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Automotive and Construction Equipment for Arctic Use

Materials Problems

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US Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

CRREL's *Cold Regions Technical Digests* are aimed at communicating essential technical information in condensed form to researchers, engineers, technicians, public officials and others. They convey up-to-date knowledge concerning technical problems unique to cold regions. Attention is paid to the degree of detail necessary to meet the needs of the intended audience. References to background information are included for the specialist.

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Automotive and Construction Equipment for Arctic Use
Materials Problems

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At low temperatures, most materials become stiff or brittle or both, including metals, rubber and other elastomers, and many plastics. This problem is exacerbated, especially in equipment with diesel engines, because the engines run rougher and the increased vibration is only slightly damped by shock absorbers and vibration mounts that become stiff and ineffective in the cold. The increased stiffness of the softer elastomers such as those used in seals, tires and belts may cause leakage or other problems. In addition, volume changes with lowering temperatures may cause problems in assemblies with close tolerances, such as bearings.

There are countless metal and nonmetal materials available, many of which are used in machinery manufacturing. Some are excellent low-temperature performers; some are extremely poor; many may be good or bad depending on the application, manufacturing technique, additive package, alloying material and so forth. The choice of which material to use for any specific application will depend on many more factors than can be considered here.

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The objective of this digest is to provide a discussion of the general types of problems that will be encountered in automotive and construction equipment when used in the extreme cold and to provide guidelines for overcoming them. The properties and problems of metals are discussed first, followed by a discussion of plastics and elastomers.

Metals

General considerations including brittleness, crack formation, differential expansion and welding will be dealt with first, followed by short discussions of particular types of metals commonly used in equipment manufacture.

Brittleness

Although in general the strength of metals tends to increase with decreasing temperature, at temperatures around –20°C some metals begin to lose their toughness (resistance to fracture) and ductility. Many steels, for example, begin to manifest brittle behavior, and their flexibility is much reduced. This temperature is known as the transition temperature. The strength under shock load of some steels may be reduced to as little as 50% of that at 20°C. At –40°C and below, brittleness can become a serious problem, especially when components are subjected to impact loading or when stress concentrators such as small cracks or defective welds are present.

The brittle behavior of metals is largely governed by their crystal structure. Aluminum, copper, nickel and their alloys all have the same crystal structure and are little affected by temperature. They do not lose their ductility at low temperatures. On the other hand, metals with other crystal structures, including that of iron, manifest a transition temperature and are strongly embrittled in the cold. However, their toughness can be influenced in several ways, including various manufacturing techniques and the use of alloys. Austenitic stainless steels, for example, have the same crystal structure as nickel as a result of their nickel content and processing. Table 1 shows metals that are subject to low-temperature embrittlement and those that are not.

In general, brittle failure becomes more likely in the presence of extreme cold, notch-type defects and shock loading. Since these

Table 1. Effect of low temperature on the brittleness of metals.

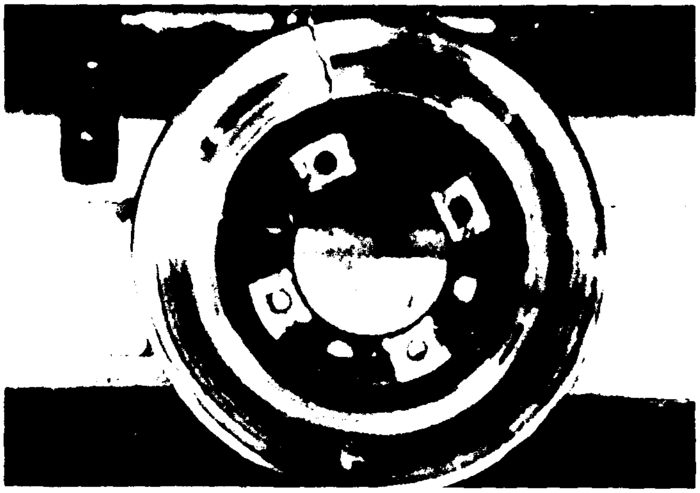
Little or no increase	*Abrupt increase*
Austenitic stainless steels	Most structural steel alloys
Copper	Chromium
Aluminum	Columbium
Nickel	Molybdenum
Lead	Tungsten
Silver	Vanadium
Gold	Magnesium
Platinum	Zinc
	Cadmium
	Cobalt
	Tantalum

factors act in an additive manner, the transition temperature can be effectively raised by shock loading and by the presence of notch-type defects. Such defects include virtually any feature that breaks the smooth surface of the material, including tiny cracks, scratches, corrosion pits, inclusions, holes, threads, machine marks or any other abrupt change in the surface geometry. Features of this sort concentrate any stresses and greatly increase the likelihood of brittle fracture, especially in the extreme cold, when the metal itself has lost much of its ductility, or under conditions of shock loading.

Crack formation

Cracks can be produced in a number of ways. Shock loads and metal fatigue are common sources of cracks in vehicle structural elements such as suspension systems and booms. In many cases these cracks are small and can and should be repaired before serious damage to the machine takes place. Figure 1 shows a crack that has

1. The box (top) shows the location on the rear of this loader bucket where a crack (bottom) had formed because of high vibration, shock loads and low-temperature operation.



