glass construction).

low-temperature use of they must be relubricated for arctic conditions. The electrical parts will function normally at low temperatures; however, time delay relays must be specified for low-temperature use. Typical time delays rely on resistor-capacitor networks for time control, and at low temperatures, capacitors and resistors change value. Time delays could thus be seriously in error.

Solid-state relays do not have lubrication problems. They do, however, suffer from mechanical failure since devices typically are potted in a plastic enclosure. Rapid changes in temperature may cause the potting or case to crack. Thermal stressing caused by highly loaded relays is a related problem. Manufacturers' specification sheets need to be studied carefully before a relay is selected for arctic use. Solid-state time delay relays are also subject to large error caused by component value changes related to temperature.

Relays with mercury-wetted contacts have very low contact resistance. However, mercury freezes at about -38°C. Operating and storage conditions need to be considered in any new design or retrofit.

Inductors

Inductors generally are coils of wire with air cores. As such, they are not affected by temperature. Coils with a metallic core may experience small inductance changes caused by physical dimension variances due to temperature, but this is not generally a problem.

Transformers for power circuits are wound from insulated copper wire. The resistance of copper wire decreases with temperature so that self heating is less of a problem. The insulation commonly used is a synthetic enamel. The input and output leads are usually a stranded wire spliced onto the transformer winding leads. At extreme low temperatures care must be taken not to bend the enameled leads. Transformer operation is not normally adversely affected by low temperatures.

Transformers used in electronic circuits are constructed in the same manner as their high-powered cousins and are subject to the same limitations. Adjustable transformers may have slight changes in their coupling efficiency ascribable to minute dimensional changes in the size of the core caused by temperature. This effect occasionally causes slight detuning of radio frequency (rf) amplifiers.

Electric motors

At extreme low temperatures, motors may fail to start because the bearing lubricant has become too stiff. A locked rotor may draw as much as seven times the full load running current and result in circuit breakers opening. Suggested remedies are to use low-temperature lubricants or preheat the bearings before energizing the motor.

Motors with brushes may experience increased brush wear due to the temperature effect on the brush springs. Brushes should be cleaned frequently and deburred so they can move freely in their slots. Any gear reduction boxes should be filled with a low-temperature lubricant or warmed prior to use.

Electric lighting

Lighting can fall into three categories: indoor, outdoor and underwater. For indoor lighting in a warm environment, the rapid-start, hot-cathode fluorescent lamp will provide adequate lighting at minimum power drain. For outdoor lighting under arctic conditions, incandescent lamps will provide the best service. Fluorescent lamps require more complicated hardware, such as the ballast, and the electrodes must be heated before they light.

The filament is the limiting factor in the operation of incandescent lights. Low voltage, 1.5-V filaments are very short and thick, thus making them hard to heat without the support wires overheating. Lamps in the 6- to 12-V range are robust enough for automotive and similar uses. Standard 120-V lamps are available in many types and sizes, including rough service bulbs. The high-voltage lamps (300-V) have long, slender filaments that are very fragile and difficult to support inside the bulb. Frequent cycling of lights and overvoltages will shorten filament life in low-temperature applications.

Underwater lighting should be from low-voltage (less than 150 V) lamps on lines protected by ground-fault circuit interrupters. Incandescent lamps are generally the most practical for underwater use. The National Electrical Code does not require a ground-fault interrupter on submersible equipment that is driven by a transformer at 15 V or less (NFPA 1984). Specifications may differ for certain applications, such as when divers are involved.

Circuit breakers and fuses

Fuses rely on a strip of metal melting. At low temperatures the current required to melt the strip may rise to 120% or more of the nominal current-carrying capacity of the fuse.

Thermal-mechanical bimetallic strip circuit breakers rely on heat generated by the current to deflect a bimetallic strip incorporated into the trip mechanism. At low temperatures the current required to trip the breaker may increase to over 200% of nominal rating.

The trip points of magnetic circuit breakers of the instantaneous trip type are unaffected by temperature. Time delay magnetic circuit breakers will be greatly affected by temperature since they rely on a fluid for damping the movement of a core inside a solenoid.

