Malone Refrigeration

An Old Solution to a New Problem

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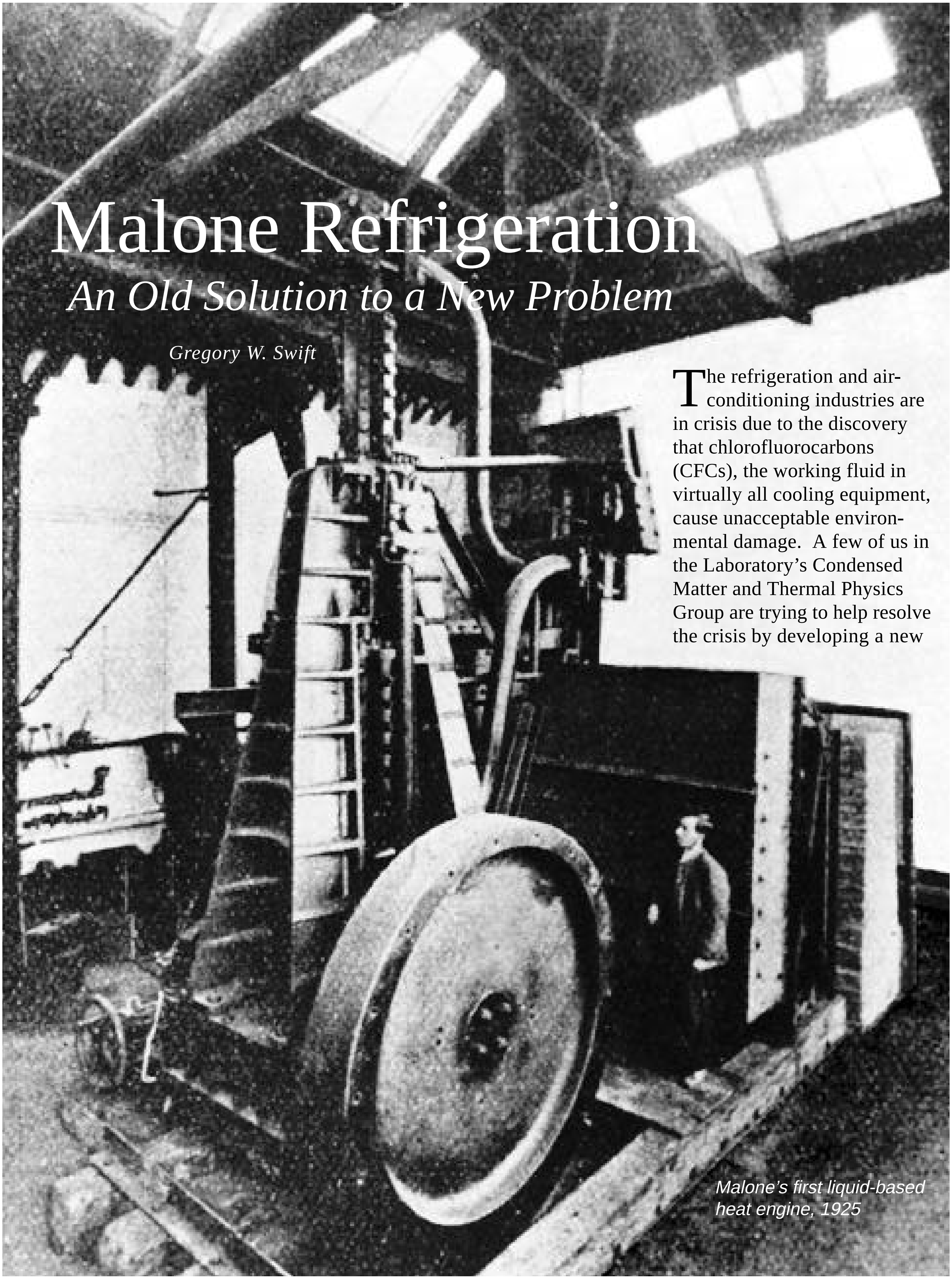


Malone's first liquid-based heat engine, 1925

The refrigeration and air-conditioning industries are in crisis due to the discovery that chlorofluorocarbons (CFCs), the working fluid in virtually all cooling equipment, cause unacceptable environmental damage. A few of us in the Laboratory's Condensed Matter and Thermal Physics Group are trying to help resolve the crisis by developing a new

CFCs and Cooling Equipment: The Size of the Problem

As recently as ten years ago, only a few experts appreciated the potentially disastrous consequences of releasing chlorofluorocarbons (CFCs) into the environment. Today it is generally believed that chlorine from CFCs is destroying stratospheric ozone, which shields the earth from the sun's ultraviolet radiation, and that the resulting increased ultraviolet radiation will soon lead to millions of fatal and nonfatal skin cancers and cataracts, to other threats to human health, and to severe damage to agriculture and ecosystems. To mitigate those effects, the United States and most other countries have committed themselves, through the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer and its later revisions, to rapid elimination of CFC production.

The rate of CFC production, though being reduced, is on the order of a million tons per year. CFCs are used extensively as working fluids in refrigerators and air conditioners, as cleaning solvents in electronics and sheet-metal fabrication, and as foaming agents in foam insulation and cushions. CFCs have the advantage for many purposes of being almost chemically inert (their behavior in the upper atmosphere is an exception); in particular they present no fire or poison danger. In addition their lack of interaction with the lubricants used in refrigerator compressors improves the efficiency and the lifetime of the refrigerator. Cooling-system efficiency has major economic and environmental impacts. Cooling consumes about 20 percent of the nation's electricity, at a cost of tens of billions of dollars per year. Kitchen refrigerators alone use 8 percent of the nation's electricity. Most of that electricity is produced by burning fossil fuels. Congress is accordingly requiring ever more efficient cooling equipment; for example, kitchen refrigerators built in 1993 must use 30 percent less electricity than those built in 1990. Clearly the elimination of CFCs should not involve making refrigerators that are much less efficient than present models. Therefore the use of CFCs in cooling is the most difficult of their common uses to eliminate.

The cooling industry is enormous. Cooling equipment worth $40 billion is sold in the United States each year, and, since it has a long useful lifetime, the total value of installed equipment is about $200 billion. Thus the appliance industry and other cooling-equipment manufacturers face a daunting challenge. The prospects of millions of fatal cancers, tens of millions of cataracts, and continued enormous energy consumption and attendant greenhouse-gas emissions have led to government regulations that are driving a $40-billion-per-year industry to an unprecedented crisis. The situation dwarfs the problems of the DOE's nuclear-weapons complex, a mere $12-billion-per-year industry responsible for less environmental and human-health damage.

