50 YEARS OF HELIUM LIQUEFACTION AT THE MIT CRYOGENIC ENGINEERING LABORATORY

Joseph L. Smith, Jr.

Massachusetts Institute of Technology, Cryogenic Engineering Laboratory
Cambridge Massachusetts, 02139, USA

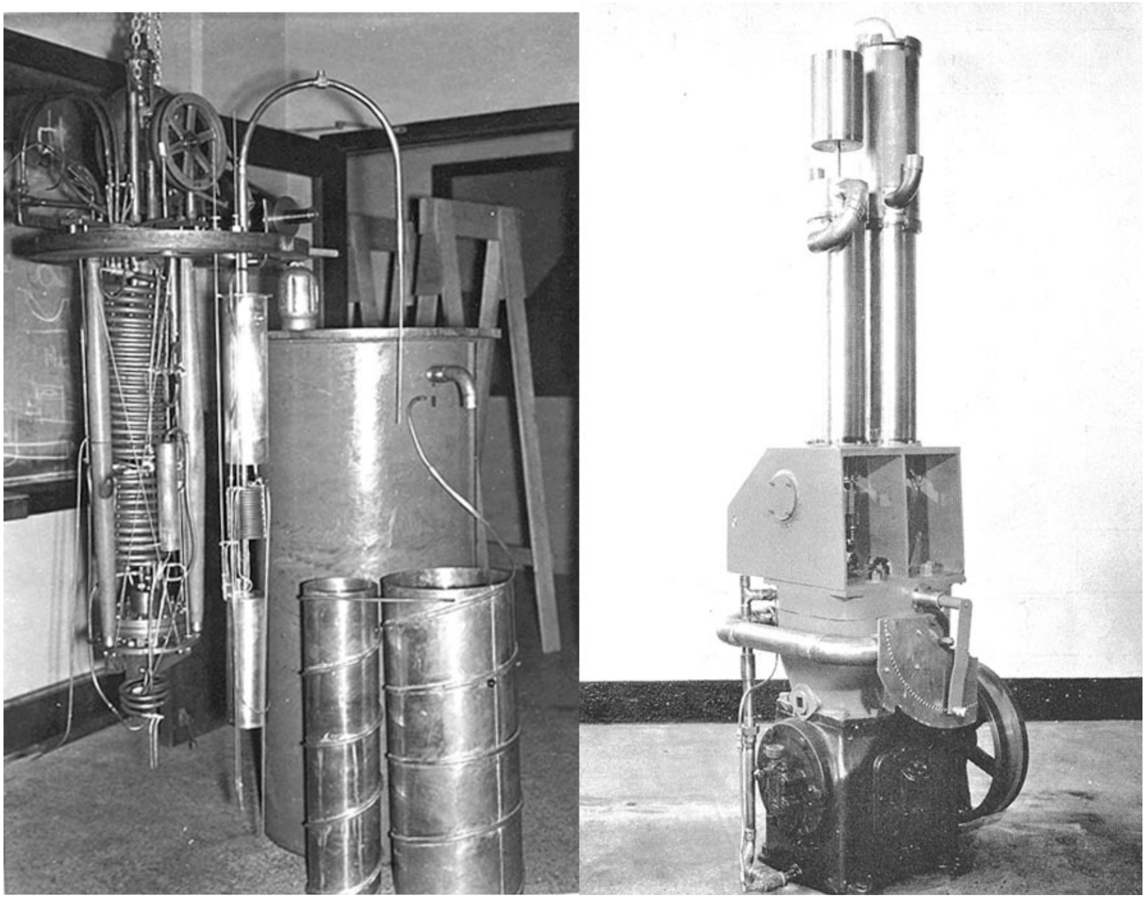
ABSTRACT

The evolution of the helium liquefaction facility of the MIT Cryogenic Engineering Laboratory and the history of its operation over the last 50 years are described. Professor Samuel C. Collins created the liquid-helium facility based on his earlier developments. The chronology of the Laboratory helium liquefiers is given with a brief description of each one. The current facility based on the Model 2000 liquefier is described and operating experience is given. The reasons for the very high availability of the liquefaction system are developed.

INTRODUCTION

The origin of the helium liquefaction operation at MIT was Professor Samuel C. Collins' early interest in mechanical equipment for cryogenic refrigeration. Before WWII Professor Collins was with the MIT Department of Chemistry working on physical chemistry with Professor F. G. Keyes. Mechanical equipment for refrigeration was not an important activity, so Collins' early experiments to achieve helium liquefaction with mechanical expansion were a sideline done out of view. FIGURE 1 (a) is an early photograph of an experiment done in 1939. According to Collins, these experiments were not successful because the heat exchanger was made from tubing that was not vacuum tight and with this early design the heat exchanger was in the insulating vacuum.

WWII interrupted Collins' work on helium liquefaction. His work at Wright Field in Dayton, Ohio, during the war was on the development of a lightweight mobile cryogenic air separation apparatus to make breathing oxygen in flight. The low-pressure cycle with a reversing heat exchanger for air purification was developed [1]. Collins was working with Howard McMahon, his first graduate student [2] who became the President of Arthur D. Little, Inc. (ADL) and is the "M" in the G-M cycle cryocooler. The flexible-rod expander that was developed by Collins [1,3] was later used for liquid nitrogen production as



(a) (b)

FIGURE 1. (a) Helium liquefier experiment, 1939. **(b)** Flexible-rod expander for liquid nitrogen production.

is shown in FIGURE 1 (b). This reciprocating expander is single-acting on the rod end of the piston so that the rod is always in tension. This allows a long flexible piston rod for thermal isolation. The flexible rod also allows the use of a close-clearance piston-to-cylinder seal since the piston can easily align with the cylinder without the requirement for a precision alignment between the cylinder and the warm crank mechanism.