2. This brake disk has cracked from overheating followed by excessively rapid cooling.

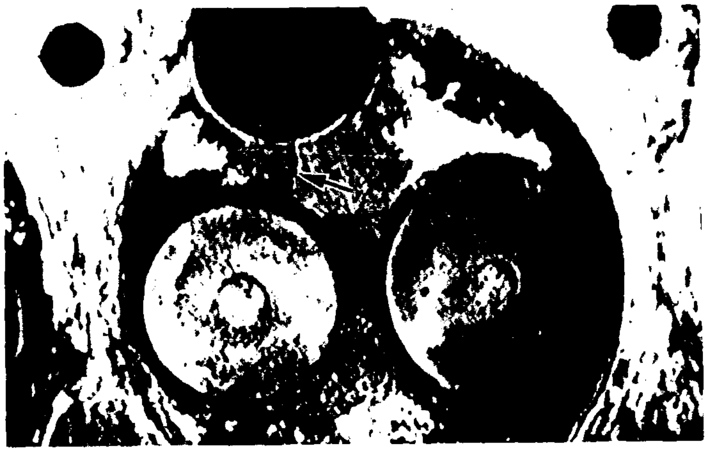
formed at the corner of a reinforcing plate on the back of the bucket of a loader at a point subject to very high stress concentration.

Extreme or uneven application of heat is another common source of cracks and most commonly affects the brakes and various parts of the engine. Brake discs become very hot if they are applied for an extended period such as down a long hill and often develop radial cracks as shown in Figure 2. If a cold fluid is added to a hot engine, cracks may develop in the block, either between the valves or through the water jacket, as shown in Figure 3, allowing water to enter the combustion chamber. In either case the consequences for the engine are serious. To avoid this, any additions of fluid should be made slowly with the engine running so that the cold fluid will be thoroughly mixed and uniformly distributed through the engine to prevent local thermal stresses.

If lubrication of the engine bearings is inadequate on start-up due to thickened engine oil, local overheating of the bearings can cause cracks to develop on the crankshaft. Babbitt material (the soft metal lining in journal bearings) then collects in the crack, preventing proper lubrication of the shaft even when the oil begins to flow properly. This results in further overheating and ultimate seizure of the bearing.

Differential expansion

Another source of problems with metals as well as other materials subject to great temperature variation relates to their expansion and contraction. Different materials contract at different rates, and if a material that contracts a great deal is tightly mated with one that does not, abnormally high stresses may develop, causing damage or catastrophic failure. Bearings are especially susceptible to differen-



3. This cylinder head has cracked, allowing water into the combustion chamber and forming heavy deposits on and around the valve and cylinder walls.

tial expansion problems because the bearing and the shaft are often made of very different types of metal and because clearances are very small. However, such problems may also occur in gear assemblies involving different metals or any part or structure where dissimilar materials are tightly bolted together.

Aluminum gear box housings may be a source of trouble because they usually are fitted with conical bearings for the drive elements. Since aluminum contracts at about twice the rate of steel, the difference in dimensional reduction between the aluminum housing and the steel gearing can cause very high stresses on the bearings, with the potential for serious bearing damage. Most gear boxes on heavy equipment are made from cast iron, but aluminum components are becoming increasingly common.

Low-temperature welding

While most structural steels become more brittle at very low temperatures and may fail catastrophically under circumstances that would pose no problem under "normal" conditions, some studies indicate that 95% of material failures in structures occur at or near welded joints (e.g. Gowda 1988). This clearly indicates that these seams will probably be the primary cause of low-temperature brittleness. Mitigative techniques, for the most part, involve ways to reduce stress concentrators caused by the weld, including shot peening, hammer peening, grinding, machining or other procedures that tend to remove the notch-like features that are the primary cause of failures. Some manufacturers have reduced the incidence of welding problems by redesigning components to reduce the number of welded joints. Some machinery now has as few as 10% of the welded joints as similar models made ten years ago. Figure 4 shows a forest machine with a weld-conservative boom. The single welded

4. The boom of this forest machine is an example of design methods of reducing structural breakage. The boom is constructed of a single sheet of steel formed to the desired configuration and welded along the neutral axis where stresses will be least.

joint is located along the neutral axis of the boom, the area of least stress. Formerly such a boom was made by welding four plates at their corners.

Weakness in welded joints may be the result of either flaws in the filler material or changes in the mechanical properties of the parent material when exposed to the high temperatures of welding. The filler material is more likely to contain inclusions such as pores or carbon particles, which can act as stress concentrators. In addition the possibility of thermal cracks developing upon cooling or the likelihood of incomplete fusion cannot be overlooked, especially if the welding was done in cold conditions.

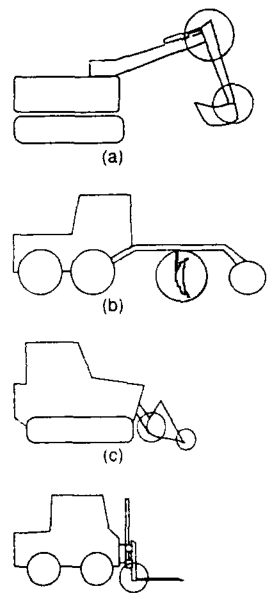
If welding has to be performed in the field at very low temperatures, the part should be sheltered using a tent or temporary shelter. The piece should be heated as slowly and uniformly as possible, and the actual welding should be performed at the lowest temperature possible to avoid local hardening of the material from hot spots. In general the rate of laying the bead will govern the final hardness and the existence of microcracks, which are often the cause of subsequent failures. Filler metals have been developed for low-temperature applications and are available commercially. These should be used.