Stopgap solutions to the CFC crisis are required immediately and are, in fact, in progress. Industry has begun extensive recycling of CFCs, especially in air-conditioner repair. Some new appliances will soon use hydrochlorofluorocarbons, which tend to break down and then rain out before carrying their chlorine to the stratosphere, and hydrofluorocarbons, which contain no chlorine at all. One German manufacturer is using ordinary hydrocarbons (a mixture of propane and butane) as working fluids, recognizing that their flammability poses negligible danger since only small quantities are used.

But these new chemicals have disadvantages. They are less compatible with lubricants than are CFCs, so they may cause present compressors to wear out more quickly. HCFCs and HFCs also significantly reduce the efficiency of cooling machinery. They are also greenhouse gases, with roughly 1000 times the global-warming potential of carbon dioxide per molecule, so their use will probably eventually be limited by international agreements. Finally, as they do not occur in nature, their release into the environment in million-ton quantities, like the release of CFCs, will be an experiment in atmospheric chemistry with unpredictable consequences.

Completely different cooling technologies that don't use any of these chemicals are still needed. Many are being developed, including Rankine cycles using CO_2, Stirling cycles using helium, and cooling by the Peltier (thermoelectric) effect. Almost by accident three new cooling technologies—thermoacoustic refrigeration, the related Sonic Sompressor, and Malone refrigeration—have been developed in part here at the Laboratory; each may become part of intermediate or long-term solutions to the CFC problem. They are described in the accompanying articles. ◻

type of cooling machinery. Its design takes advantage of modern fabrication techniques and environmentally benign materials but is inspired by a turn-of-the-century invention.

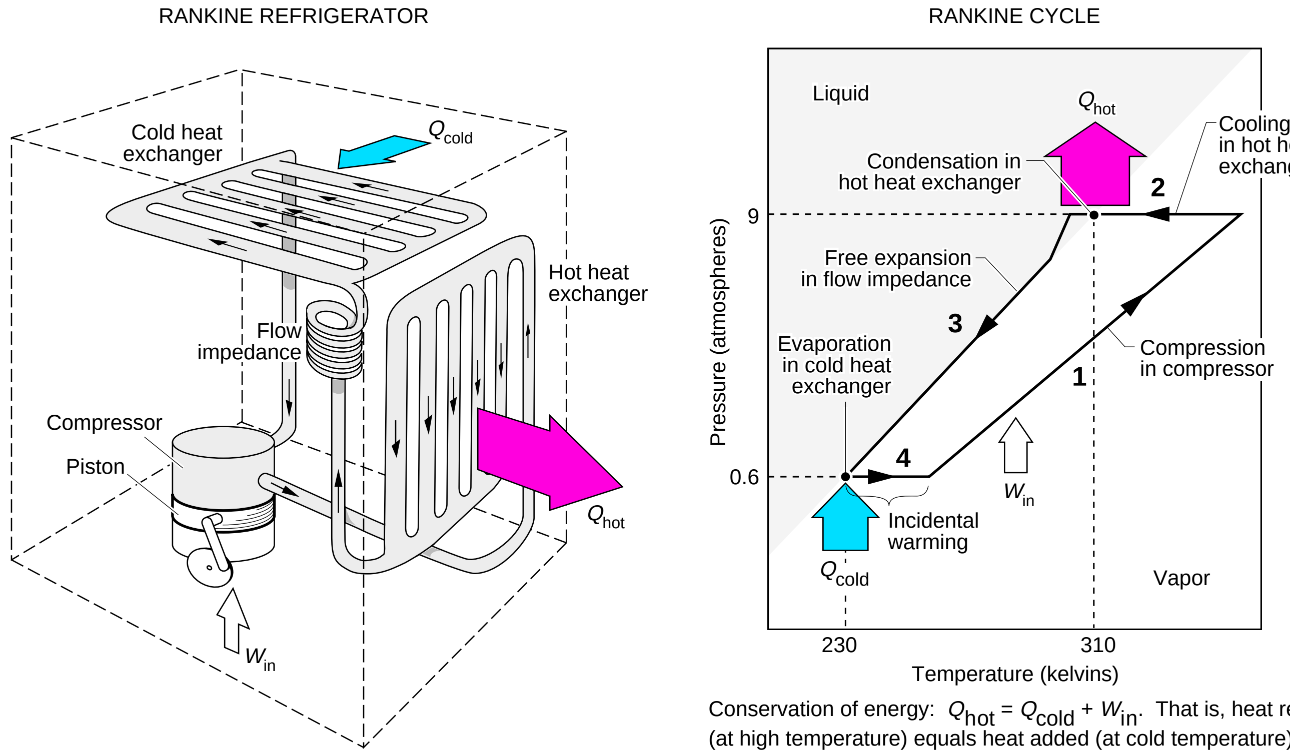
Refrigerators and air conditioners are based on heat pumps, machines that exploit mechanical power to pump heat from low temperature to high temperature. They operate by taking a working fluid through cycles of temperature and pressure changes in which the working fluid absorbs heat at low temperature (from the air inside the refrigerator, say) and loses ("rejects") heat at the higher temperature in the room. Figure 1 shows an example of such a thermodynamic cycle, the Rankine cycle used in all present household refrigerators, in which the cooling (absorption of heat at low temperature) is produced by the evaporation of the CFC working fluid. Reversing the cycle of a heat pump makes a heat engine, which converts heat to mechanical power as heat flows from high temperature to low. For example, the steam turbines that drive electric generators in large power plants use the reverse of the Rankine cycle shown in Figure 1. Water is the working fluid; its expansion on evaporation drives the turbines.

Heat pumps and engines are among the wonderful machines developed during the nineteenth century, when pistons, crankshafts, flywheels, and automatically timed valves began to replace the labor of horses, oxen, and people. Engines removed water from mines and later propelled ships and trains. Refrigerators preserved beef on the two-month voyage from Argentina or New Zealand to England. Today, the internal-combustion engines in cars and the heat pumps in refrigerators, the mature descendants of those nineteenth-century inventions, work unobtrusively and reliably—but not so well that further improvement is impossible.