After the war Collins returned to MIT and C. Richard Soderberg, then Professor of Mechanical Engineering, arranged for Collins to associate with the Department of Mechanical Engineering in 1943 and join the faculty in 1946. By 1946 Collins had developed the liquefier that became the ADL Collins Helium Cryostat. This liquefier is widely recognized as having had a major impact on research in low temperature physics. “Before Collins” research at helium temperature required a major effort and “After Collins” the commercial liquefier from ADL made helium temperature readily available to low temperature physics labs. Milton Streeter played a significant roll in facilitating the acquisition of the liquefier, first in the U S then in Europe, Japan and India.

CHRONOLOGY OF LIQUEFIER DEVELOPMENT

The Collins Helium Cryostat [4] designed in 1946 was a major innovation. First, the flexible rod expander was refined by moving the warm mechanism above the expansion cylinder rather than below the cylinder, FIGURE 2 (a). Second, the cold components of the liquefier were suspended in the low-pressure helium in the long neck of a wide mouth dewar vessel. Third, the heat exchanger was also suspended in the helium in the dewar

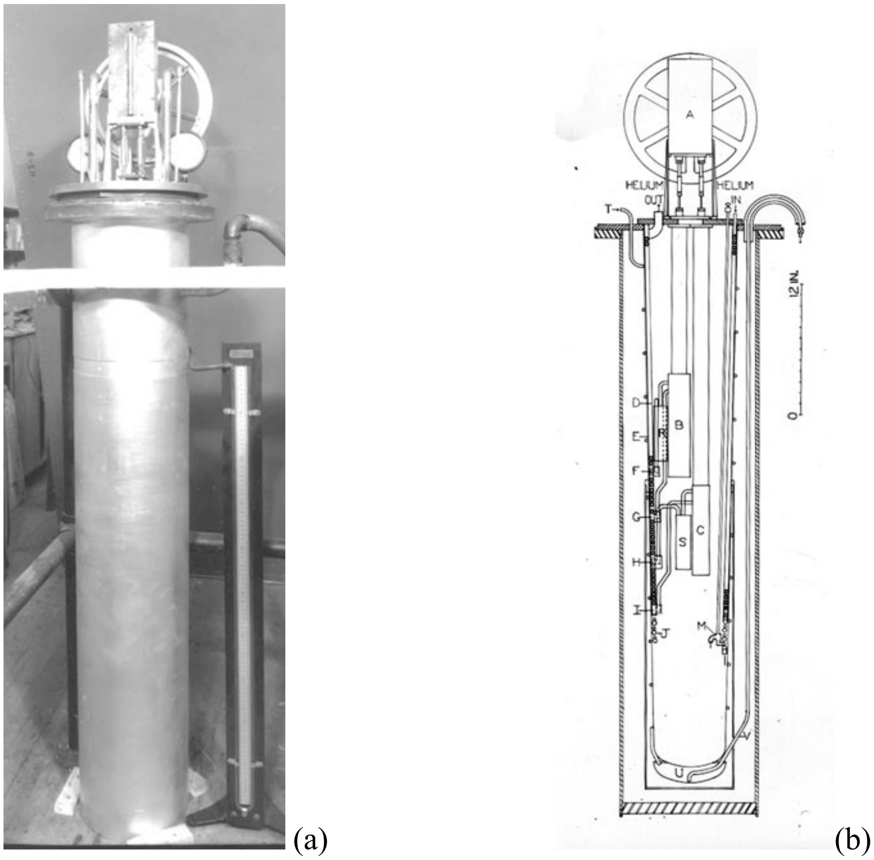


FIGURE 2. (a) Helium liquefier. 1946. **(b)** Cross section of 1946 helium liquefier.

