Magnetic Refrigeration

Magnetic refrigeration is a method of refrigeration based on the magnetocaloric effect. This effect, discovered in 1881, is defined as the response of a solid to an applied magnetic field which is apparent as a change in its temperature.[1] This effect is obeyed by all transition metals and lanthanide-series elements. When a magnetic field is applied, these metals, known as ferromagnets, tend to heat up. As heat is applied, the magnetic moments align. When the field is removed, the ferromagnet cools down as the magnetic moments become randomly oriented. Gadolinium, a rare-earth metal, exhibits one of the largest known magnetocaloric effects. It was used as the refrigerant for many of the early magnetic refrigeration designs. The problem with using pure gadolinium as the refrigerant material is that it does not exhibit a strong magnetocaloric effect at room temperature. More recently, however, it has been discovered that arc-melted alloys of gadolinium, silicon, and germanium are more efficient at room temperature.[2]

Using the magnetocaloric effect for refrigeration purposes was first investigated in the mid-1920's but is just now nearing a point where it could be useful on a commercial scale.[1] The main difference associated with this process is that it is void of a compressor. The compressor is the most inefficient and expensive part of the conventional gas compression system. In place of the compressor are small beds containing the magnetocaloric material, a small pump to circulate the heat transfer fluid, and a drive shaft to move the beds in and out of the magnetic field. The heat transfer fluid used in this process is water mixed with ethanol instead of the traditional refrigerants that pose threats to the environment.

A majority of the successful magnetic refrigeration research done to this point was completed by the Ames Laboratory at the University of Iowa and by the Astronautics

Corporation of America in Madison, Wisconsin. Karl Gschneidner and Vitalij Pecharsky of the Ames Laboratory and Carl Zimm of the Astronautics Corporation have led this research. The team has developed a working system that uses two beds containing spherical powder of Gadolinium with water being used as the heat transfer fluid. The magnetic field for this system is 5 Tesla, providing a temperature span of 38 K. The maximum values obtained from this unit include a cooling power of 600 Watts, Coefficients of Performance near 15, and efficiency of approximately 60% of Carnot efficiency.[3] Due to the high magnetic field, however, this system is not applicable for use at home.

The ultimate goal of this technology would be to develop a standard refrigerator for home use. The use of magnetic refrigeration has the potential to reduce operating cost and maintenance cost when compared to the conventional method of compressor-based refrigeration. By eliminating the high capital cost of the compressor and the high cost of electricity to operate the compressor, magnetic refrigeration can efficiently and economically replace compressor-based refrigeration. The major advantages to the magnetic refrigeration technology over compressor-based refrigeration are the design technology, environmental impact, and operating cost savings.

The process flow diagram for the magnetic refrigeration system is shown in Figure 1. A mixture of water and ethanol serves as the heat transfer fluid for the system. The fluid first passes through the hot heat exchanger, which uses air to transfer heat to the atmosphere. The fluid then passes through the copper plates attached to the non-magnetized cooler magnetocaloric beds and loses heat. A fan blows air past this cold fluid into the freezer to keep the freezer temperature at approximately 0°F. The heat transfer fluid then gets heated up to 80°F as it passes through the copper plates adjoined by the magnetized warmer magnetocaloric beds, where

E-101	E-102	P-101	D-101	M-101	V-101	B-101	B-102
Hot Heat Exchanger	Cold Heat Exchanger	Fluid Pump	Drive Shaft	Electro Magnet	Vessel	Hot Magnetocaloric Beds	Cold Magnetocaloric Beds