For some welding jobs it is necessary to ground the work. This is not a trivial task at extremely low temperatures since the ground is usually frozen and in any case is a very poor conductor due to the very low liquid water content of the soil. A simple technique is to excavate a hole for the electrode and backfill with a mixture of soil, salt and water. Further information on grounding in cold regions is given in Henry (1987).

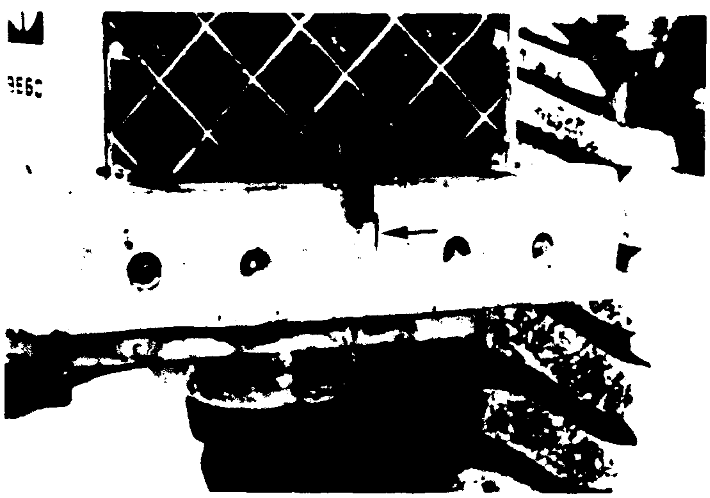
Ferrous metals

It is not surprising that the components most prone to mechanical damage under temperate operating conditions are the first to break in the extreme cold. Any element subject to shock loading is at risk, and damage will be greatest where stress risers, such as notch-type defects, are present. The following are common types of breakage:

- Fork lifts are subject to breakage at the junction of the horizontal fork element with the vertical member, since this corner is usually quite sharp, creating considerable stress concentration (Fig. 5).
- The counterweights on heavy equipment break frequently because of heavy machine vibration and the high incidence of impurities and defects leading to high local stress concentrations (Fig. 6).
- Both coil and leaf springs break more often in very cold weather than in temperate conditions, usually near their ends (Fig. 7).
- Damage to gears is most likely on start-up when thickened lubricants resist movement and all parts are very cold (Fig. 8). Final drive gears may also be damaged by trying to move off too quickly when the vehicle is frozen to the ground.

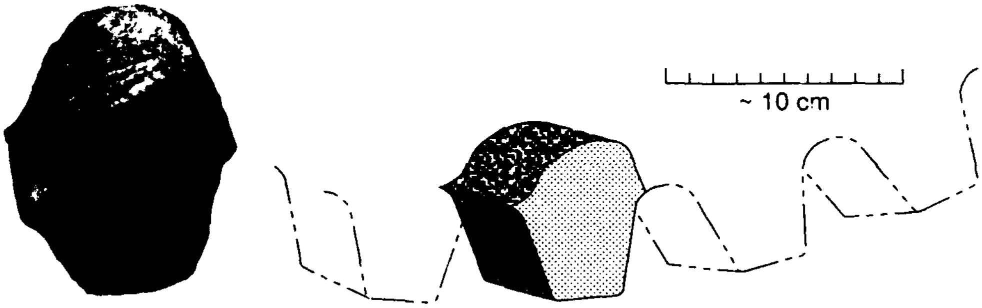


5. Certain areas on equipment are more susceptible to breakage because of the very high stresses, vibrations or shock loads they are subject to. Some common problem areas in low-temperature operations are shown in the sketches: a) pivot points on cranes and shovels, b) blades on graders and bulldozers, c) points of attachment and teeth on buckets and bulldozers, d) sharp bends on forklifts or any other load-bearing member.



6. Counterweights are commonly cracked in cold regions because they are subject to high shock loads and heavy vibration and the metal has many defects.

7. Leaf springs as well as coil springs frequently break close to their points of attachment.



8. This gear tooth was broken off the positioning wheel of a motor grader by rough handling at temperatures below −30°C.

- Lockwashers may break, leaving bolts or nuts free to work loose. Bolts themselves break, usually from a crack initiating at the thread, which acts as a stress concentrator.

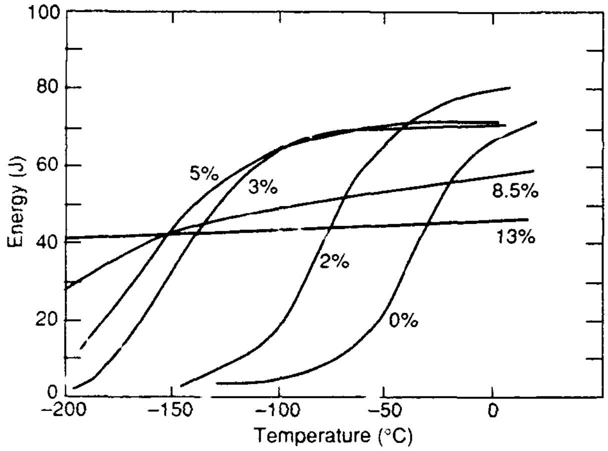
Nickel, a common alloying element of steel, has a marked effect on the toughness of the resulting material (Fig. 9). By contrast the low-temperature toughness of steels may be dramatically reduced by an increased carbon content.

Steels with good low-temperature toughness and high strength include many high-nickel steels, the low-alloy carbon group (such as 4340 grade) and the austenitic stainless steels (such as Type 301). Many of these are commonly used in cryogenic applications.

