SECTION 9.18

CRYOGENIC LIQUEFIED GAS SERVICE

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The regime of cryogenic technology has been generally taken to indicate temperatures colder than −100°F (−73°C). Fluids such as liquid oxygen, nitrogen, hydrogen, helium, argon, methane, and ethane, with normal boiling points below −100°F (−73°C) are called cryogenic fluids.

For the pump designer, the cryogenic regime requires consideration of the effect of low temperatures on the properties of construction materials and the effect of varying shrinkage rates on critical fits and clearances. The problem is further complicated by the fact that cryogenic fluids are stored at near atmospheric pressure and must be pumped at or near their normal boiling point, so the only *NPSH* available is that due to the liquid level above the pump suction.

The history of commercial cryogenic pumping divides into two eras. The first, commencing in the early 1930s with the first liquid oxygen plant in the United States, was the period in which end-suction shaft seal pumps were developed and produced for pumping liquefied atmospheric gases, such as liquid oxygen, nitrogen, and argon. This industry grew until the late 1960s. Though continuing to grow, the explosive period appears to have ended.

The second era commenced in 1959 with the first transport of a commercial cargo of liquefied natural gas (LNG) from Lake Charles, La., across the Atlantic Ocean to England. This voyage, carrying an almost token quantity of 5000 m^3 of LNG, inaugurated an era of international trade in liquefied hydrocarbon gases that has grown with astounding rapidity and seems still to be barely on the threshold of realizing its full potential.

ATMOSPHERIC GASES

Cryogenic pumps first came into being with the production of liquefied atmospheric gases in commercial quantities. The initial liquefaction of air and the subsequent separation of

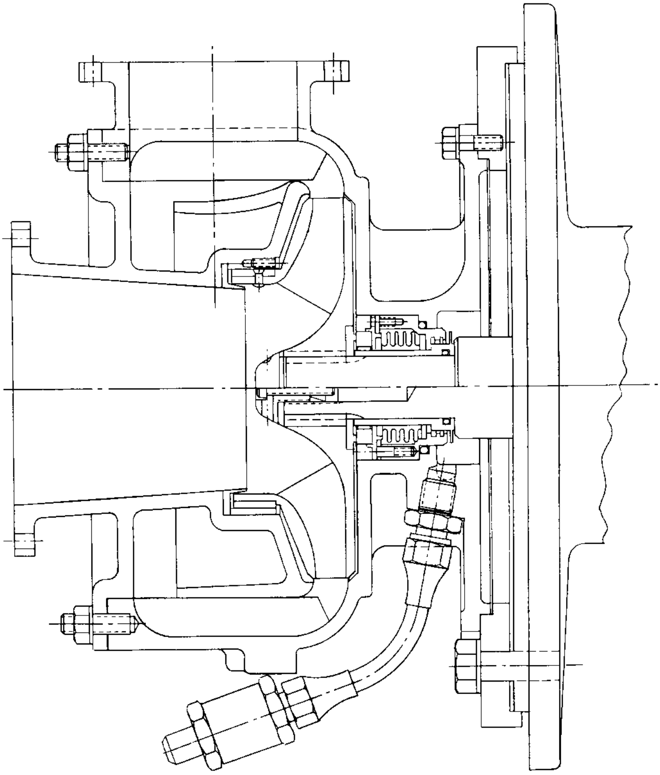


FIGURE 1A In-flight refueling pump (J. C. Carter Company, Inc.)

oxygen and nitrogen did not require pumps because the small volume of liquids produced could be readily transferred by pressure. Early pumps, where needed, were designed and built by the gas companies themselves and were primarily used to fill high-pressure bottles or cylinders. Flows were very low, so positive displacement pumps were commonly used. These were notoriously inefficient, primarily because of the flashing that occurred during the intake stroke and led to a very low volumetric efficiency. However, the low volume of product being handled permitted this efficiency to be tolerated.

The World War II development of rocket engines that used liquid oxygen as an oxidizer to burn kerosene fuel and the postwar development of the large rocket booster required the development of centrifugal pumps to feed the propellants to the engine. These turbine-driven rocket engine pumps were adapted to electric motors for use in transferring the propellants from storage into the rocket's tanks because there were no high-capacity cryogenic pumps available from the industry. Although these early rocket pumps were also inefficient, they could be tolerated in the rocket because the fluid was burned immediately and temperature rise across the pump was not a problem.