Any grease-type lubricant inside the trip mechanisms of any of these circuit breakers will be affected by low temperatures. Breakers should be ordered with dry lubrication if possible or with low-temperature silicone grease. Low-temperature testing is also recommended.

Switches

Care must be taken to ensure that contact forces are maintained between switch points for various temperatures. Mercury switches may freeze shut if the temperature drops below -38°C. Another concern is the embrittlement of the materials used for construction, such as springs, latches and case materials.

Batteries

Batteries are available in two types of cells: primary cells and secondary cells. Primary cells are used once and discarded; they are not rechargeable. Some typical primary cells are carbon-zinc, zinc-chloride, alkaline-manganese dioxide, mercuric oxide, lithium and zinc-air. For low-temperature applications, the lithium battery is usually the best primary cell battery. It has the highest energy capacity (300 Wh/kg), is rated for use to -40°C, and suffers the least loss in capacity at low temperatures. Higher capacity, less efficient batteries may be more economical to use, however. A careful analysis of the application may be necessary before the correct battery is specified.

Secondary cells must be charged before use and may be recharged many times. The main types of secondary cells are lead-acid, nickel-cadmium and silver-zinc. The best secondary cells are the lead-acid batteries, which are rated for use to -60°C and have small capacity loss at low temperatures. Batteries take longer to charge when they are cold than when they are warm. It is therefore often better to charge or recharge a battery in a warm environment even though it will be used in the cold. Table 12 contains a summary of operating ranges for common primary and secondary

Table 12. Operating temperatures for common batteries (after Mazda 1983).

Cell type	*Nominal voltage (V)*	*Energy output (Wh/kg)*	*Temperature range (°C)*
Primary cells			
Carbon-zinc	1.5	40	5 to 60
Zinc chloride	1.5	90	-10 to 60
Alkaline MnO_2	1.5	60	-10 to 60
Mercuric-oxide	1.35–1.4	100	-20 to 100
Lithium	3.0	300	-40 to 80
Zinc-air	1.4	200	-40 to 60
Secondary cells			
Lead-acid	2.1	20	-60 to 60
Nickel-cadmium	1.2	30	-40 to 60
Silver-zinc	1.5	110	-20 to 80

cells, as well as their nominal voltages and energy outputs.

All batteries lose capacity as temperatures decrease. The extent of diminished capacity is governed by the load on the battery and the temperature. Intended use must be carefully evaluated before a battery is selected.

Electrical receptacles

Electrical plugs and receptacles normally present no unusual problems at low temperatures. Plugs and receptacles need to be kept clean and dry. Plugs are most commonly made from nylon or other thermoplastic. Receptacles are most commonly made from a phenolic material reinforced with fibers and fillers. Phenolic is used for its dimensional stability. Nylon may change dimensions but there is enough flexibility in the contacts to accommodate this distortion. Materials for extension cords need to be carefully considered. Standard commercial extension cords are normally not designed for low-temperature use.

Large transformers

For this report we consider large transformers to be any transformer of 500 kVA rating or more. Insulation used in power transformers is of two types, liquid or gas. Mineral oil is the most widely used transformer insulating material, used because it has high dielectric strength. It also can recover from dielectric overstress. Sulphur hexafluoride gas is used in some cases with up to 0.303 MPa of pressure in the transformer cans, which have been rated as high as 25,000 kVA and 138 kV. Nitrogen and air insulated transformers are seldom used above 15 kV.

All sealed transformers must be checked for insulation changes. All will have seals on the ports where the leads enter the enclosure. Seal material should be checked for low-temperature performance. Transformers should be kept clean and dry. Excessively high temperatures (nominally 85°C) will lead to premature insulation failure. Manufacturers should be consulted to find the freezing point of any insulating fluids used and the expansion coefficients for the fluid, as well as any performance characteristics that may be affected by low temperatures.

All open air transformers must be kept clean and dry. If they become frosted, all moisture must be removed before the transformer is energized.