Nonferrous metals

Aluminum

Aluminum is the most common nonferrous metal used in automotive equipment and would appear to be ideally suited for arctic use since it retains its toughness and strength down to cryogenic



9 Effect of increasing proportions of nickel on the amount of energy that can be absorbed by steel before it breaks. Above a nickel content of 13% there is no detectable transition behavior.

temperatures. Its fatigue strength has even been shown to increase slightly at low temperatures, being about 20% higher at −195°C than at room temperature, though less than 10% higher at more realistic ambient temperatures. The welded joints of aluminum alloys are as strong as the parent material in most cases, or nearly so, and many alloys with joints showing reduced strength can be post-treated to improve the final product.

Cast aluminum engine blocks are becoming increasingly common, especially in smaller vehicles. At very low temperatures these can warp if the engine is shut down immediately after being run hard, which causes oil leakage around the head gasket. In some cases they may even crack, as shown in Figure 7; this sort of failure can also be caused by adding cold water too quickly to a hot engine. In extreme cases this can happen even to cast iron engines, but it is more common with aluminum components. This can be avoided by running the engine at low speed for a few minutes to allow it to cool somewhat before shutting it down.

Tin

Tin is not a major structural material in automotive and construction equipment; however, it is common in fairly major proportions in solders and in babbitt materials for the main bearings in many large machines. In these roles it may exert an important influence on the proper functioning of the equipment, and therefore its low-temperature peculiarities deserve mention.

Tin may exist in two stable forms: white tin (the familiar silvery metal) and gray tin (a gray powder). At temperatures below about 13°C white tin can change to gray tin with an associated increase in volume of more than 20%. In practice this transformation rarely takes place at temperatures above −20°C and may not transform at all even at much lower temperatures than this. The addition of alloying agents such as lead or antimony further reduces the likelihood of the transformation. However, there is strong evidence that transformations can occur spontaneously, even in alloyed tin. Thus, while there is no conclusive proof that tin babbitts (with about 80–90% tin content) are a source of bearing problems at low temperatures, it might be a good idea either to avoid using them when possible or to store them in a warm place.

High-tin solders having 60% tin content will reportedly disintegrate at temperatures below –50°C, and connections made with this material will fall apart. Solder containing more than 35% tin should not be used. Even at these lower concentrations, solder may become brittle at low temperatures.

Lead

The mechanical properties of lead are unaffected by naturally occurring low temperatures. As long as lead-based white-metal babbitts do not contain more than 15% tin, they will behave like pure lead. Similarly solders that will be exposed to ambient temperatures should not contain more than 35% tin. With proportions between 35% and 50% tin, the solder tends to become brittle but stronger in tension in extremely cold conditions.

Zinc

Zinc has extremely poor low-temperature properties, becoming very brittle at temperatures around –20°C. Flexing at temperatures below this may result in breakage. However, since the primary use of zinc is in galvanized coatings, which are seldom subjected to bending, this should not prove a serious problem. The only application with potential difficulty is in galvanized wire ropes, where some cracking or chipping may take place at very low temperatures.

Nonmetals

Wood, ceramics and glass are little affected by extreme cold. Plastics expand and contract much more than metal or glass, which may cause minor gaps or breakage. Any parts or materials made of plastic must be handled slowly and carefully. In this section a general discussion of the materials themselves will be followed by information on specific components.

Plastics and elastomers

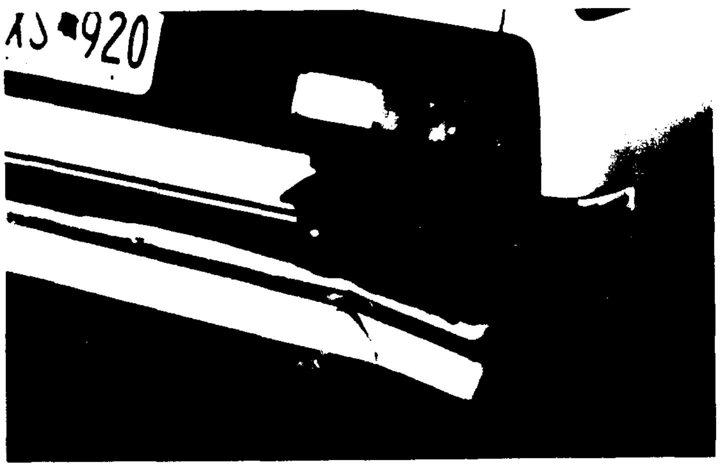
Most components made from plastics and elastomers are adversely affected by low temperatures, including tires, belts, seals, hoses and many noncritical parts such as seatcovers and trim. These materials tend to lose their resiliency and become brittle in the cold. Many standard compounds are rated for use down to –40°C but seldom below this, and many of these compounds deteriorate with age, losing their low-temperature flexibility. While there are a number of compounds available that will withstand very low temperatures, on the whole they are too expensive to be supplied as standard equipment on production vehicles and must be retrofitted before low-temperature use of the vehicle.

Cold-resistant replacements for standard elastomeric parts should be chosen with care, as some may not be suitable for certain uses. Many products cannot be used in the presence of petroleum oils, including fuels, lubricating oils and hydraulic fluids, because the fluid will, over time, dissolve the plasticizers out of the material, leaving the stiff and brittle parent material. Some reduction in volume may also occur. This is especially important in seals. In other cases the fluids may attack the material itself. Manufacturers of these components should provide information on the suitability of their products for a particular application.

There are three broad categories of these materials: plastics, elastomers and thermoplastic elastomers.