Two other developments in the early postwar years increased the volume of liquefied gases in industrial applications. The first was the development of the basic oxygen furnace for making steel, and the second was the use of liquefied nitrogen in the fast-freezing of foods and as an inert atmosphere for heat-treating and chemical processes. These developments required the storage and transfer of large volumes of liquids, so the boiloff loss due to pump inefficiency became a major economic factor in the profit and loss of the liquefaction company. The major companies instituted internal studies to reduce these losses, and soon the transfer pumps were brought under scrutiny.

Thus a two-pronged impetus developed to find pumps that would more efficiently and reliably transfer these valuable liquids; the first was the need to load military rockets with the coldest possible liquid with utmost reliability, and the second was from industry. Investigators studying the problem first turned to the producers of commercial pumps. However, because the pump volumes required were small and the technical problems formidable, they were unable to retain the interest of the major manufacturers and so turned to small producers of custom-designed pumps.

The earliest custom producer to enter the field was a builder of high-capacity in-flight refueling pumps for the military. One of these pumps was adapted to a commercial 60-Hz electric motor using a newly designed face-type shaft seal with the stationary face mounted on a stainless steel convoluted bellows. A cross section of this pump is shown in Figure la.

The refueling pump was constructed of aluminum castings with bronze wear rings and stainless steel trim. These materials were good choices for cryogenic service as well, and so, aside from the seal, it was necessary only to change to standard pipe flanges on the inlet and discharge nozzles. Figure lb shows this pump mounted on the original dc aircraft motor used on the KB29 airplane, transferred to a 60-Hz, 3-phase motor but still with the original flanges. Figure 1c shows the full commercial cryogenic configuration with ANSI

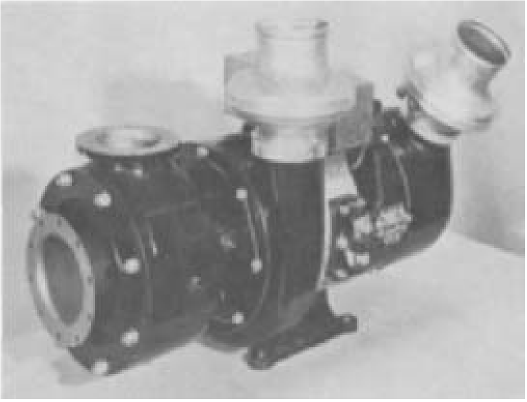


FIGURE 1B DC-motor-driven refueling pump with original flanges (J. C. Carter Company, Inc.)

FIGURE 1C Full commercial cryogenics configuration of dc-motor-driven refueling pump with ANSI flanges (J. C. Carter Company, Inc.)

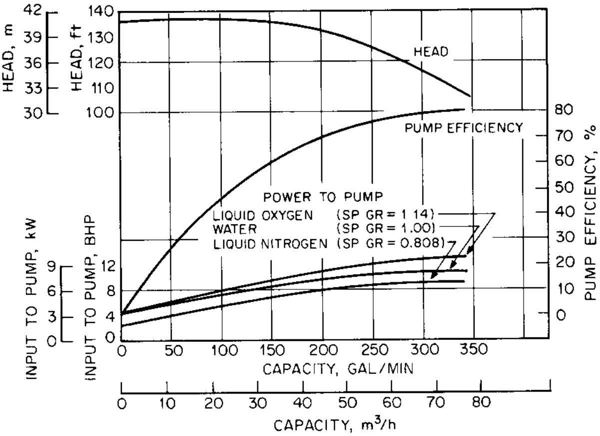


FIGURE 2 Performance characteristics for a refueling pump at 3500 rpm (J. C. Company, Inc.)