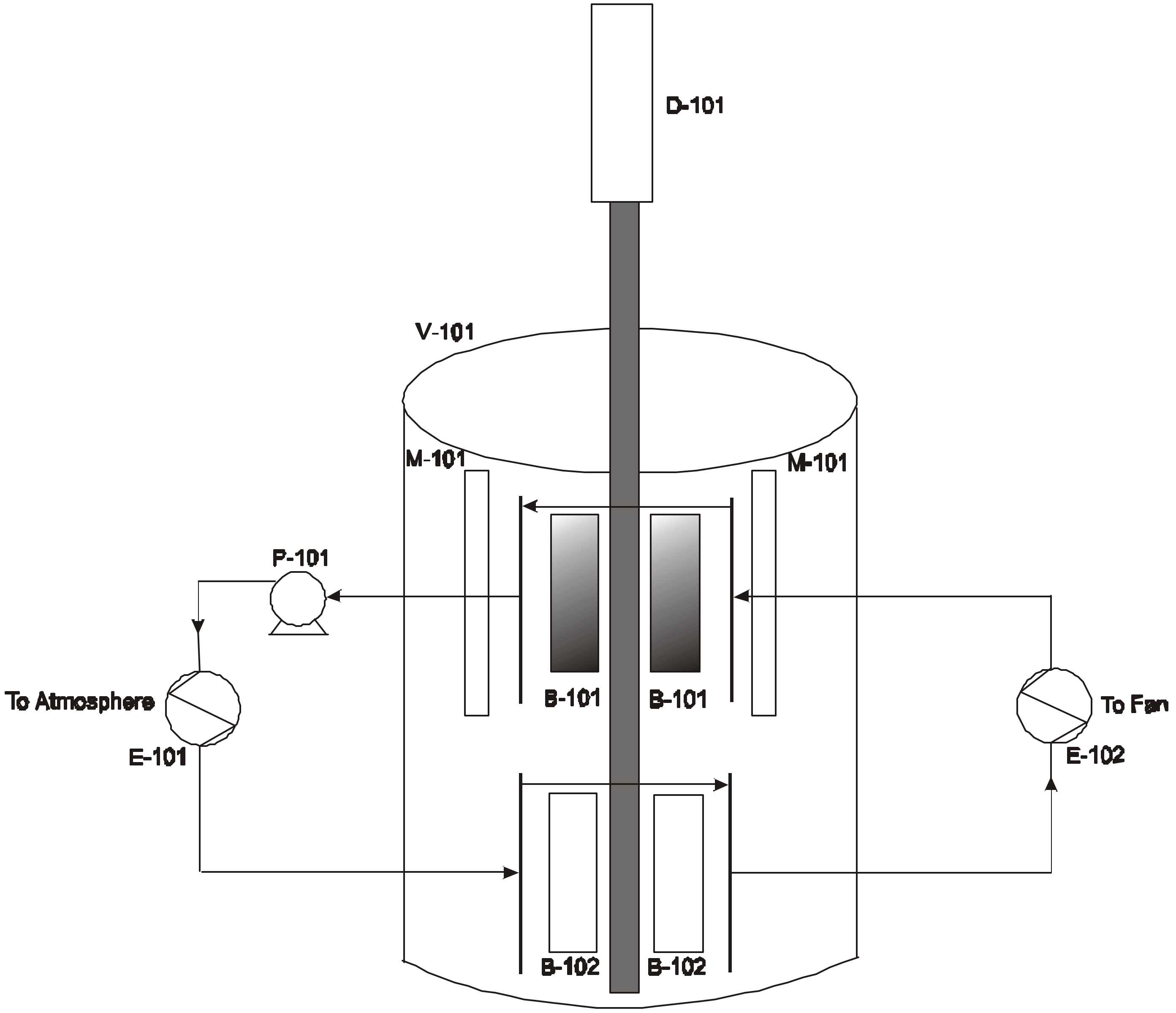

Figure 1: Cycle For Magnetic Refrigeration Position 1

it continues to cycle around the loop. However, the magnetocaloric beds simultaneously move up and down, into and out of the magnetic field. The second position of the beds is shown in Figure 2. Figure 3 shows how the cold air from the freezer is blown into the refrigerator by the freezer fan, F-102. The temperature of the refrigerator section is kept around 39°F.