Plastics

Plastics comprise a heterogeneous group of materials composed of high-molecular-weight polymers that are more or less rigid in their final configuration. They may be either thermoplastics (subject to softening or melting at elevated temperatures) or thermosets (permanently rigid after curing and therefore more useful in high-temperature applications). But most plastics of both types become brittle at low temperatures and are sensitive to shock loads and vibration. The components with inherent stresses are those most subject to brittle failure, such as curved windshields, as well as parts routinely subject to shock loading such as switches, door handles, door panels and bumper covers. The damage shown in Figure 10



10. Plastic bumper cover badly damaged in a minor collision at low temperature.

was caused by a very minor bump at about –35°C. Probably there would not have been any discernible damage above 0°C.

Like metals, plastics increase in strength and decrease in ductility in cold environments. Many plastics can be used successfully at temperatures down to –40°C provided they are not subject to shock loading; however, a sharp blow may easily crack or shatter plastic materials. Battery cases can crack from heavy vibration, and plastic bumpers are frequent casualties in even minor automotive accidents (Fig. 10). Painted plastics are reportedly more susceptible to low-temperature brittle fracture than unpainted plastics because microcracks that develop in the paint can propagate into the plastic. This problem can be mitigated by using softer paint.

Polyethylene, a thermoplastic polymer, is a versatile and useful plastic for many low-temperature applications and remains tough at temperatures as low as –75°C. The low-temperature properties of polyethylenes improve with increased molecular weight, and ultra-high-molecular-weight (UHMW) polyethylene has been tested successfully at temperatures far below any naturally occurring temperatures, both for toughness and ductility. This is a relative newcomer to the rapidly growing fraternity of multipurpose plastics. It can be spun into fibers for very strong rope and used for such goods as surgical gloves. It has been used for sled runners, bushings and bearings, self-lubricating cross-country skis, and drive sprockets for snowmobiles. Another considerable attraction is its low cost. Disadvantages of this material are that injection molding is very difficult, and small, intricate parts cannot be manufactured easily. It also is hard to bond to other materials and will not accept paint easily.

Another class of low-temperature plastics is the fluorocarbon plastics, e.g. polytetrafluoroethylene (Teflon) and polychlorotrifluoroethylene (Kel-F), which retain useful ductility at extremely low temperatures. These are unusually resistant to chemical attack and possess other advantages, but they are very expensive.

Elastomers

Elastomers are also polymeric materials but are flexible. They are defined as being capable of being stretched to twice their original length and returning to their original condition in a short time on removal of the stress. The group includes natural rubbers as well as synthetic polymers. Many of these compounds are subject to low-temperature brittleness but can be improved by the use of suitable plasticizers. Also there is an increasing number of synthetic polymers on the market that are suitable for use in extreme cold without the use of additives. These are largely silicone-based compounds.

Elastomers are beset by three classes of problems at low temperatures: simple temperature effects, crystallization and vitrification:

- Simple temperature effects include increased hardness and decreased resiliency.
- Crystallization requires a certain amount of time in a cold-soaked condition. The resultant changes affect hardness, volume and stiffness. Rubbers with high levels of plasticizers may also undergo changes with time that are not related to crystallization. The plasticizer may be lost through evaporation or dissolution, causing increased brittleness and decreased volume. This process will take hours or months, depending on the materials and conditions.
- Vitrification affects all elastomers and takes place within a narrow temperature range over a short time. The result is a noncrystalline glass-like material that is very brittle. Usually the temperature at which vitrification takes place is much lower than that for other low-temperature effects.

All of these effects are reversible if no damage has been sustained while the material has been in its altered state. They should return to normal behavior when they are warmed to their operating range. This is at variance with damage caused by high temperatures, which is usually permanent.

Aside from seals, which will be discussed later, the most common problems with elastomers generally involve plastic sheets, such as vinyl upholstery and flexible plastic windows. These will often shatter when flexed and should be avoided if possible. In the case of rubber parts like protective boots, in some cases simple low-temperature effects can be alleviated somewhat by putting oil on the affected parts. This may soften the material enough for use in the cold but will also reduce their life when the temperature rises and may not work for all compounds.

These low-temperature problems can be avoided by using materials designed for low-temperature use, which will retain their resiliency down to very low temperatures. However, there are usually trade-offs. Most low-temperature materials are soft and prone to damage from tearing and abrasion, and many are very costly.

Silicone products are very useful at low temperatures as they maintain their flexibility at temperatures down to –60°C and have good compression set characteristics. They are available in a wide hardness range and are especially useful in static sealing applications. Unfortunately they are subject to swelling in the presence of many fuels and lubricating oils and are easily damaged by abrasion and tearing, reducing their usefulness in dynamic sealing applications.

Fluorosilicones are similar to silicones in that they have a wide temperature range (–60° to 200°C) with good compression set characteristics but are subject to abrasion and tearing, making them suitable only for static seals or very slow dynamic situations. They are, however, resistant to hydrocarbon fuels and lubricating oils.

PTFE (Teflon) is the best low-temperature performer, maintaining its flexibility down to –185°C, and is inert in the presence of all automotive fluids. Its disadvantages are that it is susceptible to mechanical damage such as nicks and scratches inflicted on installation, and it tends to creep under pressure. The latter problem can be mitigated through the use of suitable fillers.