ELECTRONICS

Semiconductors

Transistors have two main temperature-related characteristics: forward voltage drop across the base-emitter junction and the collector reverse leakage current. Forward voltage drop increases with decreasing temperature—a negative temperature coefficient of about 2 to 3 mV/°C. This might be a problem in low voltage precision circuitry. However, many compensation techniques have been developed and can be found in the literature. Reverse leakage current has a positive temperature coefficient. At low temperatures, leakage current decreases and should present no problem.

Transistors should be specified for low-temperature use to ensure that the transistor has been mounted inside its case in a way that takes into account dimensional changes caused by temperature. Transistors mounted on circuit boards should have strain relieving mountings, as discussed in the section on resistors.

Diodes are single semiconductor junctions and are subject to the same temperature effects as transistors. Compensation techniques must be employed in any critical circuit. Physical mounting must allow for dimensional changes caused by temperature.

Crystals

Crystals are used in oscillating and filtering circuits. Operating frequencies may vary with temperature. These frequency shifts may ultimately render radio equipment such as transmitters and receivers unusable. Crystals are also used for clock functions, and a large timing error could accumulate. Most crystals have at least one temperature at which their temperature coefficient is zero. Crystals are available in temperature-compensated and temperature-controlled versions. Typical temperature coefficients range from ± 60 to ± 3 ppm/°C. Temperature-controlled versions are maintained at their zero coefficient temperature with stability in the range of $\pm 2 \times 10^{-7}$ to $\pm 1 \times 10^{-8}$ ppm/°C.

Integrated circuits

Digital logic Integrated Circuits (ICs) operate either on or off (one of two possible states) and may be thought of as switches. From a study of manufacturers' literature, it appears that the major temperature effect is in the turn-on and turn-off times of the various gates involved. Turn-on times tend to increase slightly with decreasing temperature. The result of these timing changes is that signal propagation through a system may be delayed a little longer than normal when the temperature is very low.

Analog ICs are seldom used as switches but rather are used as a multiplying, coupling or proportioning device between circuits. Analog devices have three main characteristics upon which temperature has an effect. Input offset voltage varies with temperature from microvolts per degree to millivolts per degree. This changing voltage will show up on the output of the device multiplied by the gain of the circuit. Input offset current and input bias current may vary from nanoamperes to picoamperes per degree. These are potentially more troublesome than the offset voltage since they can cause large shifts in the dc operating point. Also, input bias currents flowing through a high resistance source can cause very large offsets to appear.

Filters

Filters are designed to pass low, high or specific bands of frequencies. They may also be used to exclude or stop specific bands of frequencies. They are designed to have definite corner points on the frequency spectrum. Temperature effects on the components will shift the corner points by varying amounts as determined by the changing values of components. The amount of attenuation that the signals receive may change with temperature. For circuit stability over a wide temperature range, components must be selected with the expected temperature end points in mind.

Circuit boards

Printed circuits are a pattern of wiring on an insulating base. Circuit boards are available with conductors on one side, on both sides, or as a multilayer board. Board materials commonly used are one of the following: phenolic, a paper-filled phenolic resin used when temperatures are stable and near room temperature; glass epoxy laminate, the most widely used because of its excellent temperature stability; and ceramic, used generally in small pieces and when high temperature stability is required. For arctic temperatures, the glass epoxy-laminated board is the prime candidate.

Sensors and transducers

Some general guidelines for sensors and transducers are defined below. First, however, some definitions are necessary. A sensor is the primary detector or the first element in a measurement system. It responds to some external stimulus. For instance, a thermistor changes its resistance when the temperature of its environment changes. If the resistance is read with an ohmmeter, we have a temperature sensor system.

A transducer is a device that converts energy from one form to another. If we take the above thermistor and put it in a wheatstone bridge such that a change in temperature causes a change in output voltage from the bridge, the resulting device is a transducer. Thermal energy has been converted into electrical energy. A measurement system would consist of a sensor, a transducer network and some signal conditioning equipment (for instance a direct reading thermometer).

