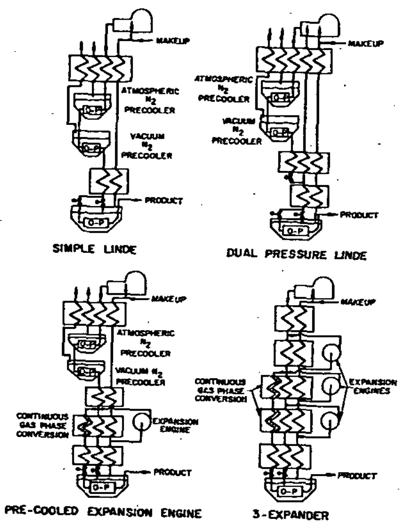

Fig. 6 .... Hydrogen Liquefaction Cycles

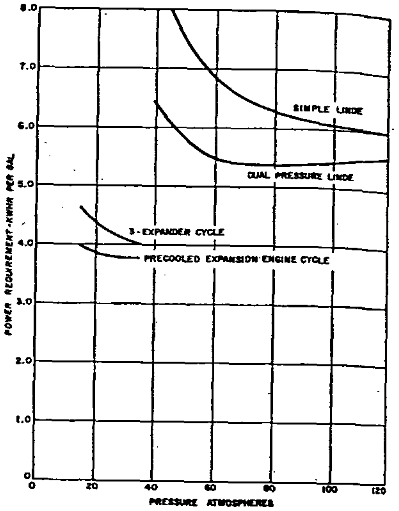

Fig. 7 .... Performance of Hydrogen Liquefaction Cycles

The simple Linde cycle is the most widely used cycle for hydrogen liquefaction. The modern Linde cycle (Fig. 6) uses subatmospheric liquid nitrogen as a precoolant and Joule-Thomson expansion for liquefaction. Particular notice should be taken of the provisions for gas and liquid phase ortho-para conversion. Overall, the advantages of the Linde cycle include its simplicity, proven design and relatively high yield. Disadvantages are its high operating pressure, liquid nitrogen requirement and high work value. (A typical Linde cycle work curve (Fig. 7) reveals minimum values 59 percent higher than the most efficient cycle shown.) The two critical design areas are the temperature approach at the warm end of the Joule-Thomson heat exchanger and maintenance of the liquid nitrogen bath as close to the nitrogen triple point as practicable.

The dual-pressure Linde cycle (Fig. 6) owes its existence to the fact that Joule-Thomson cooling is approximately proportional to the expansion pressure ratio and compression work is proportional to the logarithm of the compression ratio. Thus, the intermediate pressure stream produces most of its potentially available cooling but requires much less recompression work than the liquefaction stream which expands to one atmosphere pressure. Addition of a heat exchanger below the intermediate pressure expansion is a recent innovation which improves the performance of the cycle by reducing heat exchanger irreversibility. The advantages of the dual-pressure Linde cycle are that it retains much of the simplicity and proven design features of the simple Linde cycle and offers lower work values. Possible disadvantages of the cycle are its use of liquid nitrogen, high operating pressure, special compressor requirement, and lower yield per pound of gas circulated than the Linde cycle.

The precooled expansion engine cycle (see Fig. 6) represents a logical extension of hydrogen liquefier technology. This cycle retains much of the simplicity of the simple Linde cycle but offers the advantage of high efficiency at low operating pressures. The principal disadvantages of the cycle are its liquid nitrogen requirement and use of a low-temperature expansion engine. Critical design areas include design of the expansion engine and the heat exchanger which it brackets. From a performance and operating cost standpoint this cycle may represent the optimum since it has been shown that a combination of vapor cycle and expansion refrigeration is most efficient for supporting hydrogen liquefaction.

The three-expander cycle (see Fig. 6) is an example of a class of cycles which obtain all necessary auxiliary refrigeration from expansion engines. Since these are primarily low-pressure cycles they are particularly suited for large plants using turbo-expanders. Features of the three-expander cycle include its low liquefaction work requirement, low-pressure operation and absence of precooling liquid. Disadvantages of the cycle include a relatively low yield and heavy reliance on efficient turbo-expanders. The most critical design problem is that of achieving high efficiency from the turbo-expanders. Expander efficiences of from 75 to 85 percent of isentropic are required to make this cycle competitive with other modern cycles.

In summarizing liquefaction cycles it can be said that in the past hydrogen liquefiers were based on the simple Linde cycle because of its simplicity and proven design. As indicated by the curves of Fig. 7 for larger liquefaction plants the differences in cycle performance become important enough to support more complex systems. Low or intermediate pressure cycles, possibly with turbo-expanders, are indicated for future plants producing more than 20,000 liters of liquid per day.