In the 1970s, John Wheatley, then a physics professor at the University of California, San Diego, and at the height of a distinguished career of academic research into the properties of liquid helium, became interested in improving the efficiency of such ubiquitous heat-engine machinery. But there was trouble at UCSD. Some faculty thought that the work was "not really physics," and Wheatley shared their concern that heat-engine research would not prepare graduate students for a traditional career in academia. Furthermore, the research required more sophisticated fabrication techniques than were available at universities. So (with much encouragement from Jay Keyworth, then leader of the Laboratory's Physics Division) Wheatley moved to Los Alamos in early 1981 and assembled a team that included Al Migliori, Tom Hofler, Heikki Collan, and me, to begin fundamental investigations of old and new concepts in the fields of refrigeration and power generation. One of our research areas is described in "Thermoacoustic Engines and Refrigerators."

This article discusses another area of our investigations: refrigerators and heat engines that use liquids, without change of phase to gas, as the working fluid. We called such devices Malone refrigerators and engines after the first engineer to build such machines (see "John Malone and the Invention of Liquid-Based Engines"). Malone's ideas had been ignored for fifty years, in part because of a common misconception among scientists that liquids have small thermal-expansion coefficients (part of a larger misconception that liquids resemble idealized hydraulic fluid) and therefore do not couple heat to work well enough for use in engines and heat pumps. In heat pumps, working fluids must cool as the fluid is depressurized in order to absorb heat from the area to be cooled; in engines, working fluids must expand on heating in order to do work. The cooling on depressurization and thermal expansion of a material are both proportional to one thermodynamic property: its thermal-expansion coefficient. The thermal-expansion coefficients of gases are large, those of liquid-gas mixtures at the boiling point are essentially infinite (a fact that explains why evaporation and condensation are so useful in the Rankine cycle), but those of liquids are usually small. However, as Figure 2 illustrates, near their critical points liquids do have large thermal-expansion coefficients, larger in fact than that of an ideal gas. (The critical point is the temperature, T_{critical}, and pressure, P_{critical}, above which the liquid and gas phases of a substance are indistinguishable.) Hence liquids can indeed serve as working fluids in engines and refrigerators.

Liquids also have advantages over gases as working fluids. For instance, as shown in Figure 3, liquids are far less compressible than gases; that is, a given volume change causes a larger pressure change in a liquid than in a gas. Large pressure changes are desirable because the heat transferred in the heat exchangers is proportional to the pressure change in the previous step. Low compressibility allows fractional pressure changes to be made large with modest fractional



Conservation of energy: $Q_{hot} = Q_{cold} + W_{in}$. That is, heat rejected (at high temperature) equals heat added (at cold temperature) plus work done by the compressor.

Figure 1. The Rankine Cycle in a Household Refrigerator
The heat pumps in household refrigerators and nearly all other present cooling equipment use the Rankine cycle. This design has been by far the most popular for decades because it is simple and reliable: Many refrigerators run for thirty years with little or no maintenance, and the cost to buy and to run them is low. On the left is a sketch of the heat pump in a kitchen refrigerator. As the working fluid flows through the heat pump in a continuous loop, each element of the working fluid helps cool the refrigerator compartment by going through the thermodynamic cycle shown on the right, the Rankine cycle. The cycle requires work to be done on each fluid element by compressing it in order to raise its temperature above room temperature. The cycle has four steps: (1) The power piston in the compressor does work W_{in} on the element of working fluid, which is in vapor form, by greatly increasing its pressure. As the vapor is compressed, its temperature rises above room temperature. The high pressure is what drives the working fluid around the heat pump. (2) In the hot heat exchanger the hot vapor condenses as it rejects an amount of heat Q_{hot} to the air in the room. The pressure of the fluid remains constant. (3) The working fluid, initially all in liquid form, cools to below the temperature inside the refrigerator compartment by undergoing a free expansion in the flow impedance, a narrow tube that resists the flow of the working fluid so that it emerges at the pressure required for the next step. (4) In the cold heat exchanger the cold liquid absorbs heat from the refrigerator compartment by evaporating. The vapor absorbs a little additional heat on its way to the compressor; the total heat absorbed is Q_{cold}. The pressure of the fluid remains constant.

volume changes of the liquid. Therefore the volume change created by the power piston can be small compared to the volume available in the heat exchangers. Thus either the power piston and other mechanical components involved in volume changes can be smaller and simpler than in a gas engine, or the heat exchangers can be more capacious and consequently more efficient. The low compressibility of liquids also leads to low stored elastic energy per unit volume when they are pressurized, diminishing the hazard of explosions.

Another advantage of liquid working fluids is heat capacities per unit volume that are orders of magnitude larger than those of gases at the pressures typically reached in refrigerators and engines. Therefore when the working fluid is a liquid, the volume of working fluid that must flow through a heat exchanger is orders of magnitude less. As a result, far less mechanical power is required to pump a liquid through the heat exchanger, and heat exchangers for liquids can be far smaller. Because the heat exchanger can be particularly compact if it transfers heat to or from another liquid stream, particularly promising applications for Malone refrigerators and engines include those that both absorb heat from and reject heat to water. Among practical examples are water-cooled water chillers providing air conditioning for large buildings and perhaps ocean thermal energy conversion, in which the temperature difference between the surface and the depths of the ocean is used to produce mechanical power and ultimately electricity.

On the other hand, the high heat capacities of liquids also present a problem. Compressing or depressurizing a liquid without transferring heat changes its temperature relatively little, but refrigeration requires that the working fluid undergo relatively large temperature changes. In particular, as the working fluid flows from the hot heat exchanger to the cold heat exchanger, its temperature must decrease from room temperature to below the temperature inside the refrigerator. Cooling a liquid through such a wide temperature range must be accomplished by removing heat from the liquid in addition to depressurizing it. The most efficient way to remove the heat is to store it and use it later to warm the liquid flowing from the cold heat exchanger to the hot heat exchanger. This process is called regeneration.

