SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR999 REV. A

Issued 1968-10
Stabilized 2011-08

Superseding AIR999

Cryogenically Fueled Dynamic Power Systems

RATIONALE

This standard has historical value but is no longer utilized and should be stabilized.

STABILIZED NOTICE

This document has been declared “Stabilized” by the AE-7C Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

INTRODUCTION - For several years there has been increasing demand for self-contained, light-weight electrical and hydraulic power systems for various missile and other aerospace vehicle applications. This Aerospace Information Report intends to discuss one particular category known as Cryogenically Fueled Dynamic Power Systems.

SCOPE - In this report, "Cryogenically Fueled Dynamic Power Systems" include all open cycle, chemically fueled, dynamic engine power systems which utilize cryogenic fuels and oxidizers. For nearly all practical present day systems, this category is limited to cryogenic hydrogen or hydrogen-oxygen fueled cycles with potential in future, more advanced systems for replacement of oxygen by fluorine. Excluded from the category are static cryogenic systems (e.g., fuel cells) and chemical dynamic power systems which utilize earth storable propellants.

1. SYSTEM CONFIGURATIONS

1.1 Selection Criteria - Cryogenically fueled power systems are especially attractive where both an environmental control system and a power system are required. Typical missions are moderate to high power levels and/or short duty cycles as required in missiles or certain space vehicles. Additional benefits are obtained where the vehicle propulsion system propellants are cryogenics. Because of the highly specialized nature of the application, few actual systems have been built. However, where applicable, cryogenic power systems have demonstrated significantly lower specific fuel consumptions and system weights for a given power level when compared to those for systems powered by other fuels such as earth storables.

1.2 Configuration Classification - These systems can be classified into basically two groups: integrated and non-integrated thermal cycles. The essential difference between the two is that an integrated cycle incorporates both a thermal control and an electrical control system. A typical example of this is shown as a simplified block diagram in Figure 1. A non-integrated system consists only of a power generation system which can include either electrical, mechanical, hydraulic power, or any combination of these. The thermal or environmental control system, if required, would be independent in this type of application. A typical block diagram of a non-integrated system is shown in Figure 2.

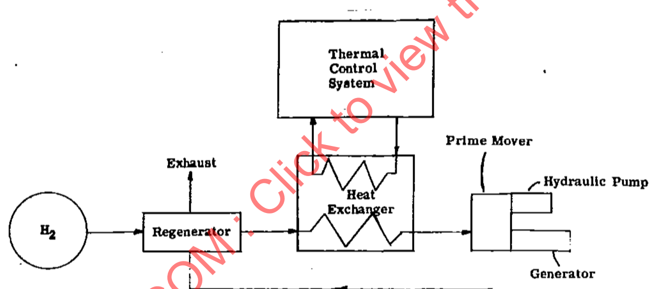


FIG. 1 - INTEGRATED CYCLE

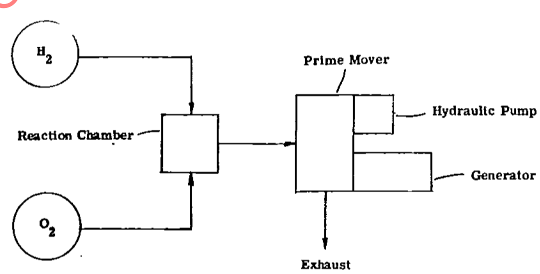
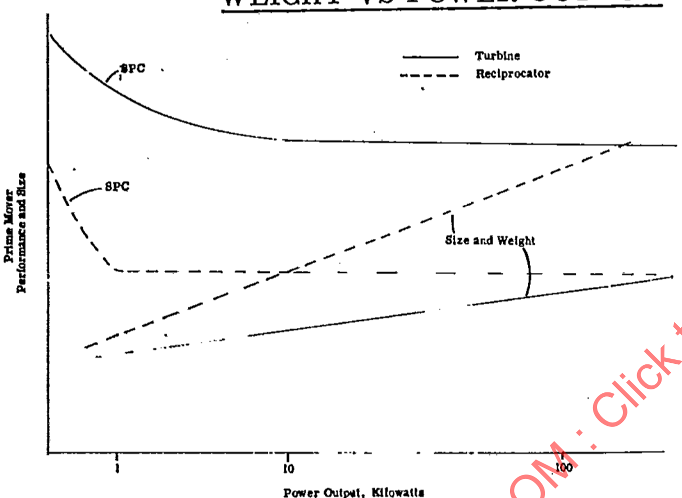