All elements in a measurement system are affected by temperature changes. Temperature-compensated elements are only compensated over a specified temperature range. The designer of any measurement system must account for all the coefficients and ranges if a workable system is to be produced. Any sensor or transducer planned for use under arctic conditions must be installed with cables and connectors suitable for arctic use, i.e., flexible cable and waterproof connectors. The following are some guidelines for design of specific transducers.

Temperature sensors must be kept free of ice. An ice-coated sensor will read the temperature of the ice, not the ambient to which it is exposed. In addition, ice growth in the space between a sensor and its protective shield could break the sensor. Temperature sensors should be protected from direct sunlight. A dark-colored sensor may read several degrees higher than it should because of solar heating.

Pressure transducers typically have a small cavity in front of a diaphragm, which is connected to the sensing element. Ice must not be allowed to grow in this cavity since this growth can destroy the diaphragm or cause a severe offset to appear on the output of the transducer.

Force transducers are of two general types, those that allow very small displacement (1×10^{-6} to 1×10^{-3} cm), such as piezoelectric or foil strain gauged rods, bars and diaphragms, and those that allow a larger displacement (1×10^{-3} to 2.5 cm), such as linear variable differential transformers, variable reluctance, variable capacitance and variable resistance transducers. The latter types rely on displacement measurement calibrated in terms of force applied. The small displacement types must have their contact surfaces free of foreign materials before any force is applied. The larger displacement types usually have very delicate movable parts and must be kept free of frost, ice or any other foreign material. Movable parts should be clean and dry or specially lubricated for low-temperature use.

Displacement transducers, whether for linear displacement or for rotary motion, must be kept free from ice, snow and frost buildup. Linear motion types may be contacting or noncontacting. Noncontacting versions generally are for measuring very small displacements. It is very important to keep the gap between the sensor and its target clear. The direct contact models are commonly coupled via a cable or a rod. Snow or ice buildup could pull the cable or bend the rod, causing a false displacement reading.

Light sensors could be affected by the bright ambient conditions of arctic summer. Light sensors will also be affected by snowfall and low temperature. The net effect of arctic conditions must be understood before light sensors are deployed.

Magnetic field sensors or Hall-effect transducers are semiconductor devices and, as such, have a temperature dependence, typically ranging from -0.05 to -0.25% of reading per degree Celsius. They normally have an operational range from -65 to 85°C.

Meters and measuring instruments

A survey of four major equipment manufacturers (Keithley, Fluke, Hewlett-Packard and Philips) indicates very little test equipment is commercially available for low-temperature use. The majority of equipment is rated for operation between 0 and 50°C, with -40 to 65°C the standard for storage. Computer systems and calibration equipment are rated for operations between 10 and 40°C and -10 and 60°C for storage. Nonoperating temperatures must be controlled while equipment is in transit to or in storage in the Arctic. Manufacturers should be consulted if temperature excursions are to be outside of the recommended limits.

Most equipment that runs on line power is capable of keeping itself warm if provided with a suitable insulated enclosure. Care must be taken to ensure that the enclosure is not too efficient, resulting in equipment overheating. Usually, a small exhaust fan and an auxiliary heat source controlled by thermostats is sufficient to maintain a stable environment for test apparatus. Often, the auxiliary heat source may be as simple as a 60-W bulb.

Please refer to Appendix B for a more comprehensive treatment of this subject.

OPTICS AND VIDEO

Although optical properties of devices such as lenses, mirrors and filters are not directly affected by low temperatures, problems can occur in mounting, alignment and moisture accumulation. Optical mounts should not incorporate dissimilar materials unless proper consideration has been given to thermal coefficients of expansion. If portable equipment with optical components is to be subjected to alternating high and low temperatures, a deflated plastic bag should be sealed around the device before it is moved from a cold to a warm environment. This will keep moisture from condensing on the cold surfaces. Specific optical applications are discussed in the following paragaphs.