Rubbers

Natural rubber will retain a large part of its elasticity down to about –30°C, although it will become much stiffer. If it is cooled fairly rapidly beyond this, it will suddenly become inelastic and brittle at about –50°C. However, if it is held for a long time at about –30°C, recrystallization will take place and again brittleness results. This should be considered when storing seldom-used items such as hoses and cables. Rubber-jacketed cables should be protected from shock loads and bending to prevent cracking of the rubber and resulting short circuits.

Although many excellent (although frequently expensive) low-temperature synthetic rubbers are available, not all rubber components can be relied upon to remain flexible in extremely cold conditions. Neoprene, a common synthetic rubber used for wire and cable jackets, becomes very brittle in the cold, and in one case, a synthetic rubber coolant hose shattered when dropped at –48°C. There seems much promise from recent thermoplastic elastomer products, which have demonstrated their usefulness in a number of automotive applications ranging from purely cosmetic (trim, bumper covers, etc.) to more rigorous and essential functions (hoses, boots, etc.).

Thermoplastic elastomers

Thermoplastic elastomers (TPEs) are essentially alloys of plastics and elastomers whose properties are a hybrid between those of the two groups. This is a relatively new technology, and these products are not yet widely available. However, the versatility shown to date, the ease of processing, and the relatively low cost are likely to inspire active research fueled by the keen interest of many end users, including the automotive industry.

Many TPEs are serviceable down to very low temperatures (because of the elastomeric phase) while still possessing sufficient rigidity for applications requiring some strength (because of the plastic phase). Since they will soften at elevated temperatures, they are in general not currently suitable for use under the hood; however, active research on this problem may overcome this disadvantage. In the meantime they show great promise for use in applications where rubbers are now used.

Electric and electronic components

One of the most conspicuous casualties of low-temperature operation among electric and electronic components is wire and cable insulation. Many materials are used in this role, and, as with other elastomeric parts, those suitable for low-temperature use are the most expensive and are seldom installed as standard equipment. Polyvinyl chloride is commonly used in wiring insulation and may be used in the cold where it will not be flexed. It is highly resistant to hydrocarbons, acids and alkalis and will not burn, but it becomes very stiff and brittle in the cold and should be replaced with a more suitable product if it is likely to be bent at all in routine service.

Another prominent materials problem of the electric system is breakage of battery cases. This can be caused by either a sharp blow or heavy vibration. Urethane cases are best at low temperatures and will not become brittle down to –45°C. They will not crack if the battery freezes and are currently available for large batteries. Polypropylene cases, which are becoming increasingly common in automotive batteries, tend to become brittle below –30°C. Rubber cases are somewhat better but are becoming increasingly rare. At extreme low temperatures, battery cases made of hard rubber or plastic may become brittle and fracture on impact, rendering the batteries completely inoperative and possibly allowing sulfuric acid to escape. Vibration can also damage plates by jarring the active material loose from the lattice. Other types of problems of batteries at low temperatures are discussed in Diemand (1990).

The increased incidence of sophisticated control systems in vehicles introduces a new set of problems that was previously exclusively in the province of electronic instrumentation. Electronic equipment is highly susceptible to shock and vibration damage. This can be mitigated to a degree by using cast resins, shock mounting and good packaging. However, shock mounts tend to lose their effectiveness in the cold and may not afford adequate protection against vibration. The low-temperature stiffening of vibration mounts increases their natural frequency and thus reduces the isolation from the equipment they are mounted on. Vibration-proof equipment is shock-proof, but shock-proof equipment is not vibration-proof. Reducing the weight of components by printed circuits and miniaturization of components reduces the likelihood of shock and vibration damage.

Some other problems that have been identified are:

- The linear characteristics of many electrical parts change in cold weather. Instrumentation, especially with solid state circuits, can become extremely inaccurate.
- Cold can change the operating frequency of some equipment and degrade its accuracy. Quartz crystals may fail to oscillate at low temperatures because of mechanical changes. They should be kept as close as possible to normal operating temperature.
- The effective capacity of electrolytic capacitors (including automobile condensers) is materially reduced when operated at temperatures below –29°C. This will increase the radio noise level in spark-ignition engines.
- The formation of ice or frost on the actuating mechanism of sensitive switches or relays render the switches erratic or inoperative.

This is not a complete list of problems of electronic equipment in the cold but is included to give some idea of the types of problems that may be encountered. In many cases the on-board computer may never be exposed to intense cold, being located in an area heated by the engine during operation and by a stand-by heater on shut-down.

Adhesives

There are many commercially available adhesives that may be exposed to extremely low temperatures after they have been applied but virtually none that can be usefully applied at temperatures below 0°C.

Silicone adhesives are widely and successfully used for many purposes. They remain flexible at temperatures as low as –65°C and are also resistant to temperatures up to 200°C or greater. For example, high-temperature silicone products are used to attach silicone rubber heating pads to oil pans, transmission housings and the like and can withstand both extremely low ambient temperatures and the very high temperatures produced when the heater is in operation. The great versatility of these adhesives in terms of the types of materials they can be used with adds to their appeal. They are often used to attach the rear-view mirror to the windshield because the adhesive remains pliable after curing and will mitigate the effects of differential thermal expansion of the two materials. They are also used successfully in many sealing and gasketing applications.

For more rigid bonding, cyanoacrylate-type adhesives (e.g. "Super Glue") are effective down to –55°C and are available in numerous formulations for various applications. However, they are generally not as effective as silicone adhesives at higher temperatures.