FIG. 2 - NON-INTEGRATED CYCLE

Prime movers can include either positive displacement devices or turbines for both types, and their selection depends upon the specific mission requirements. Reciprocators usually have a lower specific propellant consumption, but higher weights than turbines for integrated cycles at a given power level as shown in Figure 3. Lower reciprocator propellant consumptions are achieved by heating the gas during expansion or employing the recirculation feature. The higher reciprocator mechanical complexity results in a rapidly increasing prime mover weight with power level and a lower inherent reliability than that for a turbine. For example, a short duration mission of moderate to high power level normally dictates a turbine as the prime mover, because low system mechanical weight is more important than low propellant consumption in this case.

FIG. 3 - PRIME MOVER SPC AND WEIGHT VS POWER OUTPUT



Selection of the fuel and tank operating pressure is also important in determining overall system weight and volume. Cryogenic hydrogen and oxygen or hydrogen alone is normally used in this category of power systems because the highest system performance is realized with these fuels of any cryogenics with the exception of fluorine. It is desirable to store hydrogen in the liquid or "slush" condition to minimize storage volume. Although "slush" hydrogen production and storage has been accomplished in the laboratory, it has not been applied to any operational system as yet. Liquid hydrogen storage has been successfully used in many propulsion systems in the subcritical state, and in a few instances, at high pressure above the critical condition.

2. SYSTEM THERMODYNAMICS

2.1 Non-Integrated Thermal Cycle - On those occasions where vehicle and/or power subsystem cooling is not a simultaneous requirement with power generation, a non-integrated thermal cycle power system would be considered. This type of system might also be used where cooling is a considerably less important requirement.

2.2 Integrated Thermal Cycles - In nearly all space power system applications, there is a simultaneous requirement for some heat rejection. This may be in the form of cooling the power conversion system itself as, for example, alternator or expander lubricant cooling. In many cases, heat rejection systems are required to dissipate vehicle heat or heat produced by its electronic equipment in addition to the power system heat rejection. Usually comparatively narrow temperature limits are required at different mean temperatures within different parts of the vehicle. This is especially true if it is a manned vehicle.

The possibility of combining vehicle thermal control with a cryogenic power system was realized some time ago (see Reference 1). Integration of the cooling and power generation systems has been shown by two methods. One is a series or semi-integrated system; the other is a fully integrated system.

2.2.1 Semi-Integrated System - In the semi-integrated system shown in Figure 4, hydrogen is fed from the tank through a heat exchanger for the thermal control system. The warmed hydrogen then reaches a reaction chamber where it combines catalytically with oxygen. This hot gas then powers an engine or turbine driven generator.

a. One of the disadvantages of this system is that additional hydrogen above the amount necessary to power the generator is needed for the thermal control system. This hydrogen then must be dumped overboard.

b. In addition, the environmental cooling fluid comes in contact with a heat exchanger wall which is in contact with cryogenic hydrogen at -400 F. Therefore a precise control system is necessary to bypass one of the fluids around this heat exchanger to prevent freezing of the thermal control system coolant.

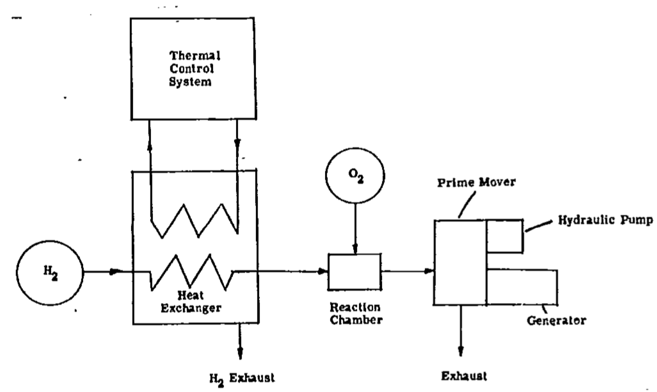


FIG. 4 - SEMI-INTEGRATED CYCLE

A typical example of a semi-integrated system is the hydrogen-oxygen powered 876C APU developed for the Dynasoar X-20 program. This system generates up to 12 kw of electrical and 3000 psi hydraulic power, but it does not include an environmental control system. A functional schematic and a photograph of this system are presented in Figures 5 and 6 respectively.