Problems with cameras in the cold are most often caused by film breakage and improper shutter lubrication. Cameras should be serviced for operation in the cold, which mainly involves cleaning and using a low-temperature lubricant on mechanical parts. This servicing should be carried out by a competent camera repair service. Film breakage is especially critical in the cold because of the sharp bends that the stiff film must negotiate while it is being advanced for the next frame. Film is even subjected to reverse bends in some cameras. Normally, as the film becomes stiffer while it cools, greater force is required to advance the film, until finally the film advance sprocket strips the track from the film. The camera operator may not even be aware of the problem until the film is developed, and expected exposures are missing. The best way to prevent breaking photographic film is to keep it warm. Keeping the camera inside your coat between exposures is often adequate, as long as the camera is not exposed to the cold too often or for too long. If the camera body and internal components become cold, problems with condensing or freezing moisture, or both, may occur when you place the camera in the warm, moist environment inside a heavy coat.

Magnetic tape consists of a thin magnetic coating applied to a flexible nonmagnetic base material. In low ambient temperatures, magnetic tape may experience problems similar to those of photographic film. In addition, as the tape becomes stiffer in the cold, it may slip. This will result in the loss or distortion of video, data or voice recordings. Inexpensive tapes sometimes use cellulose acetate for the base material. For use in the cold, tape base material should be a polyester, such as Dupont Mylar. Unnotched polyester will retain over 90% of its impact strength at -40°C with a 40% increase in stiffness.

Care must be taken in selecting fiber optic cables for use in the cold. Optical fibers are usually coated with plastic to improve their strength. When cooled, the optical fibers experience compressive stresses caused by the plastic jacket's higher thermal coefficient of expansion. The optical fiber experiences microbends, which result in increased optical attenuation. Fiber optic cables have been designed with attenuation changes of less than 2.0 dB/km over a temperature range from -55 to 85°C. This is accomplished by incorporating a low modulus "buffer" between the optical fibers and the outer jacket. An additional problem with the plastic jacket is that it may stiffen and crack at low temperatures. An elastomeric or elastomer-blended thermoplastic cover should eliminate this problem.

A number of fiber optic connectors are available with low-temperature operating ranges from -55 to -65°C. Methods for attaching connectors to cables include both crimp-type and epoxy-type joints. Operation of fiber optic boosters in cold regions should consider the performance of electronic components, which were discussed previously.

SUMMARY

This general design guide is intended to give the reader a better understanding of the challenges of design for the arctic environment. Rapidly changing weather conditions, drastic changes in material properties, deviations in component properties, and difficulties in maintenance and operations all will confront designers in their quest for a suitable end product. By following the suggested general design procedure, consulting the component charts and referencing the general design guide, a solid basis for development or modification of an end product for use in cold regions can be established.

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APPENDIX A: DATA BASES AND LITERATURE SEARCH

We conducted a literature search of three data bases to investigate the availability of information on cold regions phenomena as related to arctic design. We employed two search services: ORBIT and DIALOG. ORBIT is ORBIT Search Service of ORBIT Information Technologies, a division of Pergamon ORBIT Infoline, Inc. Access to articles is through Information on Demand, Inc., P.O. Box 9550, Berkeley, California 94709. DIALOG is Dialog Information Services, Inc. They are located at 3460 Hillview Avenue, Palo Alto, California 94304. Charges for each service vary depending on connect time and database searched.

The three databases searched were COLD, COMPENDEX and NTIS. COLD deals exclusively with cold regions and covers all scientific and engineering disciplines. It is prepared by CRREL and is available through ORBIT. COMPENDEX covers significant engineering literature, from which cold regions information can be extracted. It is prepared by Engineering Information, Inc., and is available through ORBIT and DIALOG. NTIS covers Federal government-sponsored research and development conducted through Federal agencies. Again, cold regions and low-temperature information can be extracted from this database. NTIS is prepared by the National Technical Information Service of the Department of Commerce and is available through ORBIT and DIALOG.

A breakdown of the key words used in the searches follows as Table A1. One particular note should be made. When searching for sources on gaskets, sealants and seals, we ended up with hundreds of citations for penguins, whales and seals. The seals that are of interest to this guide were mechanical seals, not Weddell seals. Mechanical should be "anded" with seals to avoid this problem.

Table A1. Cold regions key words.