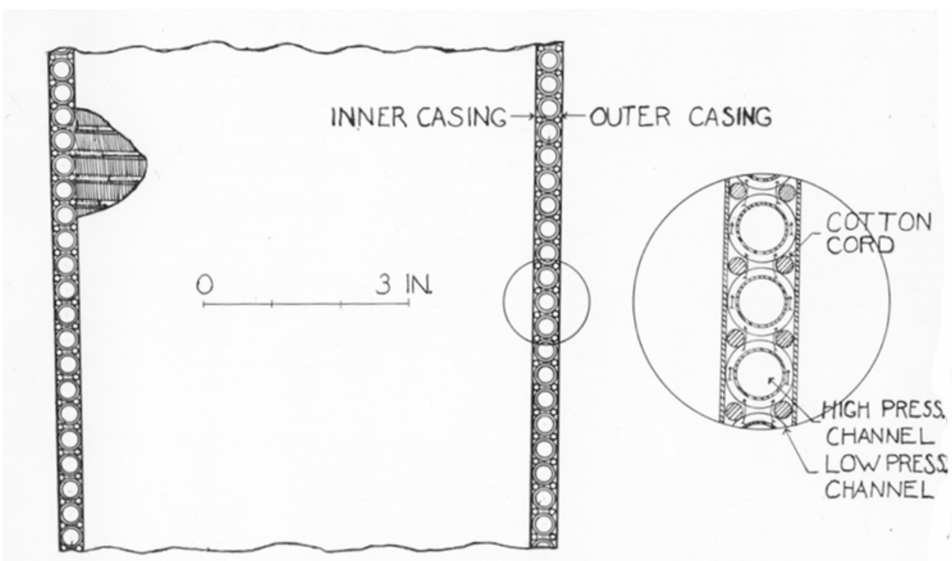
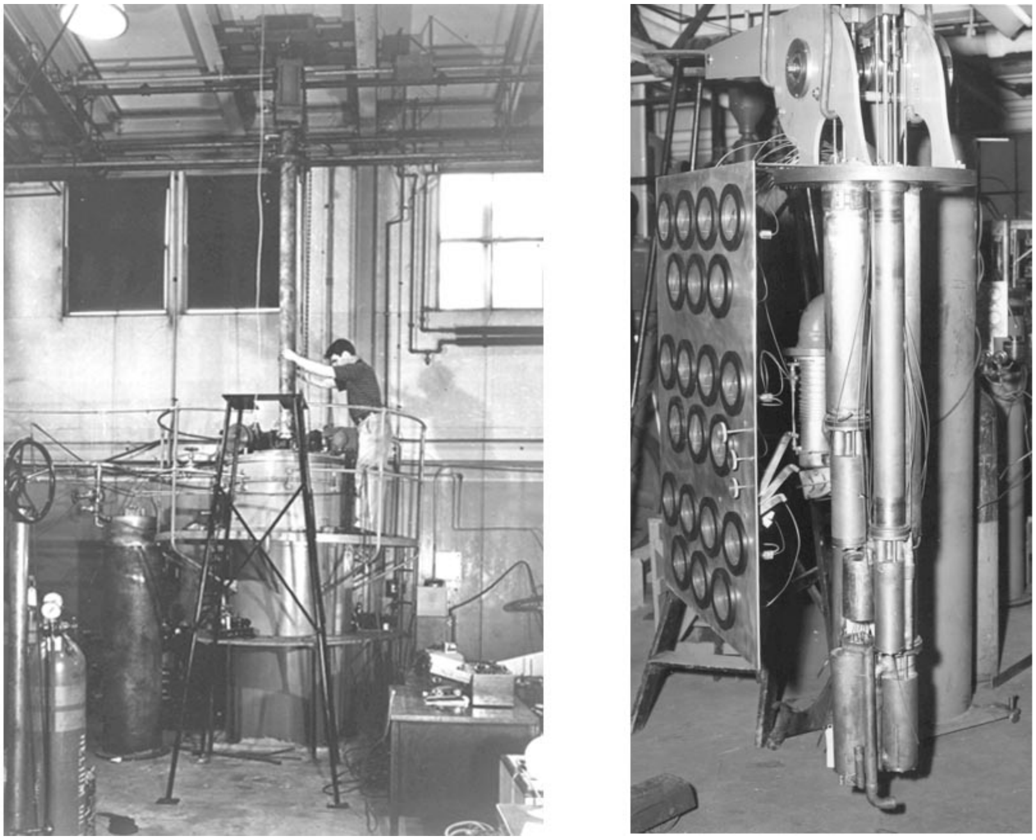


FIGURE 3. Heat exchanger for 1946 helium liquefier.

neck and surrounded the expanders, FIGURE 2(b). Even though this arrangement required a dry crankcase, the over-riding advantage was that small helium leaks that would destroy the insulating vacuum were completely negated. Fourth, the main heat exchanger was spiral wound with tubing with helically wound fins over the outside diameter of the tubes. The arrangement is similar to a Hampson spiral-wound bare-tube exchanger except the accuracy of the spacing of the tubes is not an issue since the low-pressure helium is forced



(a) (b)

FIGURE 4. (a) Helium liquefier with tensile-test apparatus, 1948. **(b)** Helium liquefier with three walking-beam flexible-rod expanders, 1956.

to flow between the fins by cotton cords that are co-wound with the finned tube, FIGURE 3. The final innovation was the arrangement of the flow to the two expanders at different temperatures, so that two stages of pre-cooling were provided for the Joule-Thompson stage rather than a single stage of pre-cooling.

Collins continued to evolve the design of his helium liquefiers and refrigerators. He completed a new model in 1948, a larger refrigerator-liquefier that was designed as a hydrogen liquefier but was used only to liquefy helium and for very early tests of mechanical properties at helium temperature, FIGURE 4 (a) [5]. In 1951, a large helium liquefier was constructed in MIT building 41, the present location of the Laboratory. In 1956, an improved version of the liquefier was completed. See page 109 of reference [3]. As shown in FIGURE 4 (b), a single shaft runs the three expanders with eccentrics and cams that operate walking beams that pull the flexible piston rod and valve actuating tension rods. FIGURE 5 (a) is a cross section of one of the one of the expanders. Wax-impregnated leather rings that are clamped to the piston maintain the close clearance seal for the piston. As the engine cools down the rings become rigid and maintain the clearance for the seal. This seal was much more tolerant to impurities than the very hard nitrided piston and cylinder used in previous engines. FIGURE 5 (b) is a photograph of one of the expanders from this liquefier that has been saved as a museum piece.

By 1956, the Laboratory helium liquefiers had become the source of liquid helium for the low temperature experiments done at MIT. This was a natural evolution from the operation of the Laboratory liquid-nitrogen plant that was supplying liquid nitrogen before it was commercially available. About 1959, a miniature helium refrigerator was constructed to demonstrate a new configuration for a heat exchanger using finned tubing.