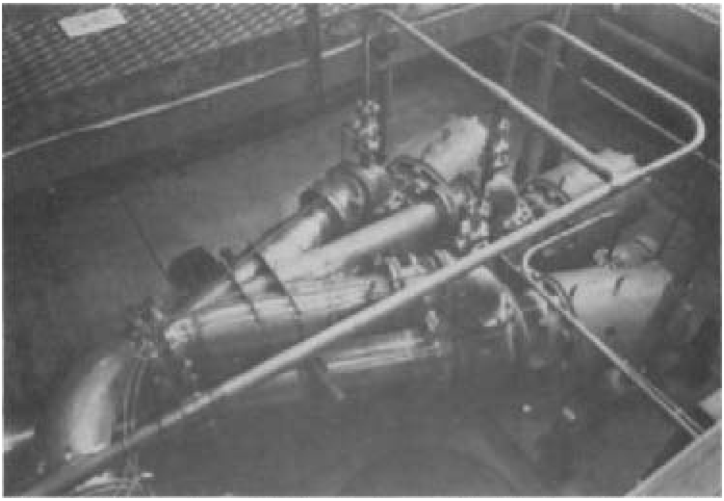
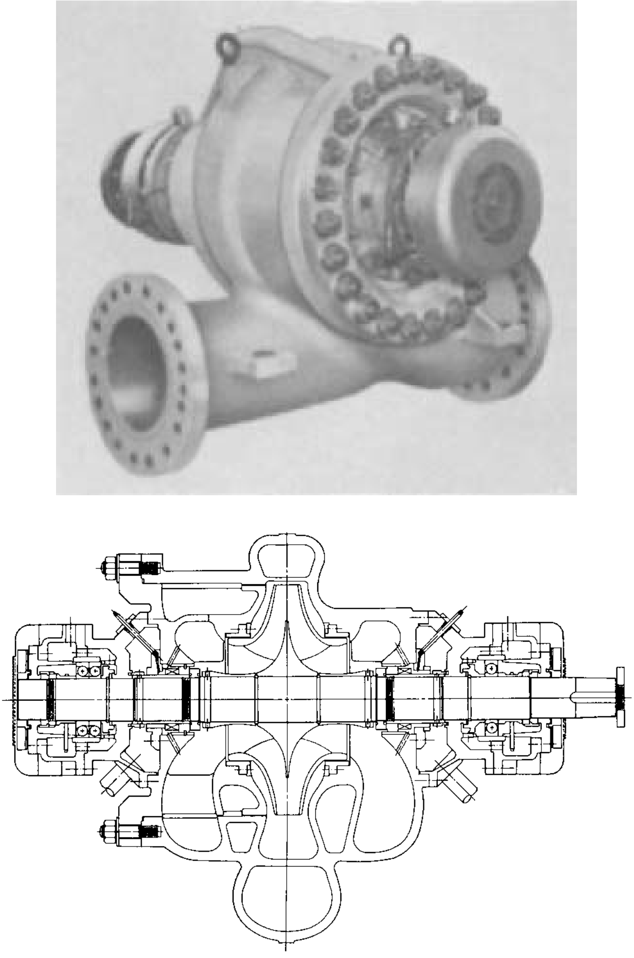


FIGURE 3 Cryogenic pumps for loading liquid-propelled ICBMs (J. C. Company, Inc.)

standard flanges and stainless steel thermal barrier/distance piece for mounting the pump onto the motor. The pump, originally designed under the space and weight limitations of aircraft service, also fit the requirements of cryogenic pumping in that the low heat capacity and surface area resulted in short cool-down time and low heat leak. Because the pump was also very efficient (Figure 2), the boiloff problem was greatly alleviated. The gas industry welcomed this pump, and it became one of the most popular transfer pumps for loading and unloading tank cars and trailers.

Following the lead set by this pump, several other small manufacturers began building similar pumps. As the industry grew, pumps of larger capacity and higher heads were built, covering the range from 4 gpm (0.9 m^3/h), used in transferring liquid from rectifier columns to storage, to more than 5000 gpm (1125 m^3/h), used for loading the early liquid-propelled ICBMs during the 1960s (Figure 3). Only one of these latter systems was built. The pumps shown in Figure 3 were about the largest end-suction close-



(b)

FIGURE 4 (a) Double-suction cryogenic pump, (b) cross-sectional view (Flowserve Corporation)

coupled pumps ever built. The pump built to load the Saturn rocket at 10,000 gpm (2250 m^3/h) was not close-coupled and was possibly the only double-suction cryogenic pump ever built (Figure 4).