Arctic Antarctic Low temperature	Primary key words: To be included in all searchers ("ored")
Underwater Remote	Secondary key words: Either could be included ("ored")
Equipment Machinery Components Materials Electronics Electrical Hydraulics Construction	Qualifiers: Key words to be "anded" to primary and secondary key words (ors)
Seals and Mechanical Bearings Batteries Power Supplies	Secondary qualifiers (ors)
Oils Fuels Greases Lubricants Plastics Metals Rubber	Tertiary qualifiers (ors)

Example—To search for Low-temperature fuel seals: (Low temperature or arctic) and[(seals and mechanical) or (seals and fuels) or (seals and hydraulic) or (seals and machinery)].

The following is also suggested if another search is to be conducted: 1) exclude the topic "cryogenics," 2) specify a cutoff date, such as 1977, and 3) unless a translator is available or trends in foreign research are desired, specify English only. A significant proportion of our citations were in Russian on our first search, when the librarian missed the English-Only specifier on the search request.

APPENDIX B: USING ELECTRONIC MEASUREMENT EQUIPMENT IN WINTER*

RONALD T. ATKINS

It is well known that heat is the enemy of electronic semiconductort devices because it causes high noise voltages and large leakage currents. But low temperatures can also present problems—for example, high junction voltages, loss of hermetic seals, and breaks in input/output lead wires.

Today, electronic instrumentation and measurement equipment can be successfully operated in a winter field environment much more readily than 10 or even 5 years ago. Semiconductor devices like transistors, diodes, silicon control rectifiers (SCRs), and operational amplifiers will work at temperatures down to -40°C. With modern integrated circuit technology it is much easier to obtain excellent thermal performance from a circuit since the entire circuit is concentrated on a small chip, guaranteeing that all its components will have a uniform temperature. Better design strategies are constantly being developed to keep electronic devices well behaved over wide temperature ranges.

Still, there are pitfalls to be avoided when using electronic equipment in a winter field environment. Before potential problem areas and ways to avoid them are discussed, a definition of "winter field environment" is necessary. For the purpose of this article it means:

- Nighttime temperatures around -12°C to -18°C but occasionally as low as -30°C or -40°C.
- Daytime temperatures around -5°C but occasionally as high as 5°C.
- Low relative humidity.
- Some days with bright sunshine and some dark days with low visibility.
- A foot or two (about ½ m) of relatively dense snow on the ground, periodically topped off by a snowfall of lighter, fluffy snow.
- Occasional blowing snow, usually fine and powdery.
- Occasional thaw periods with above-freezing temperatures, thick ground fog and rain.

The discussion of how these winter conditions can cause problems will be broken into three categories: 1) commercial equipment, 2) individual components, and 3) installation techniques. The examples cited are not meant to be all inclusive, but merely representative of the types of problems that occur. Obviously, there will be some overlapping, since certain problems are common to all categories.

Commercial equipment

Electronic equipment that is large and complex will be kept in heated instrumentation vans and therefore will probably never be exposed to cold. Nevertheless, electric power and heaters have been known to fail, so it is a good idea to check to see what the equipment's storage temperature is. If it can't be stored at -30°C or so, a backup heating system might be considered—kerosene or propane space heaters, for instance. Examples of equipment that can be damaged at -30°C include any device that uses a liquid crystal display as well as some meters, especially those with taut-band suspensions. Some instruments contain these devices as "specials," which have been designed to withstand the cold. Check the equipment manual. There may or may not be a problem.

A second group of commercial instruments that may have problems is the test equipment used to support the main instrumentation system. Examples of this equipment are digital volt-ohm meters, oscilloscopes, thermocouple readers, multimeters and counters. Very often equipment of this type is battery-operated. It may be used to install, monitor, align, calibrate or repair outside equipment, and may therefore be exposed to winter conditions for up to several hours. If test equipment is to be used in this manner, the following points should be considered.