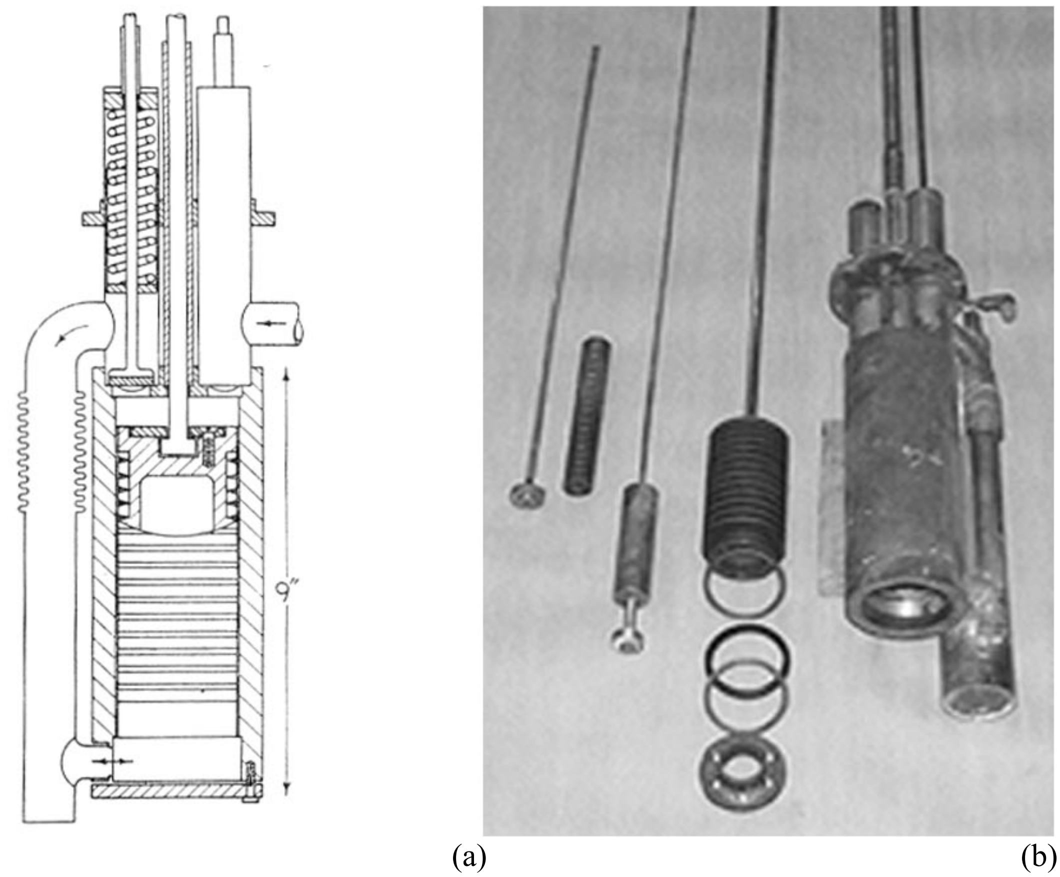
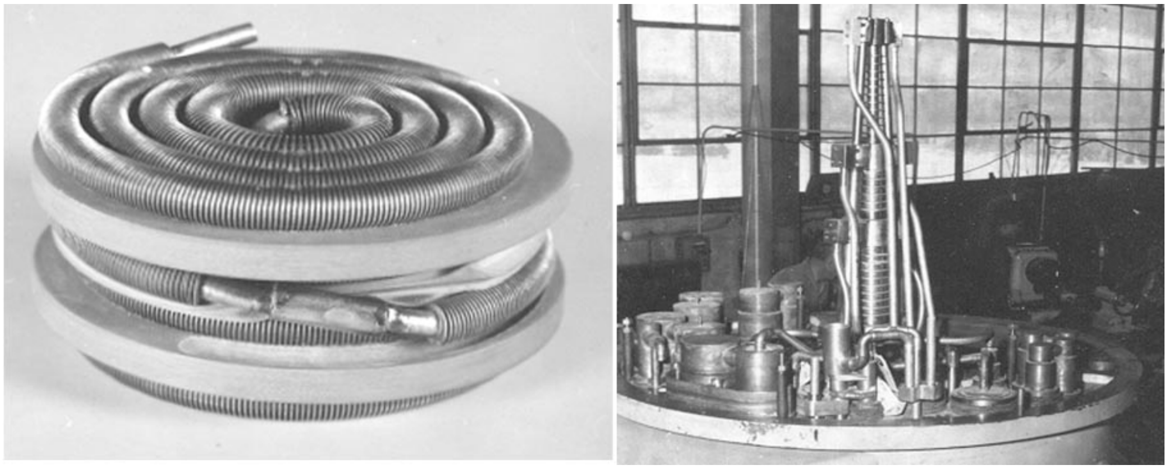


FIGURE 5. (a) Cross section of flexible-rod expander with leather seals, 1956. **(b)** Disassembled flexible-rod expander with leather seals, 1956.

The objective was to have the thermal performance of a long heat exchanger in a short axial length by arranging a single tube in a series of spiral pancakes between plastic disks, FIGURE 6 (a), [6]. The low-pressure helium flows in and out radially over the tubes and between the disks. The heat exchanger worked well but was too difficult to fabricate. The expanders of the refrigerator were the first to have the valve-spring enclosing tubes extend all the way up to room temperature. A plastic plug was used to fill the space between the valve pull rod and the enclosure tube that was larger than the valve spring. With this configuration the valve was compressed from the room temperature end of the plug. More important, the valve and spring could be removed without disturbing the expander cylinder or any of the cold piping. This provided easy access to the valves for servicing.

In the early 1960's two experimental liquefiers were constructed with a stepped piston expander nicknamed the Christmas tree expander. FIGURE 6 (b) shows one of the cylinders with four stages of expansion. One unit was abandoned because of a mechanical design flaw and the other because of vacuum leaks and poor heat exchanger performance. The unit had the heat exchangers in an insulating vacuum rather than in the low-pressure helium in the neck of a wide mouth dewar vessel.