LIQUEFIED HYDROCARBON GASES

The cryogenic fluids encountered in this service are primarily LNG (a mixture that is normally more than 90% methane), ethylene, and ethane, along with the liquefied petroleum gases (LPG) propane and butane. A novel approach to pumping these fluids was introduced in 1959 with the application of the submerged electric-motor-driven pump. Because these fluids are excellent dielectrics, part of the pumped fluid stream can be directed through the motor to cool it and lubricate the bearings. There is no need to can or treat the windings with anything other than specially selected varnishes. Many advantages accrue to this design, such as

- No cool-down requirement on pumps installed in tanks
- High inherent reliability due to protection from corrosion and humidity and elimination of shaft seal
- Low hazard due to 100% rich environment
- Minimal differential shrinkage problems
- Capability of directing rejected heat in accordance with designer's wishes

Also, the pump is close-coupled to the motor, eliminating the need for a long line shaft, line shaft bearing problems, and differential shrinkage problems. As a result, higher speeds can be used and pumps can be smaller and less expensive.

This construction has found many applications that have led to a variety of configurations, including the single and multistage units used in the liquefaction process plant to transfer to storage, load and unload cargo ships, and pump to high pressures for regasification. The pumps can be mounted in tubes inside the tanks so they can be removed for service through the roof without emptying the tank, thus eliminating the need for an opening in the bottom of the tank. They are also mounted in suction barrels that can be maintained cold indefinitely on instant standby.

A typical cargo pump for use on board ships is shown in Figure 5. This pump uses aluminum castings for all housings as well as for the pump impeller. The motor uses electrical iron laminations, a stainless steel shaft, and stainless steel ball bearings with special nonmetallic separators. The path of the top wear ring flow up through the motor and back into the tank is easily seen.

This pump stands about 5 ft (1.5 m) high from the suction flange to the discharge flange. Flow is typically in the 5000-gpm (1125-m^3/h) range. Motors with ratings up to 450 hp (336 kW) are available.

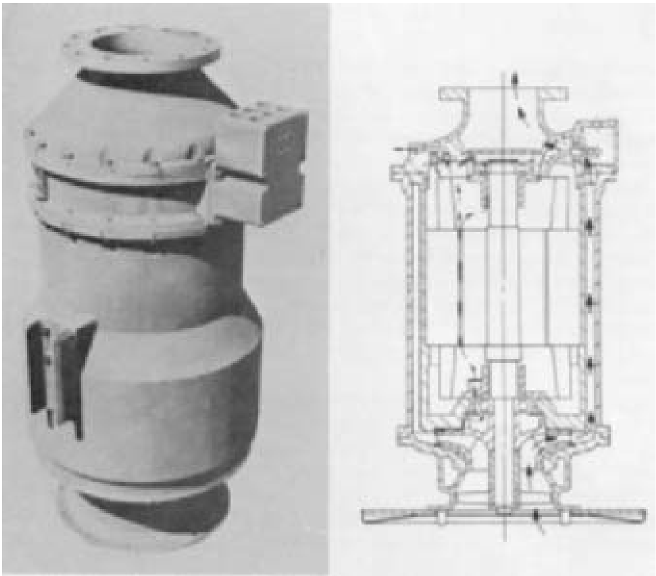


FIGURE 5 On-board cryogenic cargo pumps—photograph on left and cross-section on right showing flow through the motor (J.C. Carter Company, Inc.)

FIGURE 6 Ship-loading cryogenic pump (J.C. Carter Company, Inc.)

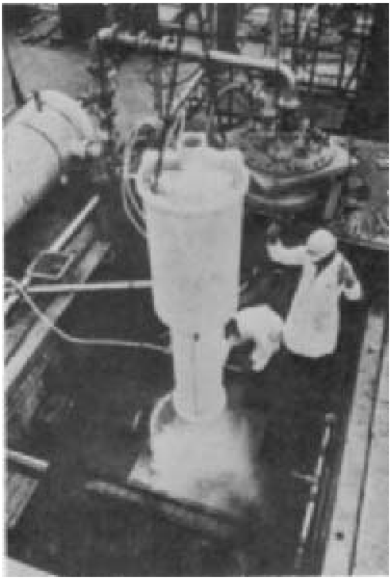


FIGURE 7 Multistage cryogenic pump on test stand (J.C. Carter Company, Inc.)