Even though a piece of equipment appears to operate correctly at low temperature, it is always a good idea to have some means of checking it, even if only at a single point. For example, a digital multimeter can always be checked by shorting its leads on its lowest "volts" range to be sure it reads zero. Another check is to keep a precise resistor with a low temperature coefficient (10 ppm or less per degree Celsius) on hand and occasionally check the "ohms" range. For a thermocouple reader a short piece of thermocouple wire can be put under the tongue to read a "known" temperature. If this is done, the thermocouple wire should be held tightly with both hands where it exits from

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the mouth to prevent an erroneous reading due to heat conduction along the wire. It is also possible to carry an ice bath as a temperature reference, but this thermal system must be kept above 0°C to work properly. For volt-ohm meters, a couple of small batteries can be kept in the pocket to check "volt" scales.

Some hand-held instruments have low-temperature "specs" down to -40°C. However, they may give inaccurate readings during the transition from one temperature to another. The reason for this is that during the transition compensation circuits may not all be at the same temperature. This problem becomes especially severe if the instrument is repeatedly taken from a heated vehicle into the cold and back again. If thermal gradients cause problems, the easiest solution is to keep the instrument inside your coat while it is in the cold, or else keep it in a small Styrofoam box so that temperature cycling is minimized. Another point is that testing of equipment at low temperatures should include a test during temperature transition.

Instruments with LED (light emitting diode) readouts may be a problem on bright, sunny days with strong reflection from the snow cover. Dark glasses help some, but it may be necessary to put the instrument under your coat or in a box to keep the display from "washing out."

Instruments that have been left in the cold long enough to become thoroughly chilled should be wrapped in air-tight plastic before being brought into a warm environment. This is to prevent the warm air from coming in contact with the cold circuit boards. If this should occur, the air will be chilled below its dewpoint temperature, and moisture will "condense" onto the circuit. Since the volume resistivity of this moisture is about 20,000 Ω or so, it will almost certainly cause problems in today's high-resistance circuits. Of course the instrument won't be permanently damaged, but it will be useless until it dries out.

As a rule, strip chart recorders must be kept warm in the field. Otherwise, the ink freezes and the lubrication on the chart drive and/or slide wire causes sluggish, unreliable operation. There are some recorders that were designed for winter field operations. They have alcohol-based inks and Teflon gears. They cost more, but may be worth it.

Individual components

Many field instrumentation systems involve some sort of noncommercial interface or control circuit which was designed and built by the users. The components that go into these circuits deserve some consideration.

Semiconductor devices can generally be purchased as military grade, industrial grade, or commercial (consumer) grade. The low-temperature "spec" for full performance on military grade devices is -40°C or lower, while on the industrial grade devices it is generally 0°C. For winter operations it is worth spending the extra money for the military grade, especially for integrated circuit devices, both analog and digital.

Small components all have their peculiar problems at low temperatures. For instance, carbon resistors and some capacitors have exceedingly high temperature coefficients (1000 ppm per degree Celsius and even higher). Some electrolytic capacitors will fail below 0°C; variable resistors become stiff and difficult to turn; liquid crystal displays get sluggish and difficult to read; and rotary switches become stiff and hard to turn. The solution is to use mil-spec components whenever possible. It is also a good idea to test completed circuits in a freezer, just to be sure.

Batteries are especially troublesome at low temperatures. All commercially available batteries lose some of their capacity as the temperature drops. However, lead-acid cells (including sealed cells) will probably give the best low-temperature performance. Ni-cad batteries also do well in the cold. Mercury cells in general will perform poorly except at very light loads. Carbon-zinc batteries are somewhat better than mercury cells, but for prolonged operation it is probably a good idea to run a second set of batteries in parallel in order to double the normal capacity.

Connectors can be particularly troublesome in a winter environment. Low temperatures normally do not bother connectors, but blowing snow will, unless the connectors are hermetically sealed. Also, snowpacks normally have some liquid water in them, especially on bright, sunny days. If a connector is lying on or in the snow it will almost certainly get water in it unless it is hermetically sealed. If connectors are to be left out for any period of time, it is probably worthwhile to wrap them with a plastic sheet and seal both ends with rubber bands or tape.