At about this same time the Laboratory was involved in the design of the cryogenic system for the Cambridge Electron Accelerator located on the Harvard University campus. The system was composed of a helium liquefier and a helium-cycle refrigerator for cooling the liquid hydrogen in a large bubble chamber. Both systems ran from a single 3-stage 300-horsepower compressor. Collins' flexible rod expanders with close-seal wax-impregnated leather rings on the pistons were used in the liquefier and the refrigerator. The original heat exchangers were 3-inch-diameter concentric-tube exchangers manufactured



(a) (b)

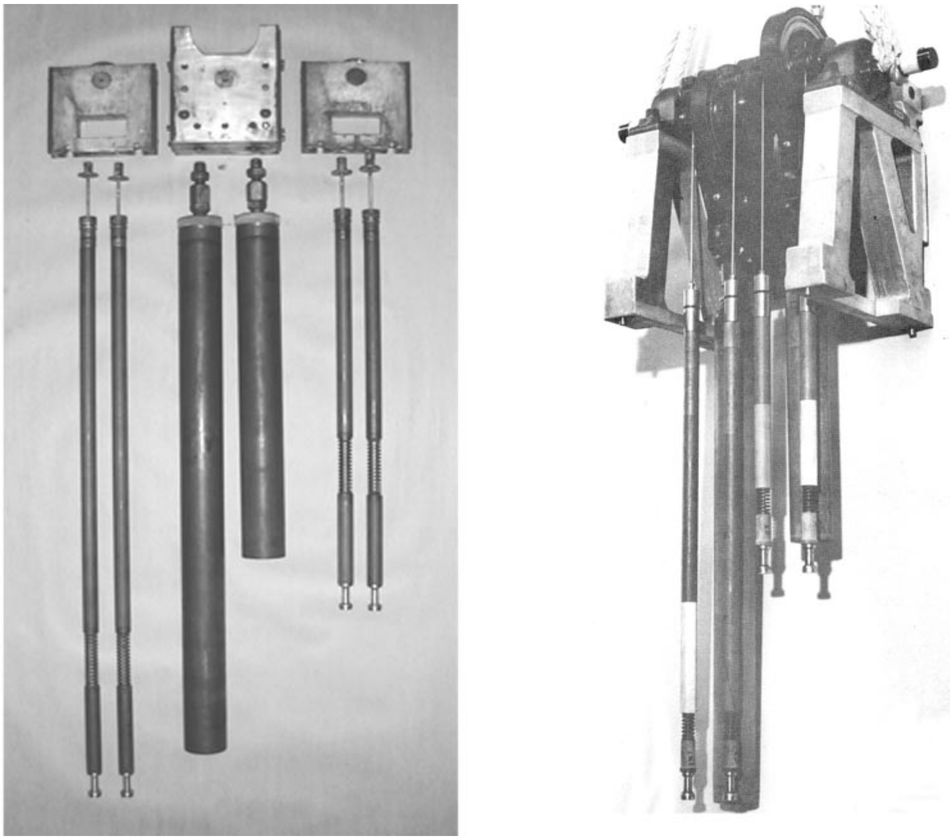
FIGURE 6. (a) Compact heat exchanger with spiral pancakes, 1959. **(b)** Helium liquefier with "Christmas-tree" expander, 1960.

by Joy Manufacturing Co, [7] with spiral fins in the annuli. These exchangers had unsatisfactory performance because of poor bonding of the fins and were replaced with brazed-aluminum plate-fin exchangers. Both machines ran quite well, but the accelerator never recovered from the explosion of the hydrogen from the bubble chamber. The liquefier was later moved to the MIT reactor for in-core helium-temperature irradiation experiments.

During the year before he retired from MIT in 1964, Collins developed the first of a long line of displacer-piston expanders. Two of these expanders were used in a new liquefier [5] that fit into the wide-mouth dewar that was originally constructed for the 1951 liquefier. The pistons were 3-inch diameter solid phenolic-plastic bars as shown in FIGURE 7. (a) The piston seal was a single buna rubber O-ring at the warm end. Lubrication of the O-ring was by a felt ring wet to a specific degree with compressor oil.

With this design the clearance gap between the piston and cylinder wall is pressure cycled with the displacement volume of the expander. Prior to this machine, it was thought that the circulation of helium in and out of the gap would cause an unacceptable heat leak to the expander. Although the success of this design was not fully understood at the time, it is now clear that the heat leak is small because of the pulse tube effect. As the gap is pressurized, the helium flowing up the gap is increased in temperature as the pressure increases. Since this adiabatic compression temperature approximately matches the temperature distribution along the gap, the gas does not pick up significant heat. When the gas re-expands, the temperature drops back as the gas flows back along the gap so that it does not deliver significant heat at the cold end of the piston.

This liquefier, with two expanders and liquid nitrogen pre-cooling, had good performance and consistently made about 40 liters of liquid helium per hour. Pre-cooling was used, since inexpensive liquid nitrogen had become commercially available. The liquefier required significant maintenance, but the easy disassembly of the pistons and valves allowed an overhaul in several hours. One of the main problems was due to cooling of the piston and valve O-rings by the low-pressure gas at the warm end of the heat exchanger mounted in the dewar neck. Since the warm ends of the cylinders were flush with the top plate and the cylinder and top plate were exposed to low-pressure gas at the exit temperature, the O-rings ran at too low temperature, especially during cool down before liquefaction started. Electric heaters were placed on the crosshead guides to heat the top plate to improve the life the O-rings.



(a) (b)

FIGURE 7. (a) Displacer-pistons, valves and cross head sliders for 1964 liquefier. **(b)** Displacer-pistons, valves and cross head mechanism for 1969 Model 2000 liquefier.

The pistons and valves were actuated by eccentrics and cams mounted on a single shaft. The crosshead slider for the pistons carried a needle-bearing cam follower that rolled on the eccentric. With this design, a positive gas pressure in the cylinder was required to maintain contact between the eccentric and its follower. Whenever the pressure went sub atmospheric or the pistons developed excessive friction due to contamination, there was significant hammering. The mechanism had to be rebuilt several times during the life of the liquefier from 1964 to 1969.

In addition to the frequent maintenance, the liquefier had the operational disadvantage that the liquid helium reservoir in the bottom of the dewar accommodated only about 60 liters. This required the operator to transfer the liquid into an external dewar every 1.5 hours. Transfer required lifting the external dewar to insert the rigid transfer tube.