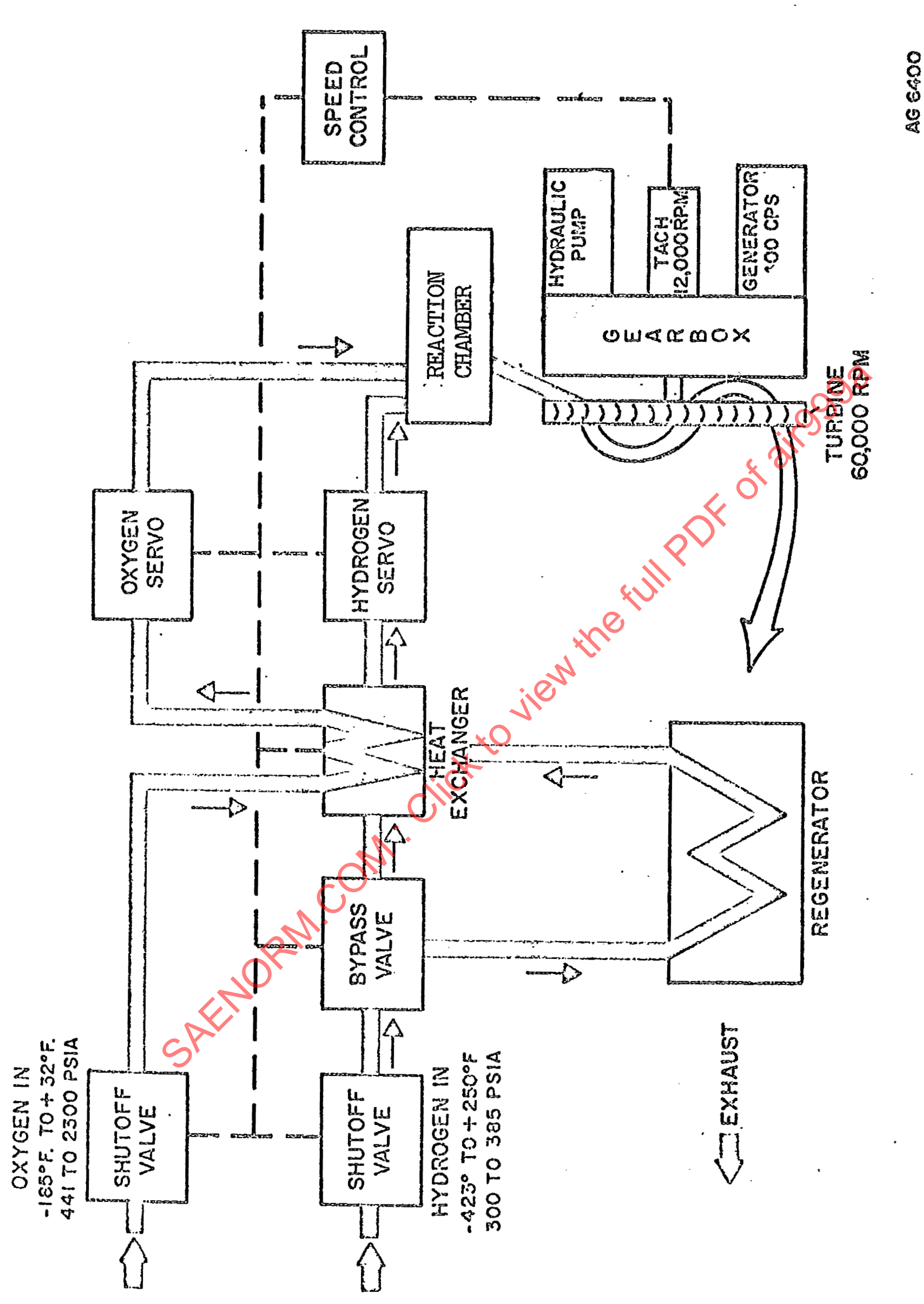


FIGURE 5 MODEL 876C APU SCHEMATIC

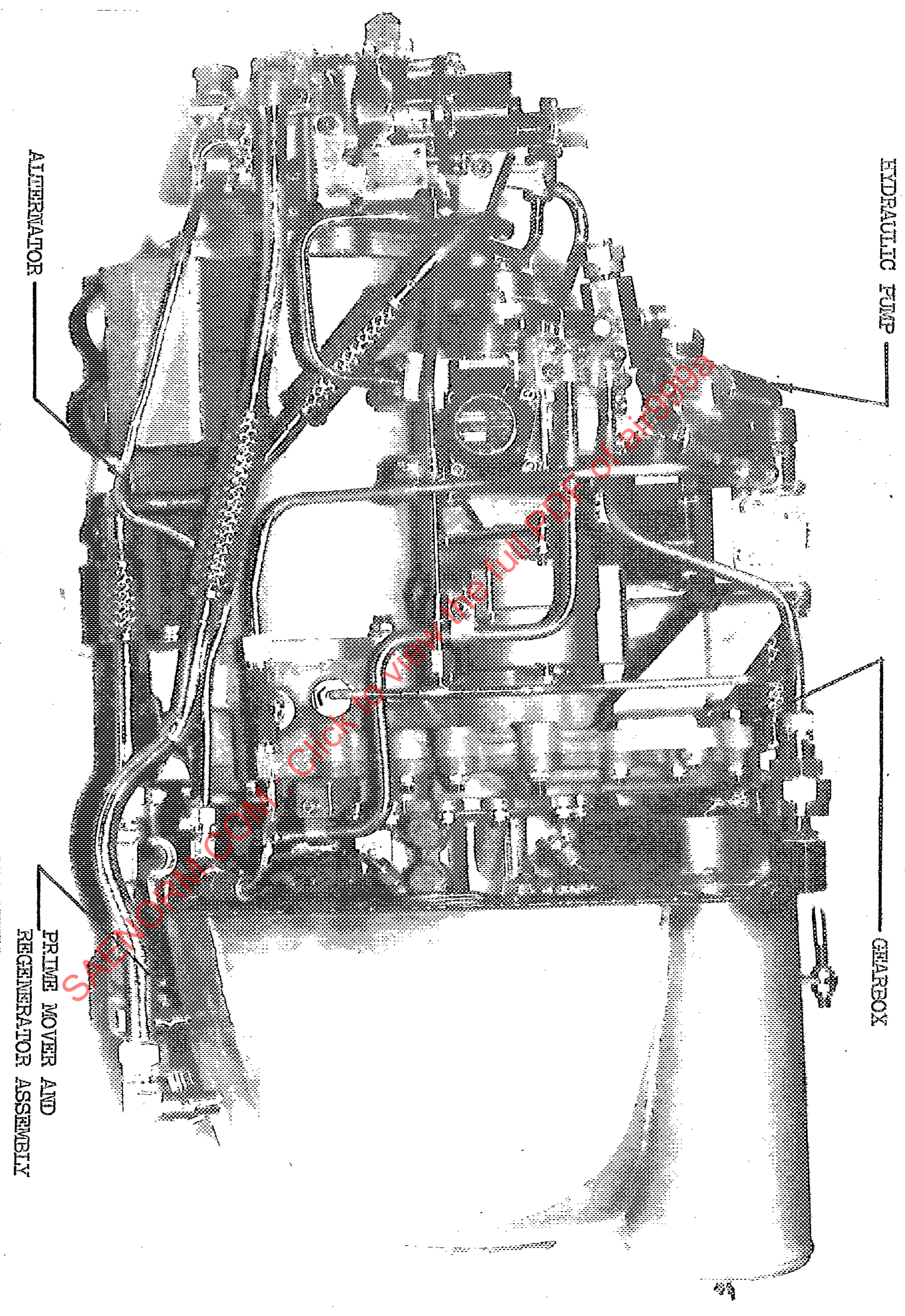


FIGURE 6 - MODEL 876 ACCESSORY POWER UNIT

2.2.2 Fully Integrated System - In the example of a fully integrated system shown in Figure 1, hydrogen passes through a regenerator prior to entering the thermal control system heat exchanger. From there, the hydrogen is expanded through a multi-stage reciprocator or turbine which in turn drives a generator.

a. This is the only cycle known which has an appreciable capability for cooling in excess of its generated electricity. This cooling can exceed power production by as much as 60 percent (see Reference 1). Since the hydrogen passes through a regenerator first, it is no longer at cryogenic temperatures when it reaches the thermal control system heat exchanger. Therefore, the thermal control system need not be as sophisticated as for the semi-integrated system discussed previously.

b. This system also has a characteristically low specific fuel consumption when compared with other systems, because the sole fuel is hydrogen which has the lowest molecular weight of any known substance. Specific fuel consumptions of 2 lb/kw-hr have been demonstrated on such a system and some additional projections to 0.8/kw-hr have been deemed possible through additional development.