The cost for mass production can be estimated using a learning curve.[4] The equation used is shown as Equation 1.

$$Y(N) = AN^{n} \tag{1}$$

Where: $Y(N)$ = Amount for Nth unit of production

A = Amount for 1st unit of production

B = Exponent of improvement

Following the assumption that serving one-half of the refrigerator market would result in the production of 7 million refrigerators per year, and assuming a prototype cost of $1000, it was found that the cost per unit would be approximately $500. This relationship is presented in Figure 4.

E-101	Hot Heat Exchanger
E-102	Cold Heat Exchanger
P-101	Fluid Pump
D-101	Drive Shaft
M-101	Electro Magnet
V-101	Vessel
B-101	Cold Magnetocaloric Beds
B-102	Hot Magnetocaloric Beds

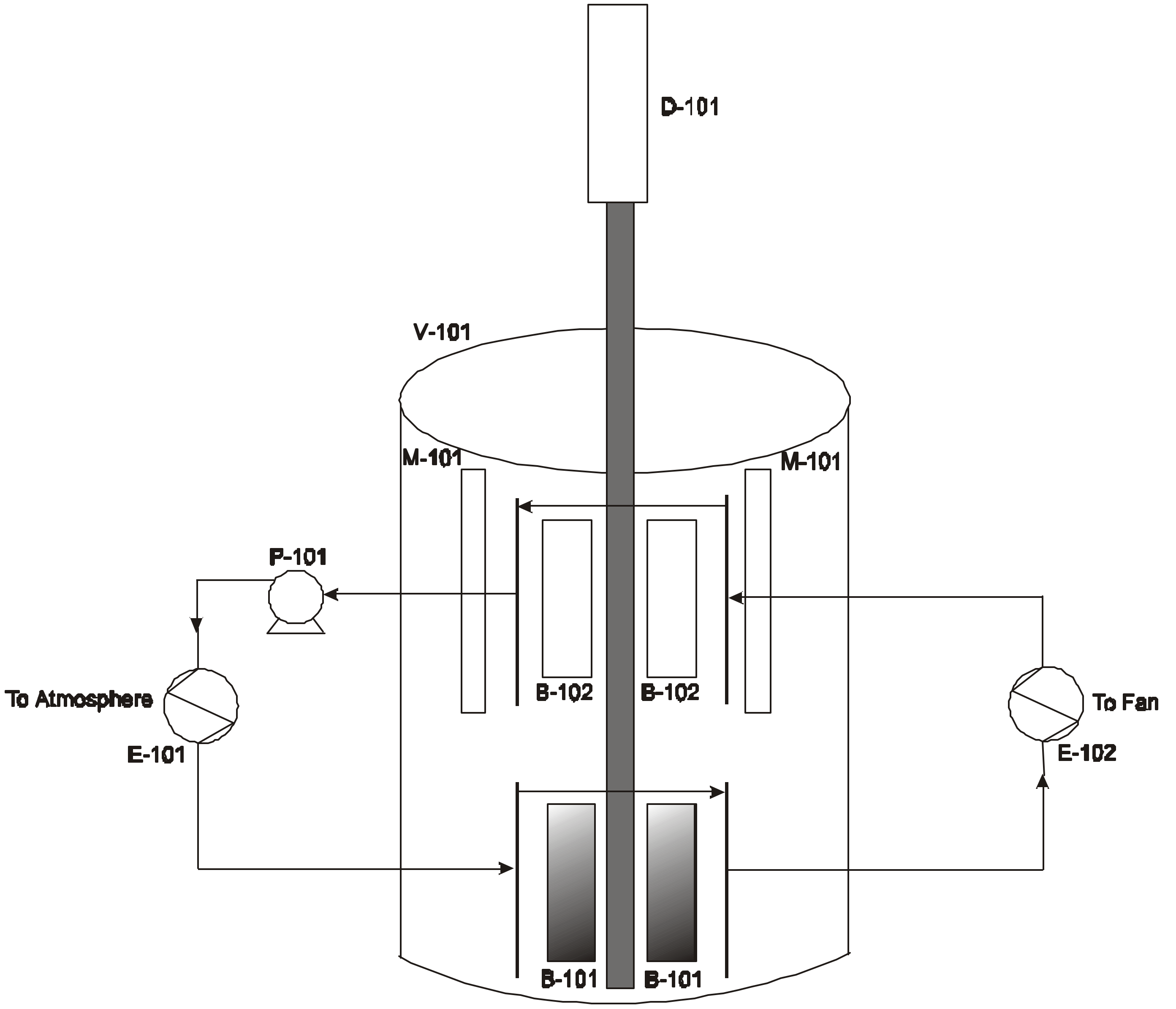

Figure 2: Cycle For Magnetic Refrigeration Position 2

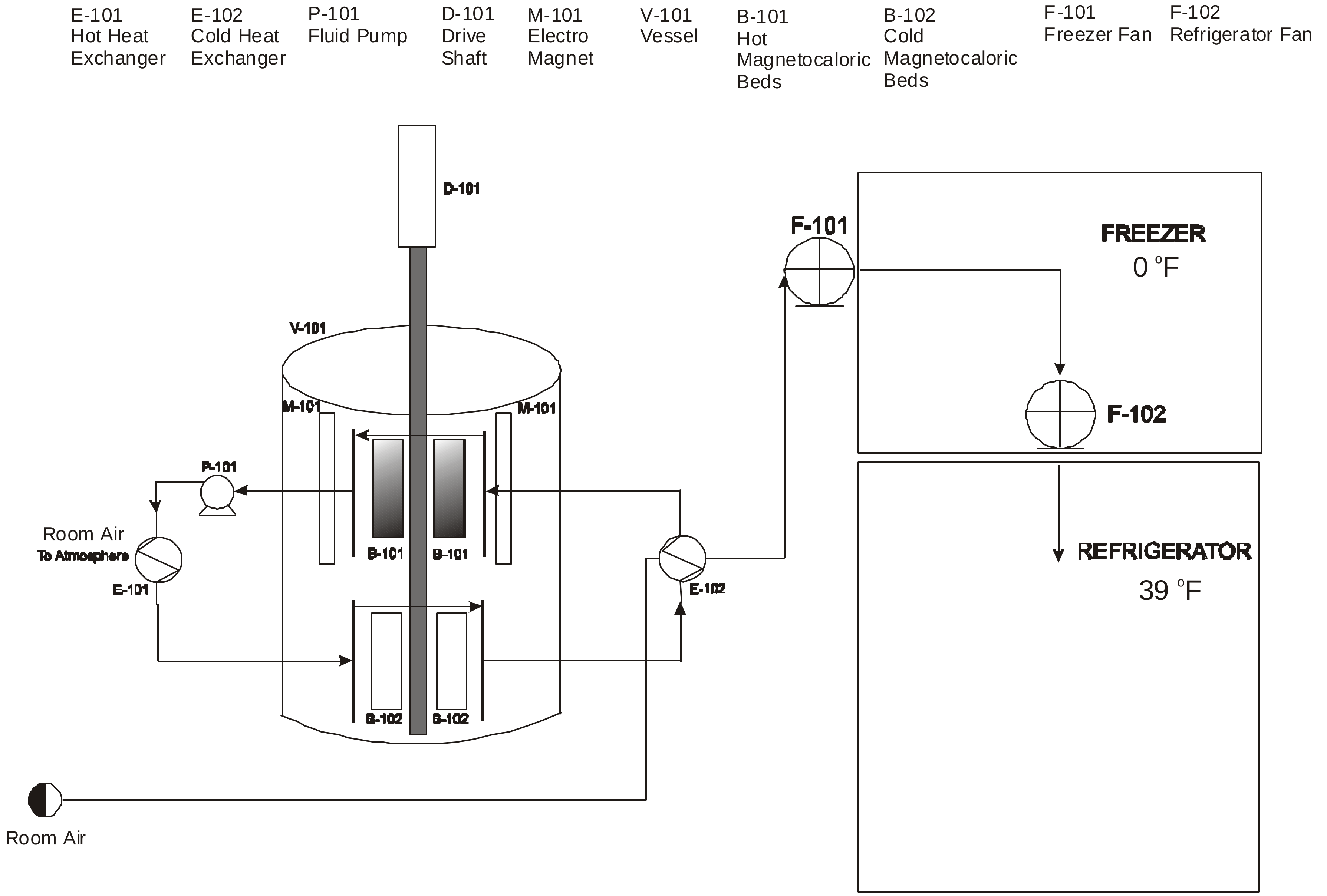

Figure 3: Refrigerator Configuration For Magnetic Refrigeration

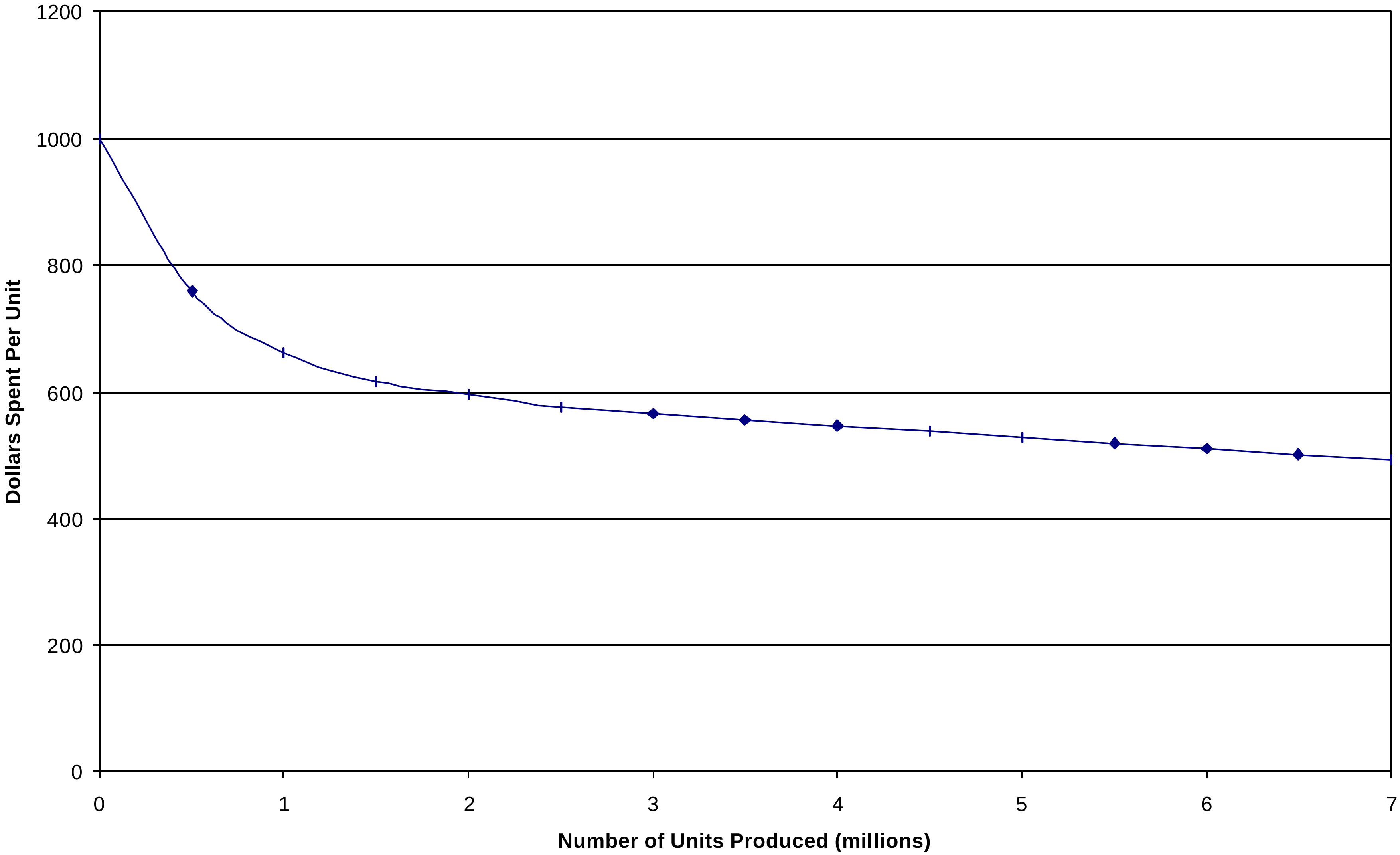

Figure 4: Spending Changes Due To Mass Production

Magnetic refrigeration utilizes the magnetocaloric effect. This effect causes a temperature change when a certain metal is exposed to a magnetic field. All transition metals and lanthanide