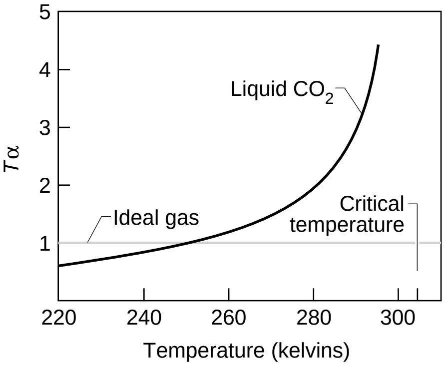


Figure 2. Thermal-Expansion Coefficient of CO_2 near $T_{critical}$
The thermal-expansion coefficient, denoted by Æ , is defined as $(@V=@T)_P=V$, where V is volume, T is temperature, and P is pressure. Here TÆ (the dimensionless thermal-expansion coefficient) of CO_2 is plotted as a function of temperature at the critical pressure of CO_2, 73 atmospheres. Like many thermodynamic derivatives, the thermal-expansion coefficient goes to infinity exactly at the critical point. Plotted in gray is TÆ for an ideal gas, which is unity at any temperature and pressure. Since the gases often used in heat engines and heat pumps are nearly ideal, the fact that TÆ of CO_2 near the critical point exceeds TÆ of an ideal gas implies

The first thermodynamic cycle to use regeneration was the Stirling cycle, invented for engines by the Reverend Robert Stirling in 1816. As shown in Figure 4, a Stirling heat pump or engine differs from a Rankine heat pump or engine in including a regenerator, which consists of walls that bound a number of narrow channels through which the working fluid flows from the hot heat exchanger to the cold heat exchanger and back. (A Stirling machine also differs from a Rankine machine in that the working fluid flows back and forth rather than around a continuous loop.) The temperature of the channel walls decreases steadily from the temperature of the hot heat exchanger at one end of the regenerator to that of the cold heat exchanger at the other end. The walls should have low heat conductance along the channels so that they do not conduct heat from the hot heat exchanger to the cold heat exchanger. The narrowness of the channels creates excellent thermal contact between the working fluid and the walls. Therefore the temperature of each small element of the working fluid is always nearly the same as that of the adjacent part of the channel walls. As the working fluid is displaced through the hot heat exchanger and the regenerator (step 4 in Figure 4), it gradually cools to the temperature of the cold heat exchanger by transferring heat to the channel walls, which store the heat. (The heat capacity of the walls should be sufficiently high that the stored heat does not change their temperature significantly.) The working fluid is then ready to be further cooled by decompression in step 1. When the cold working fluid flows back through the regenerator in step 2, it is warmed by the heat stored in the channel walls. Since the fluid is always at almost the same temperature as the nearby walls, heat transfers to and from the regenerator are nearly the reverses of each other. Therefore each part of the regenerator is restored to its original state at the end of each cycle.

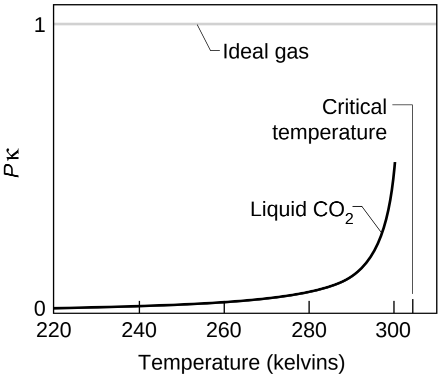


Figure 3. Compressibility of CO_2 near $T_{critical}$
The compressibility, denoted by ∑, is defined as $(@V=@P)_T=V$. Here, P∑ (the dimensionless compressibility) of CO_2 is plotted versus temperature at the critical pressure of CO_2, 73 atmospheres. Plotted in gray is P∑ for an ideal gas, which, like TÆ , is equal to unity at any temperature and pressure. Since P∑ is lower for liquid CO_2 than for an ideal gas except at temperatures closer to the critical point than are shown, liquid CO_2 has advantages as a working fluid over gases.

In 1981 we chose the Stirling cycle for our research on engines and heat pumps that used liquids as working fluids. As the working fluid in our first Stirling heat pump, we chose liquid propylene (C_3H_6) from more than a dozen hydrocarbon, CFC, and inorganic fluids with critical points just above room temperature. The machine we built,

John Malone and the Invention of Liquid-based Engines

It is hard to imagine using a liquid instead of a gas in a heat engine, but John Malone did—perhaps partly because he was not prejudiced by a proper scientific education. Malone was born in England in 1880. His formal education ended in his eighteenth year, when (probably in part to avoid some trouble with the police) he joined the merchant marine. He remained at sea for nearly all of the next fourteen years; during that time he was wounded seventeen times in Arab and Latin-American wars.

Leaving the merchant marine, Malone founded the Sentinel Instrument Company and, later, the Fox Instrument Company. He began experimenting with liquids as engine working fluids in the 1920s. As part of that project, he measured the compressibilities and thermal-expansion coefficients of many liquids, including hydrocarbons, mercury, carbon dioxide, and sulfur dioxide. In 1925 he completed his first liquid-based engine, shown on the title page of “Malone Refrigeration. It burned coal, used high-pressure liquid water as working medium, and produced 50 horsepower. Malone referred to that first engine as crude and cumbersome, but claimed that with perseverance it would have eventually produced 500 horsepower.

Instead, in 1927 Malone completed a much smaller and more versatile 50-horsepower water engine and began an extensive program of experimentation with it. Malone claimed that his second engine was very efficient. In 1931 he wrote, “Trials by three different independent engineers gave 27% indicated efficiency. Thus, after allowing for furnace and mechanical losses in a commercial engine, 20% overall efficiency between the heat in the coal and the shaft horsepower can be expected.” The efficiencies of the steam engines that powered ships at the time were between 9 and 12 percent and those of locomotives were between 5 and 7 percent, much lower than the efficiency of Malone’s engine.

Curiously, the “27% indicated efficiency” quoted above is the only quantitative experimental datum in any of Malone’s publications and patent disclosures. In a 1939 letter to Selwyn Anderson, Malone wrote about his measurements, “I refused to publish this information because it cost me a lot to learn it and I may yet obtain some reward if it is not known. Also because to my amazement I found my enemies were alleged centers of learning. Universities and the like.” Later in the same letter his bitterness is more evident: “A study of liquids as mediums in thermodynamics will teach an engineer more about the art of thermodynamics than all the universities on earth, or the memory men who infest them, and knowledge for knowledge’s sake is better than their parasitical life.” After Malone’s death in 1959, his son Ray wrote, “Now as patent rights have long expired I can see no advantage in publishing any of the information which he accumulated while developing his liquid engine.”