Liquefaction Equipment

Despite the low temperatures involved and hazardous nature of the material, hydrogen liquefiers are constructed with commercially available components to a great extent. With provisions for explosion-proofing, purging or isolation, commercial equipment is used exclusively for compressors, vacuum pumps, instruments, controls and gas handling equipment. High pressure cycle heat exchangers, expansion valves, liquid valves, and liquid lines have been constructed as custom items. Brazed, extended-surface heat exchangers are commercially available for low-pressure cycles.

Of all liquefier components, hydrogen turbo-expanders stand as the main item requiring some degree of development. This is due to the high sonic velocity of hydrogen and the small size of hydrogen liquefiers built in previous years. The high sonic velocity of hydrogen imposes higher tip speeds on the turbine wheel than is common with air expanders and results in high rotative speeds for small units. However, even with turbine wheels of 4 to 6 in. diameter, the possible throughput of a hydrogen expander is large. Thus, there is a minimum size of plant for which a turbo-expander is practicable.

MEASUREMENT OF LOW TEMPERATURES

The gas thermometer is the most accurate means of determining the true thermodynamic temperature according to the definition of Lord Kelvin. Precision gas thermometry is an arduous and exacting occupation and requires complex and bulky equipment that is not suitable for ordinary practical temperature measurement. However, a simple constant-volume gas thermometer is sometimes very well suited for measuring low temperatures. Such a thermometer can consist of a bulb having a volume of one or two cubic inches connected by a capillary tube to a manometer or dial pressure gage of small volume and filled with pure helium. The pressure will be almost proportional to the absolute temperature of the bulb, so calibration at a few points is sufficient.

A vapor-pressure thermometer consists of a bulb partly filled with a volatile liquid or solid and partly with vapor in equilibrium with the condensed phase, connected by a pressure-transmitting tube to a pressure measuring instrument. This instrument is especially adapted to certain applications because it is simple and quite sensitive in certain temperature regions. Also its reproducibility is limited only by the pressure measuring device. The principal disadvantages of the vapor-pressure thermometer are its limited temperature range and its non-linear response. A precaution that should be observed very strictly when using a vapor-pressure thermometer is to make certain that the bulb is the coldest part of the thermometer.

Thermocouples are widely used to measure low temperatures. They can be used in relatively inaccessible locations, have low heat capacity, respond quickly to temperature changes, and can be read at a convenient location. Their disadvantages are that they require expensive accessory equipment and they become rather insensitive at very low temperatures. The sensitivity of all thermocouples approaches zero at absolute zero. Many materials have been used to construct thermocouples of which the most popular for low-temperature use at the present time are copper and constantan. It is common practice to calibrate a few pieces of wire from spools of copper and constantan and use the calibration for all thermocouples made from the same two spools. The constantan wire should be of thermocouple quality for good results because some constantan wire has inhomogeneities that will behave like local thermocouples and cause errors when they are located in a temperature gradient. Thermocouple junctions may be made with soft or hard solder or by welding. The method of making the junction will have no effect on the calibration of the thermocouple. For low temperature work it is usually advisable to use rather small thermocouple wire, for example, No. 30 B&S gage. Care should be exercised in

Table 1 .... Emfs of Some Thermocouple Materials at Low Temperatures

(Emfs Are for Thermocouples Made of Copper With the Indicated Alloy as the Other Element)

T	Electromotive Force		
	Au + 2.11 Atomic % Co	Constantan	Ag + 0.37 Atomic % Au
K	microvolts	microvolts	microvolts
0	0.00	0.00	
2	2.04	0.70	
4	8.04	2.76	
6	17.76	6.14	
8	37.01	10.79	
10	47.57	16.64	
12	67.23	23.66	
14	89.78	31.78	
16	115.0	40.97	
18	142.9	51.22	
20	173.1	62.48	0.00
25	259.5	95.18	0.65
30	360.1	134.1	2.05
35	472.6	178.6	4.25
40	595.8	228.5	7.40
45	728.3	283.3	11.15
50	869.0	342.8	15.25
60	1171.1	474.7	24.10
70	1495.4	622.4	33.20
80	1836.3	784.4	41.70
90	2190.3	960.5	49.5
100	2555.8	1149.8	57.1
110	2930.5	1351.9	64.2
120	3312.6	1566.5	71.1
130	3700.6	1793.1	77.9
140	4093.2	2031.8	84.3
150	4489.6	2282.4	90.7
160	4888.7	2545.0	96.9
170	5290.1	2819.8	103.1
180	5693.3	3106.7	109.4
190	6098.1	3405.2	115.9
200	6504.0	3714.1	122.4
210	6910.6	4033.3	128.9
220	7317.6	4362.7	135.3
230	7724.8	4702.2	142.2
240	8131.9	5051.9	148.8
250	8538.8	5411.7	155.5
260	8945.3	5781.5	162.3
270	9351.1	6161.5	169.7
280	9756.3	6551.7	177.1
290	10160.0	6952.1	184.8
300	10564.0	7362.9	192.9