series elements obey this effect. These metals, known as ferromagnets, tend to heat up as a magnetic field is applied. As the magnetic field is applied, the magnetic moments of the atom align. When the field is removed, the ferromagnets cool down as the magnetic moments become randomly oriented. Soft ferromagnets are the most efficient and have very low heat loss due to heating and cooling processes. Gadolinium, a rare-earth metal, exhibits one of the largest known magnetocaloric effects. Most modern magnetic refrigeration designs employ arc-melted alloys of gadolinium, silicon, and germanium, which provide greater temperature ranges at room temperatures. The presented design utilizes such an alloy with the formula $Gd_5(Si_{0.455}Ge_{0.545})_4$. This alloy has a temperature range of –12°F to 80°F.[5]

The typical household refrigerator has an internal volume of 21 ft^3, where the freezer represents approximately 30% of this volume. Freezers are designed to maintain a temperature of 0°F. Refrigerators maintain a temperature of 39°F. The refrigerator will be insulated with polyurethane foam, one of the most common forms of insulation available. The refrigerator is kept cool by forcing cold air from the freezer into the refrigerator by using a small fan. The control system for maintaining the desired internal temperatures consists of two thermostats with on/off switches. The freezer thermostat regulates the temperature by turning the compressor off when the temperature gets below 0°F. A second thermostat regulates the fan that cools the refrigerator to 39°F.

To maintain a frost-free environment in the freezer, a defrost timer will send power to a defrost heater on the coils for a fifteen minute time period every eight hours. In the first six minutes, the walls of the freezer will be defrosted. The water will then drain into a pan at the base of the refrigerator. The next nine minutes involve the safety factor of not reaching a temperature in the freezer that is too high. Also, a safety thermostat keeps the liquid water from freezing as it drains.

The heat transfer fluid for the magnetic refrigeration system is a liquid alcohol-water mixture. The mixture used in the design consists of 60 % ethanol and 40 % water. This mixture has a freezing point of –40°F[6], assuring that the mixture does not freeze at the set operating temperatures. This heat transfer fluid is cheaper than traditional refrigerants and also eliminates the environmental damage produced from these refrigerants.

The temperature of the fluid throughout the cycle ranges from –12°F to 80°F. The heat transfer fluid at approximately 70°F gets cooled to –12°F by the non-magnetized cold set of beds. This cooled fluid is then sent to the cold heat exchanger, E-102, where it absorbs the excess heat from the freezer. This fluid leaves the freezer at 0°F. The warm fluid then flows through the opposite magnetized set of beds, where it is heated up to 80°F. This hot stream is now cooled by room temperature air in the hot heat exchanger, E-101, to 70°F. The cycle then repeats itself every three seconds after the beds have switched positions. Copper tubing is used throughout the loop and in the two heat exchangers.

The two sets of beds, B-101 and B-102, contain the small spheres of magnetocaloric material. The size of the beds resembles that of half of a soda can.[7] The beds are alternated in and out of the magnetic field using a chain and sprocket drive shaft. The drive shaft rotates the beds back and forth while still keeping them in contact with the heat transfer plates.

References

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