After retiring from MIT, Collins moved to ADL Inc., where he continued to refine helium liquefiers, utilizing displacer-piston expanders. Among the several machines that he designed and built were the Model 2000 and the Model 1400. The Model 1400 was a major product line for CTI, and is still being built by a successor company. One of the early model 2000 liquefiers was purchased and installed in the MIT Laboratory in 1969, with the first run on August 18. After 32 years, this machine is still the major source of liquid helium at MIT.

THE CURRENT LIQUEFACTION FACILITY

The Model 2000 [8] had a number of significant improvements over the 1964 MIT liquefier that was the basis for its design. The main heat exchanger system was significantly enlarged and improved with closer-spaced fins on the tubes and longer lengths of tubing. The heat exchangers, the expanders and the other cold components were arranged in a high vacuum environment. With this environment the component arrangements did not have to match the temperature gradient in the dewar neck so the heat exchanger was folded into an arrangement of concentric cylinders separated by a vacuum space. The overall heat exchanger length was about twice that of the 1964 model.

The cold components of the two expanders were essentially the same as in the 1964 model. The mechanical design of the mechanism to stroke the pistons and operate the valves was improved to significantly increase the operating reliability and life. Disassembly for maintenance of the valves and displacer pistons was made much easier. Large diameter ball bearings were placed over the eccentrics keyed to the shaft. Connecting rods over these bearings drove crosshead sliders that rolled on needle-bearing wheels. The cams on the shaft rolled on cam-follower bearings that lifted pivoted beams. The beams operated pull rods to lift the valves. FIGURE 7 (b) [9] shows the pistons valves and warm operating mechanism. The expanders drove a hydraulic pump in a flow loop with an adjustable throttle for speed control.

The MIT Model 2000 liquefier was built with a supercritical wet expander connected in parallel with the normal J-T valve [10]. The expander was operated by an electro-hydraulic system rather then by a more conventional mechanical crank and cams. A conventional hydraulic cylinder was directly coupled to the warm end of the displacer-piston. Custom-designed short-stroke air cylinders operated the expander valves. The coordinated motion of the displacer-piston and the expander valves were controlled by commercial solenoid valves through relay logic in response to position signals from the piston. Throttle valves in the air system and the hydraulic system provided speed control for each of the processes of the expander cycle.

When operating on the J-T valve, the liquefier produced about 60 liters per hour of liquid helium. When operating on the two-phase expander, the system produced about 80 liters per hour, with the same compressor conditions and the same liquid nitrogen pre-cooling flow. In addition to the increased production, operation with the two-phase expander is much more stable than with the J-T valve. At the start of a cool down, the expander is set to 30 cycles per minute. No significant adjustment is required during cool down or for steady liquid production or during liquid transfer from the storage dewar. This is in sharp contrast to the complex adjustment strategy of a J-T valve during cool-down and the continual adjustment normally required during steady operation. Production is maximized when the speed of the two-phase expander is set at 30 cycles per minute and the speed of the main expanders is adjusted to about 210 RPM, which takes the full flow of the compressors at a high pressure of 265 psi. This condition is for an inlet temperature for the second expander of 17 to 20 K. The liquefier is so easy to operate on the two-phase expander that the liquefier has never been operated for any significant time on the J-T valve.

The liquefier was connected to a transfer system designed and assembled in the Laboratory. A liquid transfer line carried the liquid and vapor exiting the two-phase expander through a valve box to an external storage dewar which served as a phase separator. The separated vapor returned to the liquefier through the valve box and a vapor-return transfer line. The valves in the valve box were combined with the transfer tube bayonets by placing a valve operating tube between the bayonet of the transfer tube and the socket in the valve box. A telescoping transfer tube fixed in the storage dewar was used to transfer liquid from the storage dewar into transport dewars. The three flow passages together with the operator for the foot valve passed down through the neck of a standard 1000-liter transport dewar.

In 1983, a helium recovery and repurification system was designed and installed, with support from the NSF helium conservation program. Nine second-hand high-pressure storage tubes were installed to store 80,000 scf or recovered gas. A six-stage compression system was built from second hand compressors to compress the gas to 2400 psi. The first two stages were a modified air compressor that was followed by a Cardox four-stage booster compressor. Additional clearance volumes were added to the appropriate stages to match pressures at a lower compression ratio for each stage. The bore of the cylinders of the Cardox compressor were chrome plated to reduce piston ring wear.

A repurification system was designed as a student thesis [11] and was constructed in the Laboratory. Internal coils cooled the activated-charcoal bed with liquid nitrogen inside. The vertical bed was constructed from a 20-foot length of 4-inch stainless steel pipe. High-pressure helium from the storage bank passed at 1500 psi through a counter-flow exchanger constructed from "Joy tube" inside high-pressure pipe. The helium then passed through a phase separator to remove liquid air, a final cooling coil immersed in the liquid nitrogen reservoir, and finally through the charcoal bed. The high-pressure helium from the bed goes directly to the liquefier pure-gas feed station, thus avoiding any need for return to pure gas storage. A thermal conductivity gas analyzer samples the gas leaving the bed. When impurities break through the bed, the analyzer signals an automatic switch to switch to purchased pure gas.

In the fall of 1992, a student project adapted the liquefier for unattended operation and automatic unattended shut-down. The first system used an old IBM XT computer with a simple data acquisition and control board. The software was written in basic. Pressure, temperatures and the dewar liquid level were monitored. When any parameter was out of range, the shut down sequence was initiated. First the clean gas and the liquid nitrogen were shut off, and then the operating pressures were lowered gradually so that the recovery system could capture all the helium gas. Finally, the transfer tube valves were closed to isolate the storage dewar. These isolation valves that were originally hand operated were modified for automatic operation by adding air cylinder operators.