We can only guess why Malone’s promising work came to an end. The worldwide economic depression of the 1930s must have made venture capital scarce. Some may have dismissed the idea of liquid working fluids because it contradicted conventional wisdom. Large coal-fired steam turbines with 20 percent efficiency were in the ascendancy for applications above 10,000 horsepower. The internal-combustion engine (including what we know today as the diesel engine) was already more advanced than Malone’s engine, and its incomparable power-to-weight ratio made it seem the only practical choice for airplanes and automobiles. By the time the Great Depression and then World War II had ended, the steam engine was disappearing, internal-combustion engines and turbines were becoming ubiquitous, and Malone’s work had been forgotten. It took another independent thinker, the late John Wheatley, to see the promise in Malone’s work fifty years later and resume the study of liquid-based engines. □

Figure 4. A Malone Heat Pump Using the Stirling Cycle

Typically an electric motor (not shown) supplies the work required to compress the liquid working fluid by turning a crankshaft (also not shown) that operates the pistons. (Only the power piston does work; the displacer piston is operated by the same crankshaft for proper phasing.) The graph shows the thermodynamic cycle of pressure and temperature changes undergone by the working fluid; the object is the absorption of heat Q_{cold} at the cold heat exchanger in step 2. The graph of the Stirling cycle has been simplified by assuming that the four steps are separate from each other; that is, that each piston is stationary while the other one moves. In real machines the pistons oscillate sinusoidally in time. The simultaneous motion of the two pistons causes consecutive steps of the cycle to overlap; the overlaps would be reflected in a graph of the Stirling cycle by rounded corners. In addition, because the volume of working fluid displaced by the pistons is small compared to the volume in the heat exchangers and regenerator, different elements of the working fluid are carried through variations of the single thermodynamic cycle shown. Liquids are practical working fluids for the Stirling cycle and others because they possess certain thermodynamic properties. Specifically, their thermal-expansion coefficients (α) are large, their compressibilities (κ) are small, and their heat capacities per unit volume at constant pressure (C_P) are large. The heat Q_{cold} absorbed in step 2 is given by $(\partial Q/\partial P)_T \Delta P$, where ΔP is the pressure difference brought about in step 1. From a thermodynamic identity and the definition of α,

$$\left(\frac{\partial Q}{\partial P}\right)_T = T\left(\frac{\partial S}{\partial P}\right)_T = -T\left(\frac{\partial V}{\partial T}\right)_P = -T\alpha V;$$

where S is entropy. It follows that $Q_{cold} \approx -T_{cold}\alpha V\Delta P$, where T_{cold} is the temperature of the cold heat exchanger, and V is the volume of liquid displaced through the heat exchangers. Thus a large thermal-expansion coefficient leads to absorption of a large amount of heat. On the other hand, the energy wasted in heat absorption is proportional to the square of the temperature drop ΔT caused by the depressurization in step 1, which is given by $\Delta T = (T\alpha/C_P)\Delta P$. Therefore a working fluid with a small value of α/C_P is desirable. Fortunately, liquids near their critical points typically have thermal-expansion coefficients that are a little larger than that of an ideal gas and heat capacities per unit volume that are orders of magnitude larger than that of an ideal gas, so that the cooling can be both powerful and efficient. Finally, the low compressibilities of liquids are an advantage in steps 1 and 3, as can be seen from the relation $\Delta P = \Delta V/V\kappa$, which follows from the definition of κ. Thus large pressure changes ΔP can be achieved in the entire liquid volume V by power-piston strokes that displace small volumes ΔV.

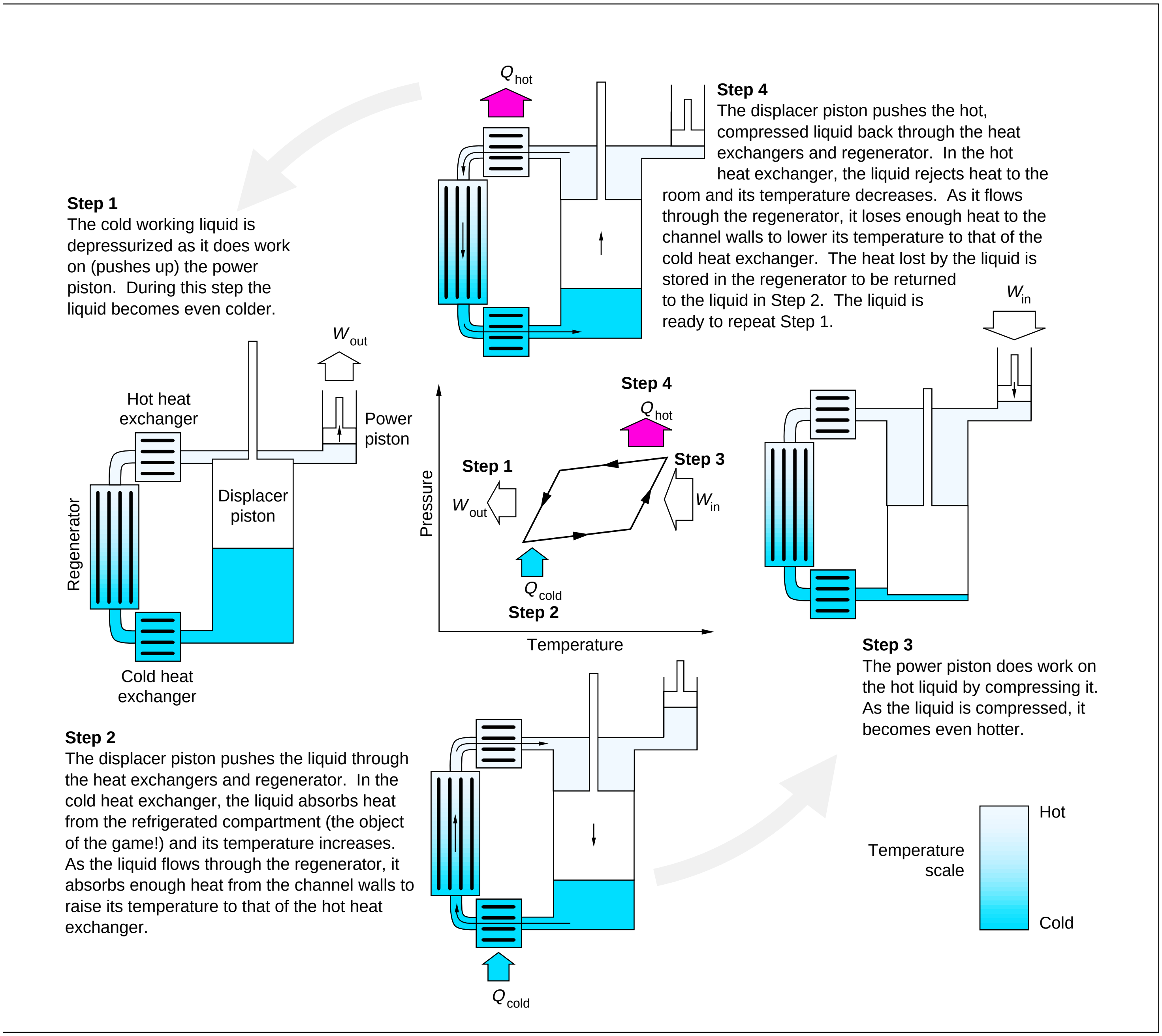
shown in Figure 5, could function as engine or heat pump, and was heavily instrumented to allow simultaneous measurement of mechanical power, heat flow, and temperatures and pressures throughout. Our extensive program of measurement on that machine, coupled with simple theoretical work, taught us how liquid properties, machine geometry, and cycle thermodynamics all work in concert to process each of the countless volume elements of the liquid through its own closed cycle. As a result, we believe we can now predict the power and efficiency of Malone machines with reasonable accuracy.