Glass and ceramics

Glass and ceramic materials suffer very little, even in the extreme cold unless exposed to abrupt temperature changes. All things being equal, glass should not become any more brittle at low temperatures than it is at room temperature. However, it is also true that at very low temperatures, small cracks on windshields, such as those caused by flying gravel, tend to propagate more easily than in temperate regions. This is probably because of the large temperature gradient between the warm interior of the car and the exterior. The expansion of the interior layer of the laminated glass is transmitted to the cracked outer layer by the laminating material, tending to widen (i.e. lengthen) the crack. This problem can be mitigated to a degree by turning on the defroster while the engine is still cold on start-up so that heat is applied to the window gradually. In this way large local stresses are avoided as much as possible.

Wood

Many problems with the use of wood at extremely low temperatures are the result of the very low moisture content in the air rather than of the cold itself. Although relative humidities may be very high, the actual water content of the air is very low because of the low temperatures. (If saturated air at –30°C is warmed to room temperature, its relative humidity drops to about 4%.) If wood is left outside, in most cases it will not lose sufficient moisture to cause any deterioration in properties, but it becomes difficult to work in the cold because it becomes very hard. Nails bounce off, the wood splits easily, and it is very difficult to saw. On the other hand, if it is kept in a warm place it is likely to become extremely dry. Fasteners such as nails and screws may become loose, and it may tend to split. Similarly, it may break abruptly with little warning if it is overloaded.

Problems of non-metal components

Tires

If left for several hours at very low temperatures, rubber tires on vehicles become rigid, creating flat spots where they touch the ground. This results in a slow, bumpy ride until the tires warm enough to regain their pliability. In extremely cold conditions they become brittle and develop cracks on the sidewalls. These cracks are often initiated by raised letters molded into the sidewalls. Tires with prominent molded lettering or logos should be avoided for this reason. As with all other components at low temperatures, tires should be used with care until they warm enough for normal operation. A tire dropped from the back of a truck at very low temperatures can crack on impact with the ground and will be useless after this. Similar damage can be sustained if the vehicle is driven too fast over an angular object such as a stump or a stone. This sort of damage usually cracks the rubber only, not the cords.

The temperature at which tires begin to suffer low-temperature problems is variable and depends largely on the composition of the rubber. This varies between manufacturers and between types made by the same manufacturer. In general, radial tires appear to be superior to bias ply types, and the costlier types are less prone to trouble than the economy models. A low-quality tire can shatter at extremely low temperatures.

At temperatures below –40°C chunking may become a problem. This is a condition where relatively large fragments are lost, usually from the treads. This problem is seldom encountered except in unusually rough terrain at very low temperatures.

It is not a good idea to use retreaded tires in cold regions, as the bonded layer peels off very readily when exposed to very cold conditions. A similar and somewhat bizarre form of tire failure is the separation of the lining material in tubeless tires. This self-sealing material coats the inside of the tire and in temperate regions serves to prevent air loss if the tire is punctured. However, it becomes brittle at extremely low temperatures and breaks away from the tire as a mass of slivers and shards. When the temperature increases somewhat, these fragments form themselves into a single large lump weighing more than a kilogram which can move freely inside the tire and wreak havoc with the wheel balance, causing a very noisy, bumpy and dangerous ride.

The primary low-temperature problem with tires is their tendency to lose air, especially in tubeless tires. One cause of this is that as the temperature drops, the material loses its ability to form an airtight seal with the rim and air is slowly lost through very slow seepage in this area. This problem is especially noticeable on tires with old rims that may be slightly scratched or rusted and on those heavily exposed to mud and dirt. Air may also seep through tiny cracks in the body of the tire. These cracks are present on both the inside and the outside surfaces of the tire. Consequently inner tubes are often used in cold regions, even in tubeless tires. Although inner tubes are also subject to low-temperature cracking, the problem is less severe, and for extreme conditions, arctic-grade inner tubes are available and should be reliable down to –50°C or below.

Tires may also appear to lose air when they are inflated in a warm area such as a garage and then taken outside where the temperature may be 40–60°C colder. A tire inflated to 40 psi at 20°C will only

Table 2. Tire pressures required at 20°C to achieve recommended pressures indicated at low temperatures.

Recommended pressure (psi)	*Tire pressure (psi) at 20°C*				
	−10°C	*−20°C*	*−30°C*	*−40°C*	*−50°C*
30	33	35	36	38	39
40	44	46	48	50	52
50	55	58	60	63	65
60	66	69	72	75	78
70	78	81	84	88	91
80	89	92	96	100	104
90	100	104	108	113	118
100	111	115	120	125	131
110	122	127	132	138	144

be pressurized to about 33 psi when taken into a −30°C environment. Table 2 shows the pressure to which a tire should be inflated at 20°C when it is to be used in low ambient temperatures. If the tire is inflated in the cold, it should be filled to the proper pressure.

Low-temperature loss of pressure is self-sustaining in that it results in the tire being somewhat looser on the rim than when properly inflated, which will increase air loss. In extreme cases the tire may slip sufficiently on the rim to tear out the valve stem in a tire with an inner tube. Improper air pressure is a common factor in premature deterioration of tires.

The Soviets have reportedly used an ingenious system on some of their equipment to prevent air loss through slow leaks. A compressor is mounted on the equipment and is connected to all tires. It is set for the desired pressure level in the tires and ensures that the tires do not fall below this level.