OPERATING EXPERIENCE WITH THE MIT MODEL 2000 LIQUEFIER

Since 1969 the liquefier has proven to be a very robust system. There have been only about 4 or 5 times in the 31 years that no liquid from the system was available for researchers. The machine has run on the average about 10 hours every working day. Typically the liquefier is warmed every other weekend by putting helium in the vacuum space. Then a vacuum pump with a glass nitrogen-cooled trap is used to pump on the working helium passages and thus the two internal charcoal absorbers. Typically the trap collects 10 to 20 ml of water. After the vacuum is pumped, and liquid nitrogen pre-cooling is started, the machine makes liquid in about 3.5 hours. For rapid cool down, helium from the pre-cooling exchanger is bypassed around the main heat exchanger directly to the second lower temperature expander. The third two-phase expander is started immediately and the exhaust that normally goes to the storage dewar is by-passed directly to the main exchanger. Normally, unattended operation is set at the end of the day shift. At 70 liters per hour, the dewar is full in about 14 hours, at the most, and the machine shuts itself down. At the start of the next day, the machine is liquefying in about 1.5 hours. Transport dewars are then filled for the days demand. The transport dewars are filled by cooling down the telescoping transfer tube, rolling the dewar into position and then lowering the tube into the neck of the dewar. The flash-gas return connection makes up to the fitting on the dewar neck when the tube is fully lowered. After a short purge, the flash gas is returned to the compressor suction. When the dewar is full, the transfer tube is removed and immediately lowered into the next dewar to be filled. When demand is high, a second sequence of transfers is done at the end of the shift. When demand is very high, additional transfers are done in the evening as required. Demand has seldom been high enough to require around-the-clock operation. The majority of users at MIT do not recover any helium gas, especially since the National Magnet Laboratory closed down, and the Materials Center operates a Model 1400 liquefier in their facility. Gas recovery is now from operation of the facility in the Laboratory. After several weeks or recovery, a run is made using recovered gas.

The most frequent maintenance requirement, other than normal cleaning and lubrication, is replacement of O-ring seals on pistons and valves. After an O-ring has reached its wear limit it will start to leak helium from the cold region. This quickly turns into a larger leak and a lot of frost. A manual or automatic shut down then follows. To replace a piston O-ring, the valve rod clamps and the drive belts are removed so that the crankshaft assembly can be lifted, extracting the cold pistons from the two cylinders. The displacers are unbolted from the cross heads and then they are warmed rapidly, cleaned of any O-ring oil and wear debris. New O-rings and properly-oiled new felts are installed. Hot copper slugs are lowered into the cylinders for warming. The displacers are reassembled and as the crankshaft assembly is lowered, the displacers slide back into the cylinders. This operation takes only three to four hours. An individual valve O-ring replacement is even simpler. The valve-rod clamp is removed and the lifter beam swung away. A valve spring compressor is used to unload the retaining snap ring that is removed to allow the entire valve assembly to be removed from the valve tube. While the valve O-ring is being replaced, care is taken to exclude air from the valve tube. Once the valve assembly is warm and dry, the assembly is returned to the valve tube. The piston O-rings run for several thousand hours, which is more than a year in our operation. The valve O-rings last even longer. The piston O-rings must have adequate oil, but not so much that oil moves down the displacer to the cold region resulting in a frozen-in displacer.

Over the 31 years of operation the system has undergone a number of modifications and major repairs. The electro-hydraulic drive mechanism for the two-phase expander has had the most modifications. Shortly after installation it was discovered that the threaded end of the commercial hydraulic cylinder was not precision aligned with the axis of the piston rod. When bolted tight to the displacer, it was at a slight angle to the hydraulic cylinder. When assembled with the expander, a significant side load was required to flex the piston rod. Premature seal wear resulted. The solution was to make the thread in the nut slightly oversize to allow alignment without side force. A cotter pin was used to prevent the thread from unscrewing

The original magnetic reed switches used to sense the piston position had to be replaced almost immediately. They welded shut under the inductive load from the relay coils. The replacement mechanical micro switches stood up reasonably well but were frequently destroyed from misalignment of the cam that moved with the piston. The control relays that were original equipment would last only about a year before the contacts failed from the inductive load of the solenoid valve. The relays of successively increased rating were used. A 30-ampere motor-starting relay finally gave satisfactory contact life. After 5 or so years even the mechanical hinge of these relays failed. Finally a solid-state circuit with solid-state switches and solid-state hall sensors for position was built. This component has operated since 1985. The four-way air solenoid valve that controls the expander valves was replaced several times. The Parker valve now installed has stood up much longer than the original valve, which is no longer available.

The original valves for the main expanders had the Teflon seal washers held on the face of the valve with a single flat-headed screw. When cold the Teflon shrank and the screw came loose. One screw came completely out and left its imprint in the end of the long displacer before it disappeared out through the exhaust valve. The second set of valves had the washers held on by a retaining ring that was welded to the valve head. When cold, these washers were slightly loose and could rotate freely. When warm the washer would deform to match the slight out-of-square of the valve seat. When the washer rotated on the valve, it would leak significantly making the expander performance very erratic. It took some time to diagnose the cause of the erratic behavior of the expanders. After several attempts to restrain the rotation of the valve washer, finally in 1976 a single heavy strike with a cold chisel deformed the retaining ring into the washer sufficiently to prevent rotation. In 1973 a cam-follower bearing failed. The single-row bearing with grease seals was replaced with a double-row bearing with the same dimensions. These bearings lasted until 1988.

In 1974 an end flange cracked away from the warm end of a high-pressure valve tube. The valve spring and the entire valve assembly were fired out of the tube by the pressure. The valve pull rod pierced the crank case cover. The valve rod was straightened, and the flange re-welded so the machine was back on line in a few hours. A number of times a pull rod has cracked off at the clamp that is lifted by the cam follower. It takes only an hour or so to remove the valve and weld on a new length of rod.