As this fundamental phase of the work drew to a close in the middle and late 1980s, our situation underwent a number of important changes. Recognition that CFCs cause unacceptable health hazards and environmental damage by destroying atmospheric ozone (see “CFCs and Cooling Equipment: The Size of the Problem”) gave new motivation to our development of cooling technologies based on other working fluids. But the pace of the research did not increase. Wheatley’s sudden death deprived us of our leader, our keenest intellect, and our most successful fundraiser.

Escalating costs of experimental work—especially of fabrication—slowed progress further. The next step in the development of a Malone refrigerator needed much more support than our earlier work, but support was hard to find: the DOE’s Office of Basic Energy Sciences was not interested in increasing our funding for this applied work, and the DOE offices that support conservation and renewable energy seemed interested in funding only those projects that promised to make an impact in the marketplace within two or three years. A prolonged, time-consuming attempt to get Navy support for our research ended with no Navy funds coming to Los Alamos, but with researchers at a Navy laboratory beginning their own development of Malone machines. Fortunately, during this difficult interim phase of basic technology development, the Laboratory’s own research funds have provided a partial bridge.

For our current Malone-refrigerator research, we picked the most environmentally acceptable of the liquids with critical points just above room temperature—carbon dioxide. Liquid carbon dioxide and dilute mixtures of methanol or ethanol in liquid carbon dioxide are efficient and safe working fluids for Malone refrigeration. The amount of carbon dioxide used has negligible environmental impact compared even with the effect of the pounds per capita per day we each exhale; the amount of alcohol also has negligible environmental impact.

Our first Malone machine, though designed for ease of measurement rather than for efficiency, was half as efficient as present-day CFC-based equipment. There is little



Step 1
The cold working liquid is depressurized as it does work on (pushes up) the power piston. During this step the liquid becomes even colder.

Step 2
The displacer piston pushes the liquid through the heat exchangers and regenerator. In the cold heat exchanger, the liquid absorbs heat from the refrigerated compartment (the object of the game!) and its temperature increases. As the liquid flows through the regenerator, it absorbs enough heat from the channel walls to raise its temperature to that of the hot heat exchanger.

Step 3
The power piston does work on the hot liquid by compressing it. As the liquid is compressed, it becomes even hotter.

Step 4
The displacer piston pushes the hot, compressed liquid back through the heat exchangers and regenerator. In the hot heat exchanger, the liquid rejects heat to the room and its temperature decreases. As it flows through the regenerator, it loses enough heat to the channel walls to lower its temperature to that of the cold heat exchanger. The heat lost by the liquid is stored in the regenerator to be returned to the liquid in Step 2. The liquid is ready to repeat Step 1.

doubt that a liquid-CO_2 Malone refrigerator can be built with an efficiency higher than that of existing CFC-based refrigerators. There are two important questions, which we are pursuing simultaneously. Can an efficient Malone refrigerator be built inexpensively enough to enjoy widespread manufacture? What are the environmental costs of the manufacturing process?

The CO_2 Malone refrigerator we are building now should provide partial answers to those questions. We are using modern fabrication techniques when necessary but are avoiding expensive (and sometimes environmentally questionable) "space-age" materials and techniques. For example, the heat-exchanger/regenerator assembly is a furnace-brazed stack of stainless steel sheets; slots in some of the sheets form fluid channels when the sheets are assembled. Although we now fabricate the sheets by photolithography and chemical milling for speed and flexibility, we know that they can ultimately be mass-produced very inexpensively and cleanly by punching. The brazing metal is pure copper, which is cheaper than the more commonly used silver alloys. The copper can be very thin and can be applied to the sheets by electroplating before punching or chemical milling, as another cost-saving measure. And we hope we can eventually save still more money by making some of the parts from ordinary carbon steel instead of stainless steel.

The configuration of the pistons and other moving parts is also influenced by the need to reduce costs. Our original Malone machine had too many high-precision and hence expensive moving parts, including a dozen roller bearings. The cost of the bearings alone was higher than the cost of the compressor in a con-

Thermoacoustic Engines and Refrigerators

Thermoacoustic effects, which convert heat energy to sound, have been known for over a hundred years. They have generally been considered mere curiosities, but in the early 1980s our engine-research group at Los Alamos, led by John Wheatley, began to consider thermoacoustic effects as a practical way to make efficient engines. One serious impediment to rapid progress on our experimental Malone engines was the large number of precision moving parts required. While looking for simpler engine designs, we came across the work of Peter Ceperley at George Mason University, who had realized that the timing between pressure changes and motion in Stirling engines and heat pumps is the same as in a traveling sound wave. Inspired by his work, we eventually invented thermoacoustic heat pumps (and new types of thermoacoustic engines) that had at most one moving part.

As Figure 1 shows, our thermoacoustic heat pumps use standing (rather than traveling) sound waves to take the working fluid (a gas) through a thermodynamic cycle. They rely on the heating and cooling that accompany the compression and expansion of a gas in a sound wave. Although ordinary, conversational-level sound produces only tiny heating and cooling effects, extremely loud sound waves produce heating and cooling effects large enough to be useful. Whereas typical heat pumps have crankshaft-coupled pistons or rotary compressors, thermoacoustic heat pumps have no moving parts or a single flexing moving part, such as a loudspeaker, and have no sliding seals. The lack of moving parts gives thermoacoustic refrigerators the advantages of simplicity, reliability, and low cost. Because the sound waves are confined in sealed cavities, the machines are fairly quiet.