2.3 Materials - In general, many of the materials and manufacturing techniques utilized in other systems using cryogenics such as rocket engines are applicable, although there are often problems unique to a particular system and some extensions to existing technology are therefore necessary. However, in many cases the output, control, and prime mover components can be obtained directly from existing technology for new systems and will involve no new materials nor technology advancements.

3. COMPONENTS

3.1 Rotating Expanders - Rotating expanders are characterized by their high performance, light weight and simplicity in comparison to non-rotating expanders. They are especially attractive at moderate to high power levels and for short duty cycles. Although recently TRW has indicated that a multi-stage hydrogen-oxygen pulsed turbine power system is capable of specific fuel consumptions of approximately 2 lb/horsepower-hour at very low power levels (see Reference 2).

3.2 Non-Rotating Expanders - Generally, non-rotating expanders offer better system performance at low power levels with the exception mentioned above. Usually, the size and weight of a non-rotating expander is greater than that of a turbine for the same power output. Low piston speeds and low fluid operating temperatures contribute to high reliability. Heat transfer into the expanding gas is improved because of the lower flow rates. This results in improved efficiency particularly in the case of an integrated system.

3.3 Tankage and Fuel System Super Critical Tankage - A basic storage system is the super critical tank where the fluid is stored above its critical pressure. In this condition, the fluid is essentially at a uniform pressure and temperature, so the requirement for separating the vapor from the liquid or the need of a pumping system is eliminated. The tank is emptied by the addition of heat, and therefore the temperature increases as the pressure and volume remain fixed.

3.3.1 Disadvantages

a. Obviously, not all of the fluid stored initially can be used with this method of expulsion. Typically approximately 10 percent of the hydrogen by weight remains in the tank. (It can be shown that a greater expulsion percentage can be realized by increasing the initial hydrogen density in the tank. This can be accomplished by filling the tank with hydrogen near the saturated condition or even in the "slush" or partially solid condition.)

b. Another disadvantage of super critical tankage is high tank weight compared to that for a subcritical tank system. This limits the operating pressure of a super critical system closer to the critical pressure (188 psia) than the 3000 psia peak cycle pressure used in subcritical systems. Tank pressures between 250 psia and 400 psia are typical for super critical systems (see Reference 1).

3.3.2 Advantages

a. This super critical tankage system is unaffected by gravity, and less insulation is needed because heat must be added.

b. No pump is required in the thermodynamic cycle. Elimination of the pump requirement is a significant system simplification. Although heat must be added for expulsion, this is usually easier to accomplish than to incorporate a pump.

3.4 Subcritical Tankage - The subcritical system is the most commonly used method of hydrogen storage where liquid hydrogen is stored at a pressure significantly below its critical pressure (188 psia).

3.4.1 The advantages of this system are the low tank weight and no significant residual fuel weight upon completion of the mission. However, a pump is required to insure positive fluid flow and obtain operating pressures consistent with good cycle efficiency.

3.4.2 The pumping power which must be considered in the cycle analysis along with the additional mechanical complexity are drawbacks in this system. Also subcooling at the pump inlet and capillary baffling for zero gravity missions are required to insure that liquid is available to the pump at all times for proper cycle operation. Usually a double-walled tank is used and the volume between the walls is evacuated and filled with superinsulation to minimize heat leakage.

It is therefore readily apparent that the overall mission envelope must be considered in terms of tank weight, reliability, volume, and cost to determine the tankage configuration for a given mission.

3.5 Fuel Pump - In most systems where hydrogen fuel pumps are required, the fluid pressures are very high (3000 psi) and the flowrates are relatively low (.3 lb/min). This usually dictates a positive displacement pump. It is desirable if the pump is designed to be lubricated with the work-