Other configurations are shown is Figures 6 and 7. Figure 6 is a typical ship-loading pump provided with an 800-hp (597 kW) motor and capable of pumping more than 20,000 gpm (4500 m^3/h). This type of pump is designed for mounting in a suction pot. Figure 7

FIGURE 8 Multistage variable geometry expander on test stand (Flowserve Corporation)

shows a 1200-hp (894 kW) multistage pump being removed from the test tank. Pumps such as this are capable of more than 1000 lb/in^2 (69 bar[1]) discharge pressure pumping LNG and are in service with motors of 2500 hp (1860 kW).

Many users are migrating toward the vertical canned-style pump for critical LNG services. Liquefied gas producers are keenly aware of the high reliability and capability of immediate start-up these vertical units offer. These pumps are used more often for continuous process service than for standby service that merely backs up gas compressors. There is a trend in this industry toward an increase in flows and pressures—up to 4000 ft (1220 m). The vertical canned-style pump provides space saving, a neat installation, and superior suction performance when there is little net positive suction head (*NPSH*) available.

The LNG and liquefied air industries utilize both fixed- and variable-geometry, multistage vertical turbines (Figure 8). These units are referred to as expanders in the LNG industry and dense fluid expanders (DFEs) in the air separation industry. The units are

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[1] 1 bar = 10^5 Pa.

capable of breaking down pressure in a product flowstream or a closed refrigeration loop very efficiently as compared to a common pressure breakdown (control) valve. Expanders dramatically increase overall plant process efficiency and can actually lower initial plant construction costs by allowing downsizing of main compressors. The expanders break down the product efficiently, produce electricity as a by-product, and allow for vaporization of the product. The amount of sellable product increases by up to 5% when utilizing expanders rather than valves to break down the flowstream pressure. Payback periods of 6 to 12 months are common.

ENGINEERING PROBLEMS

The pumps described in the preceding pages, although widely diverse in configuration, still have a number of common problems. First, there is the extreme, paralyzing cold. It is small wonder that the early pumps were considered successful when they did not freeze into immobility. The cold penetrated the motor, causing grease-lubricated bearings to seize and filling the inside of the motor with ice that locked the rotor fan blades and kept them from turning. The piping attached to the pumps shrank, distorting the pump casings into heavy rubbing contact with the impeller. Frost and ice entered the external side of the seal, immobilizing it so that leakage was uncontrollable. It was difficult to find materials for construction that did not become unusually brittle, and there were almost no data available on the total shrinkage of common materials at cryogenic temperatures.

Sources of data on the properties of materials at low temperatures are listed at the end of this section.

Other problems resulting from low-temperature operation are mainly mechanical and are surmounted by using thermal barriers, flexible sections of piping, and dry purge gas to prevent the ingress of moist air. Gasketing and lubrication problems are both currently being solved by materials that did not exist when the problems were originally encountered.

One common problem has to do with the characteristics of the fluids being pumped. Cryogenic fluids are stored in insulated tanks maintained at pressures only slightly above atmospheric, and the fluids become saturated at the storage pressure. Because it is not possible to obtain any pump elevation relative to the tank bottom, net positive suction head becomes a real problem. Various style of inducers have been used to improve the suction performance of the pumps, but in nearly all cases some degradation of performance must be anticipated as the tank is drawn down to low levels and cavitation operation is inevitable. Fortunately, operation in cavitation is not as severe a problem in cryogenic fluids as it is in water, because of the much lower energy of the cryogenic fluid bubble, and so severe cavitation damage to pump parts is seldom encountered.

Testing of pumps for cryogenic service is difficult and requires a heavy investment in test loop equipment. It is also fraught with problems that are peculiar to testing and will not be present in actual operation. One such problem has to do with the recirculation operation in a test loop. The work put into a saturated fluid is usually released by allowing some of the fluid to boil away. Because it proves nearly impossible to extract all the vapor from the liquid, the test fluid specific gravity effectively decreases by an unknown amount. This makes it difficult to establish the exact performance that has been obtained because the data will be lower than true values based on the specific gravity of the unadulterated fluid. It has been found with careful testing that exact duplication of water head-capacity performance will be obtained on any cryogenic fluid, subject only to adjustment for the shrinkage in impeller diameter.

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