For us thermoacoustic heat pumps had the additional advantages of conceptual elegance and easy, low-cost prototype development. We hoped that those features would lead to near-term successes (which would help keep our research well funded and lend credibility to our longer-term Malone program). The development of thermoacoustic refrigerators has indeed had successes, such as the 1992 flight in a space shuttle of a thermoacoustic refrigerator built at the Naval Postgraduate School and a 1993 test of a thermoacoustic sonar projector (an engine rather than a heat pump) by Bill Ward in the Laboratory's Advanced Engineering Technology Group.

After Tim Lucas, an inventor, noticed an article about our thermoacoustic work in a popular science and technology magazine, he added yet another chapter to the story of novel refrigeration at the Laboratory. Lucas had invented the Sonic Compressor (Figure 2), a device for compressing conventional refrigerant vapors that contains no sliding parts. Instead a resonant sound wave in a cavity compresses the vapor and two one-way valves ensure that only low-pressure vapor enters and only high-pressure vapor leaves the compressor. Since the Sonic Compressor needs no lubricating oil, it is attractive for compressing HFC refrigerants, which do not destroy the ozone layer but have the drawback of being less compatible with lubricants than CFCs are (see "CFCs and Cooling Equipment: The Size of the Problem"). The lack of sliding parts should also lead to higher efficiency in small systems. Furthermore, the Sonic Compressor can replace the piston-driven compressor in present refrigerators without requiring any changes in other parts.

Lucas needed to suppress the production of shock waves in his compressor by the high-amplitude sound because the shock waves wasted energy by turning it into heat. He sought help from us because of our experience with high-amplitude sound in thermoacoustics. Working together we found that the shock waves resulted from nonlinear self-interactions in the desired fundamental resonance in the cavity and from unwanted resonances at frequencies that were exact integral multiples of the fundamental frequency. When we changed the shape of the cavity to that shown in Figure 2, the frequencies of the extra resonances changed so that they were no longer significantly excited by nonlinear self-interaction in the fundamental.

Lucas's collaboration with us was an example of totally successful "tech transfer." During

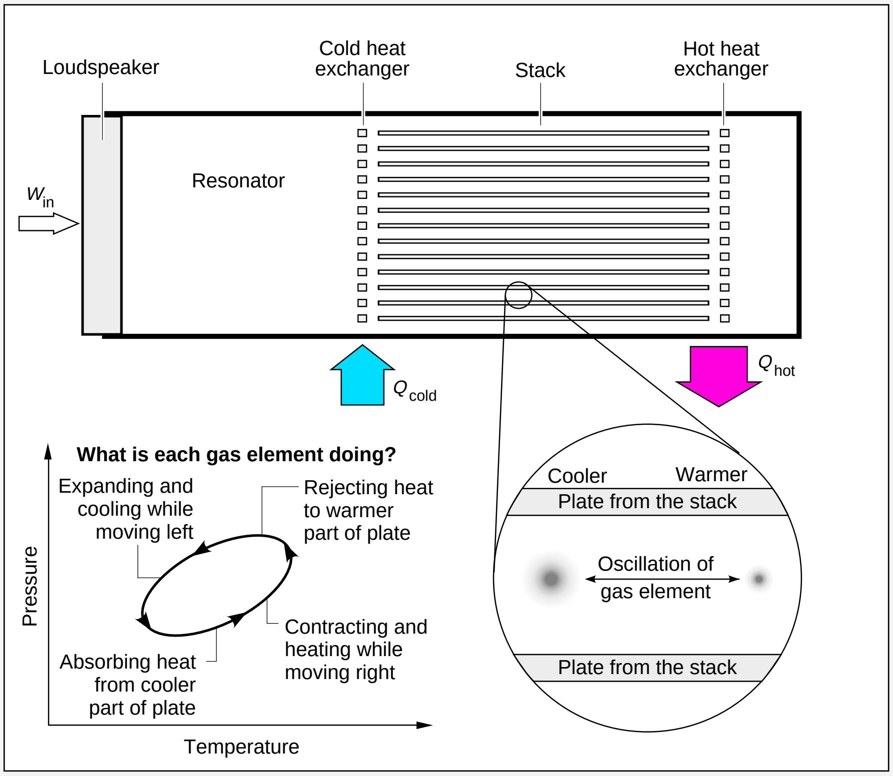


Figure 1. The Thermoacoustic Refrigerator

An electrically driven, radically modified loudspeaker maintains a standing sound wave in an inert gas in a resonator. The sound wave interacts with an array of parallel solid plates called the stack. The resulting refrigeration can be understood by examining a typical small element of gas between the plates of the stack. As the gas oscillates back and forth because of the standing sound wave, it changes in temperature. Much of the temperature change comes from compression and expansion of the gas by the sound pressure (as always in a sound wave), and the rest is a consequence of heat transfer between the gas and the stack. In the example shown the length of the resonator is one-fourth the wavelength of the sound produced by the speaker, so all the elements of gas are compressed and heated as they move to the right and expanded and cooled as they move to the left. Thus each element of gas goes through a thermodynamic cycle in which the element is compressed and heated, rejects heat at the right end of its range of oscillation, is depressurized and cooled, and absorbs heat at the left end. Consequently each element of gas moves a little heat from left to right, from cold to hot, during each cycle of the sound wave. The combination of the cycles of all the elements of gas transports heat from the cold heat exchanger to the hot heat exchanger much as a bucket brigade transports water. The spacing between the plates in the stack is crucial to proper function: If the spacing is too narrow, the good thermal contact between the gas and the stack keeps the gas at nearly the same temperature as the stack, whereas if the spacing is too wide, much of the gas is in poor thermal contact with the stack and does not transfer heat effectively to and from it.