In 1987, a nitrogen-to-vacuum leak developed in the pre-cooling heat exchanger. This annular heat exchanger is nested inside the top of the annular main exchanger. The pre-cooling exchanger surrounds the two-phase expander. All the heat exchangers would have to be disconnected and removed to gain access to the leak. To avoid this complex task, a new heat exchanger was constructed and mounted externally to the vacuum tank. The high-pressure helium going to the first expander is cooled in the external exchanger and then passes through the helium passage of the original exchanger and then to the expander. The nitrogen passage of the original exchanger was disconnected and plugged so that it is evacuated through the leak. The external exchanger was made over a weekend from two 5-foot lengths of 1.5-inch "Joy tube" arranged in parallel. The exchanger was housed in a plywood box and insulated with rock wool. This modification did not significantly degrade the capacity of the liquefier, but somewhat more liquid nitrogen is required.

In 1991, the ball bearings in the pillow blocks supporting the crankshaft were replaced. In 1992, the hydraulic pump that serves as the load for the expanders was replaced. In June 1999, the crankshaft was rebuilt. Very early in the life of the machine it was evident that the keys that restrained the eccentrics on the shaft were not tight so that the eccentrics rocked back and forth hammering the keys. For many years this problem was overcome by tightening the compression nut that clamped the stack of cams and eccentrics against a shoulder on the shaft. As a result of the fretting due to years of relative rotation, the eccentrics were very loose on the shaft and the key slots were badly deformed. For repair, the shaft was turned down true in the wear areas, the bore in the eccentric re-bored larger to a true diameter and the key slots reworked to larger true dimensions. With the aid of a series of clamps the eccentrics were pressed over thin shims with a gap for the key. A slightly tapered wedge was used to fill the oversized key slot in the eccentric and wedge the key against any rotational slack.

In June 1999, the computer monitoring and automatic shut-down system was changed to a Pentium computer running Labview software. This change was required because parts were no longer available for the XT computer.

In February 2000, the liquefier developed a helium-to-vacuum leak, which halted production. The liquefier was removed from the vacuum tank for the first time in 30 years.

The leak was located using the mass-spectrometer detector in about one day. The leak was in a weld where a tube was inserted through a hole in the wall and welded on the inside. This joint design has poor fatigue performance because of the stress concentration at the root of the weld. The leak was repaired by fillet welding the tube to the wall on the outside. Many of the lateral braces on the components had broken and a number of bolts had fallen out. A vapor pressure capillary tube had worn through from rubbing on one of the interconnecting tubes. Fortunately only a notch had worn in the tube. New multi layer insulation was applied and the machine was returned to the vacuum tank. The entire operation was completed in four days, which included a weekend.

In April 2001, two rotary screw compressors were added to the system so that the liquefier can be run with either the old or the new compressors. These compressors are part of the CTI model 2800 liquefier that provided liquid helium for the rotor of the MIT 10 MVA superconducting generator. When the generator project was terminated, the liquefier was integrated into the Laboratory helium facility. Even though the screw compressors consume over twice the power of the reciprocating compressors, the reduction of the helium loss from leakage gives the screw compressors a significant advantage. The computer automated shut down system was modified for the new compressors.

During 1998 and 1999, the CTI model 2800 liquefier from the superconducting generator project was moved to the Laboratory, MIT building 41. A new 480-volt power feeder was installed and an existing laboratory space was modified for high lift to service the liquefier. A new transfer system was constructed to meet the requirements to fill transport dewars rather than supply the superconducting generator on a continuous basis.

In the spring of 1999, the system was ready for trial runs, filling transport dewars for customers around MIT. The system experienced major problems with the turbo expanders. First the low-temperature turbine failed and wiped out the gas bearings. The spare turbine was installed and testing continued. In early June 1999, the high-temperature turbine failed and wiped out the bearings. No spare for the upper turbine was available, so testing could not continue. There was also a problem associated with financing the repair of the upper temperature turbine. There is considerable concern about the suitability of the expansion turbine system for the intermittent operation that is required of the MIT system.

REFERENCES

1. Collins, S. C., "Reversing Exchangers," in Chemical Engineering, **53**, 106 (1946).
2. McMahon, H. O. MIT PhD thesis, Chemistry, 1941.
3. Collins, S. C. and Cannada, R. L., *Expansion Machines for Low Temperature Processes,* Oxford University Press, London, 1958, p. 54.
4. Collins, S. C., "A Helium Cryostat," in *The Review of Scientific Instruments,* **18,** 157 (1947).
5. Collins, S. C., "Helium Refrigerator and Liquefier," in *Advances in Cryogenic Engineering*, **11**, edited by Timmerhaus, K. D., Plenum Press, New York, 1965, pp. 11-15.
6. Fleming, R. B. "Design and Test of a Novel Counter-Flow Heat Exchanger," MIT MS thesis, Mech. Eng., 1959.
7. Trumpler, P. R. and Dodge, B. F., "The Design of Ribbon-Packed Exchangers for Low Temperature Air Separation Plants," in Trans. Amer. Inst. Chemical Engineers, 43, 2 (1947).
8. Robinson, Jr., G. Y., and Hogan, W. H., in Cryogenic Engineering: Present Status and Future Development, Heywood Temple Industrial Publications, Ltd., London, 1968, p. 219.
9. 500 Incorporated, "Operator's Manual, Series 2000 Helium Liquefier," 500 Incorporated, 1969.
10. Johnson, R. W., Collins, S. C. and Smith, Jr., J. L., "Hydraulically Operated Two-Phase Helium Expansion Engine," in *Advances in Cryogenic Engineering*, **16**, edited by Timmerhaus, K. D., Plenum Press, New York, 1970, pp. 171-177.
11. Walker, J. H. "Design of a Helium Recovery and Repurification System," MIT MS thesis, Mech. Eng. 1983.