Cables and wires are normally not troublesome in the winter, but their insulation can be. The polyvinylchloride (PVC) insulation used on most standard wire and cables becomes stiff and difficult to work at temperatures much below -8°C, and at very low temperatures (-20°C and below) it becomes brittle and cracks if flexed at too small a diameter. Nevertheless, it is possible to use PVC at low temperatures if it is positioned in the field while relatively warm and then not unduly flexed. Polyethylene insulation doesn't crack at low temperatures but it becomes so stiff it is almost impossible to work with. One particularly irritating characteristic of polyethylene is its tendency to coil back up on itself if spooled out at low temperatures.

Teflon and nylon both perform well in the cold, remaining reasonably flexible. Most rubber insulations also will cause no problems but should be checked for low-temperature use.

Coaxial cable sometimes becomes noisy at low temperature due to charge generation caused by thermal expansion of the wire, insulation and shield. Special low-noise coaxial cables are available but are generally quite expensive. However, they may be the only answer in circuits with low level signals. Testing cable for this problem is easy: a coil can be placed in a freezer and checked for normal system performance while it is cooling.

Panel meters also have problems in winter environments. The low temperatures cause sluggish response in meters with jewel-bearing suspensions; and taut-band meters may be permanently damaged by thermal contraction at low temperatures. Fortunately, both types of meter movements are available in low-temperature versions and the use of one of these "specials" may be advisable.

Some panel meters have plastic face covers which will retain electrostatic charge to the point where the meter movement can be pulled from its "correct" position and held there. A quick check for this condition is to draw a finger across the plastic face of the meter just above the needle and see if the needle moves. If it does, the meter's reading is suspect. This problem is really not peculiar to cold environments but it is definitely intensified by the low humidity found in the winter environment. A temporary solution to this problem is to wet a finger and rub it on the meter's face cover. This process will eliminate the static charge long enough to ensure a correct reading. Antistatic sprays are also useful in solving this problem.

Installation techniques

When an instrumentation system that will be operated in a winter environment is being planned, there are certain points that need to be considered.

It is almost impossible to solder leads in the typical winter environment because of the difficulty in heating the wire enough for the solder to flow. Therefore, if cables need to be permanently made up in the field, crimping leads together or using "poke-home" connectors is advisable.

If a junction box is to be installed in the field, spade lugs and barrier strips are the easiest way to make connections. If possible the spade lugs should be out on the cable leads before the field work begins. In fact, all possible installations should be completed ahead of time.

Junction boxes have to be sealed against blowing snow and meltwater in the snowpack. If snow gets in, it will almost certainly melt due to solar radiation, and the meltwater could very well provide a low impedance path between circuits.

Many of today's digital multimeters (DMMs) use push buttons to change ranges and functions. A check should be made to see if they can be operated with gloves on. If not, a small wooden dowel can be used as a range change "tool."

Field personnel can protect instruments by keeping them under their coats. A coat that is a little oversized helps.

If a connector or similar type equipment is dropped in the snow, it should not be blown on to get the snow out of it. The human breath has a lot of moisture in it and it will freeze onto the connector's pins or sockets, creating "open circuits" in some of the connector leads.

If electrical power is available a Styrofoam box can make a cheap heated shelter for small instruments. For example, a 1-m cube made with 7-cm-thick Styrofoam can be easily heated by a 40-W lightbulb. This will keep the instrument above freezing down to ambient temperatures as low as -30°C. A cheap thermostat (on–off controller) can be used to keep the box from overheating. In extremely cold weather a 60-W bulb can be used.

APPENDIX C: BIBLIOGRAPHY

The following is a bibliography of books and periodicals from which information on design of equipment for low temperatures may be found. The list is broken up into fields for easy reference.

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Journal of Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers, 345 E. 47th St., New York, New York 10017.

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Handbooks

Standard Handbook for Civil Engineers (F.S. Merritt, Ed.). McGraw-Hill Inc., 1221 6th Ave., New York, New York, 10020, 1968.

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Periodicals

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Military Engineer. Society of American Military Engineers, 607 Prince St., P.O. Box 21289, Alexandria, Virginia 22320.

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Hydraulics and fluids

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