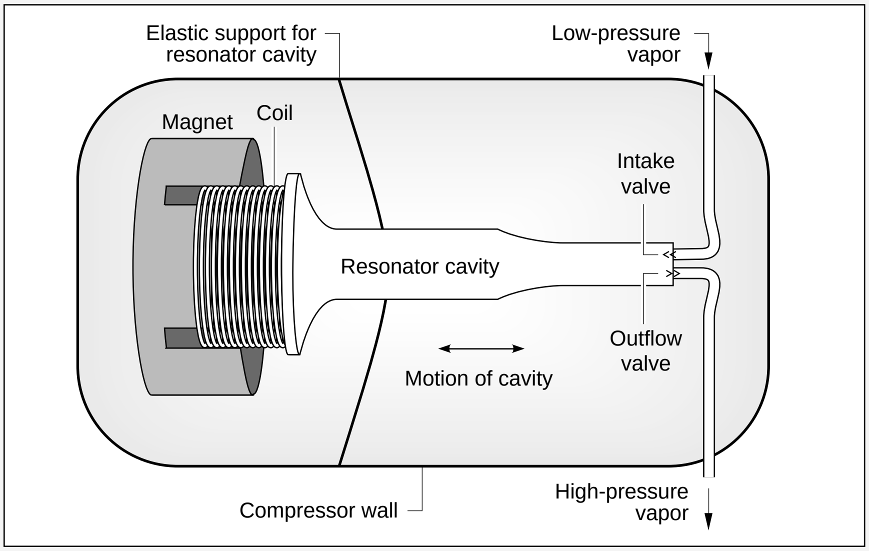


Figure 2. The Sonic Compressor
The Sonic Compressor uses electric power to compress a conventional refrigerant vapor by means of a high-amplitude sound wave; the model depicted can replace the piston compressor in a conventional cooling system such as the household refrigerator shown in Figure 1 of "Malone Refrigeration." The electricity drives a radically modified loudspeaker that shakes a cavity back and forth at a resonance frequency of the working-fluid vapor inside (300 hertz). In the figure the cavity is shown at the rightmost point of the vibration. The motion of the cavity causes the vapor to slosh back and forth—in other words, the motion generates a standing sound wave. The shape of the cavity is designed to prevent the formation of shock waves. The standing sound wave compresses and expands the gas; at the end of the tube farther from the loudspeaker, the range of pressure is 8 atmospheres. A pair of one-way valves at that end, which are opened and closed at the operating frequency by the pressure itself, admits low-pressure vapor from the intake pipe and ejects high-pressure vapor into the outflow pipe.

the year he spent here, we solved his shock problem. Of equal importance to him, we did not jointly invent anything patentable, so the business aspects of his project were not complicated by the involvement of intellectual-property rights belonging to the Laboratory. As Lucas's visit was successful, the Sonic Compressor could come into production in a few years. Thermoacoustic refrigeration will not be ready for the market until a few years later. Malone refrigeration will take still more time to develop but appears to be the most efficient option of the three to which we at Los Alamos are contributing. □

ventional CFC refrigerator! A totally different design was clearly required if Malone technology was ever to enjoy widespread use. So in our present CO_2 machine we are using a linear free-piston configuration, which was invented only recently and is being employed in gas-based Stirling engines intended for solar power or for use in space. The pistons in a linear free-piston machine are driven, not by a rotating motor connected to a crankshaft, but by a "linear" electric motor that provides reciprocating force and motion directly in the same way as a loudspeaker. This configuration minimizes the number of moving parts and eliminates the need for high-force bearing surfaces. Careful design can even eliminate the need for any mechanical connection to the displacer piston—the piston moves with the correct amplitude and phase simply in response to the fluid pressures acting on it.

The present crisis in the cooling industry is a unique opportunity for a new, potentially more efficient technology to break the monopoly of a technology that has enjoyed decades of incremental improvement. The primary challenge of the next year or two is to keep this difficult experimental project moving ahead, though the funding only pays for a third of the time of one researcher, while trying to attract the interest of an industrial collaborator. At best, years of further work costing millions of dollars will be required to bring Malone refrigeration to the threshold of possible widespread application. Meanwhile, as described in "CFCs and Cooling Equipment: The Size of the Problem," industry is proceeding promptly with more straightforward interim measures. In the intermediate time scale, mature new technologies such as the Sonic Compressor and perhaps thermoacoustic re-

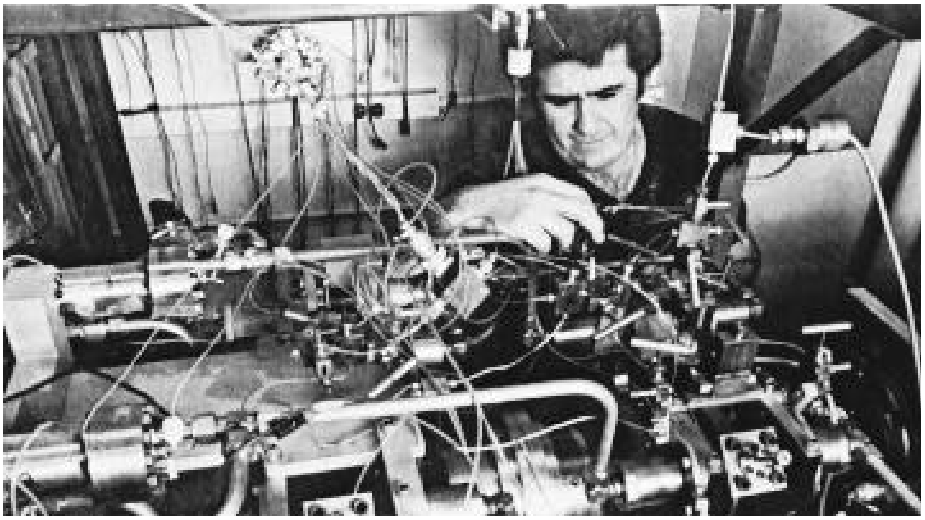


Figure 5. Chris Espinoza Adjusts Our First Malone Refrigerator (1989)

frigeration may come into use.

If we succeed in developing a widely used refrigerator, it would be the first Laboratory product since the implementation of the Atmospheric Test Ban Treaty to find its way into homes and businesses throughout the world. If we fail for unforeseen technical reasons, we will not regret having tried. But if we fail because of inadequate support, an opportunity to improve the world environment and reduce its energy consumption will have been lost.

It is a pleasure to acknowledge the contributions of Al Migliori, Sonia Balcer, Chris Espinoza, Frank Murray, and Alex Brown to the development of Malone refrigeration at the Laboratory and to thank the Department of Energy's Office of Basic Energy Sciences for steady support of fundamental engine and refrigerator research at Los Alamos National Laboratory.

Further Reading

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Information about the Sonic Compressor can be obtained by calling Timothy S. Lucas (president of Sonic Compressor Systems in Glen Allen, Virginia) at (804) 262-3700.

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