Belts

At very low temperatures, fan belts lose their flexibility and break very easily. They are mostly designed for use down to about −30°C and are reasonably reliable down to −35°C, but below this they are prone to brittleness and delamination. During one military exercise in winter in Alaska, 400 belts were broken in three days. This problem is especially common in vehicles with small-diameter pulleys, which cause the belt to bend sharply when the material is rigid from the cold. This is most severe on start-up, when the equipment is at its lowest temperature and the process of starting may impose uneven stresses on the belt. Also, local build-ups of frost or ice may inhibit smooth operation of the belt on the pulleys. However, breakage can occur at any time. The problem is prevalent enough in the interior of Alaska that the numerous ruptured fan belts on the highways shed by passing vehicles are referred to as "Alaska snakes." In addition, some vehicles are equipped with elastomeric timing belts, whose failure has a devastating effect on the engine. These especially should be conscientiously checked and replaced at intervals recommended by the manufacturer.

While arctic-grade belts do not appear to be commercially available, various unofficial techniques have been used to reduce the likelihood of belt breakage. The most prevalent method is to break in the belt in warm conditions prior to use in the cold. This may be done by installing a new belt in the summer and using it for a week or so. It should then be replaced by the old belt and kept for later use in case the old one breaks in the cold. If a broken-in belt is not available in the winter, a new one can be partially broken in by idling the equipment in the garage for a short time before taking it out into the cold and running it for as long as possible before shutting it down. The belt should be installed a little loose initially—just tight enough to run the alternator—until it is worn in. Another method, infrequently used, is to soak the belt in antifreeze overnight before use. This apparently softens it enough that it will not break readily, but when the temperature rises it will dry out and must be replaced. Wiping brake fluid on a new belt before installing may help, as well as the use of belt dressings.

Hoses and tubing

Problems with hoses are numerous and varied. Hoses must not only resist low-temperature stiffening and breakage but also chemical attack by petroleum products (i.e. hydraulic oils, fuels etc.) and water-soluble fluids, such as coolant. Crimped hoses are prone to break or crack under the crimp, causing leakage that may or may not stop when the hose warms. Rubber fuel hoses may stiffen and break at low temperatures because the fluids extract compounds from the rubber that impart the original low-temperature qualities. However, in recent years much progress has been made in applying the many newly formulated elastomers to the problem, and hoses are available with a wide variety of linings, coverings and reinforcing materials and are readily available for almost any application down to –40°C. Hoses suitable for use down to –50°C are fairly common, but below this the selection rapidly diminishes. Some northern operators recommend conditioning a replacement hose by soaking it overnight in hydraulic oil at 65°C to prevent blow-out.

Plastic tubing is often used in hydraulic brake systems and is often subject to leakage in the cold due contraction and stiffening of the tubing. Fittings in systems of this sort should always be designed for installation on the inside diameter of the tube so that the inevitable contraction will tend to improve the seal rather than draw the tube away from the fitting.

Seals and gaskets

In general, standard seals do not work at very low temperatures. One of the most common causes of seal damage is tearing when ice or frost form from condensation between the seal and the metal surface. They also leak because of volume changes and fail when they become brittle. Fortunately there are an increasing number of compounds available that are suitable for low-temperature use and are resistant to attack by all common automotive fluids. Arctic-grade seals, often softer than normal, are subject to abrasion damage, especially dynamic seals exposed to high temperatures. Many are adversely affected by petroleum products. Manufacturers' recommendations should always be followed.

Nitrile rubber (NBR) is one of the most common materials used in seal manufacture. It is a copolymer of butadiene and acrylonitrile and is available in proportions of acrylonitrile from 18% to 50%. When the acrylonitrile content is low, the low-temperature characteristics are good, but resistance to petroleum oils is reduced. Increasing the content will improve oil resistance but at the cost of low-temperature effectiveness. Polyurethane seals are often used in hydraulic systems because of their good oil resistance, abrasion resistance and strength, but their resistance to water and steam is poor. Silicone and fluorosilicone seals are useful in some special applications where they will not be subject to mechanical damage. PTFE is an excellent choice for U-ring seals, anti-extrusion rings and profile rings in composite seals, since it is resistant to all automotive fluids, has excellent low-temperature characteristics, and has a very low coefficient of friction on steel. The performance of a seal will depend upon the application (i.e. static or dynamic; expected pressures), the material, the operating temperature and the fluid type. If there is any doubt about the best choice of seal for the job, it would be a good idea to discuss the problem with the seal manufacturer.

When two mated surfaces of different types of metal must be sealed, it is better to use a gasket than formed-in-place rubber, which is essentially an adhesive. This is because the differential contraction of the two metals will tear the formed-in-place rubber, while the gasket will be more likely to retain its integrity. When possible, many arctic veterans use cork gaskets and seals in low-pressure applications as these are not subject to problems of shrinkage and hardening as so many of the others are.

Conclusions

There are no universal rules to prevent failures at arctic temperatures. The only reliable prediction that can be made about operations at extremely low temperatures is that they will be expensive and time-consuming. However, by observing the following guidelines. materials problems can be reduced to a minimum:

- Use arctic-grade seals and hoses when possible.
- Reduce demands on the equipment at temperatures below –30°C. As the temperature falls, decrease loads accordingly.
- Never do anything quickly, especially on start-up when all components are cold:
  - Preheat the engine gradually before trying to start it.
  - Exercise the hydraulics slowly without a load before using the equipment.
  - Drive slowly until the flat spots on the tires are no longer apparent.
  - Don't run the engine hard before it is warm.
  - Don't turn the engine off after a heavy load before it has cooled a little.
  - When adding cold coolant to a hot engine, do so slowly with the engine running.

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