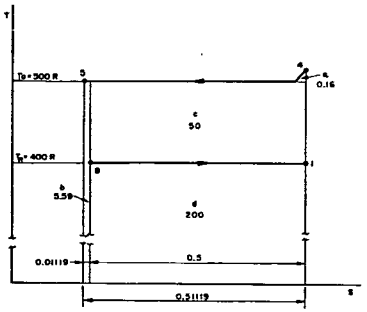

Fig. 15 .... Temperature-Entropy Diagram for Dual-Compression, Dual-Expansion Cycle of *Example 9*

fruits and vegetables) than Evaporator I (5 F, for frozen fish or poultry). Each evaporator could also carry a different load. Moving valve A to location B would improve the performance of the system, while the elimination of Compressor II and the installation of line C with back-pressure valve D would decrease the complexity, but would also decrease the coefficient of performance.

The possible practical combinations of refrigeration equipment are numerous, and the reader may consult References 16 to 23 for detailed information on complex cycles.

In the next example, a Second-Law analysis shows how the introduction of a flash chamber and the duplexity of other equipment will improve the thermodynamic performance.

Example 9: In this more complex cycle, the data are those of *Example 8*. The equipment diagram is presented in Fig. 14, which shows compound compression in a low-stage compressor (I) and a high-stage compressor (II), a flash intercooler, and two expansion valves. All processes of the refrigerant are reversible, except those in the flash intercooler and expansion valves.

When compared with the ideal basic vapor cycle of *Example 6*, the cycle in this example reduces the irreversibilities caused by the refrigerant, decreases the available portion of the heat rejected to the atmosphere, and effects a reduction in the net work input to the cycle.

The T-S diagram is given in Fig. 15. Inasmuch as the flow of refrigerant through each compressor is different, the liquid and vapor saturation lines are omitted.

State-Point Properties

State	P psia	t F	x	h Btu/lb	s Btu/lb°R
1	5.4090	−59.69	1.0	70.727	0.17708
2	16.0	2.46		78.178	0.17708
3	16.0	−17.99	1.0	75.329	0.17078
4	51.940	56.23		83.977	0.17078
5	51.940	40.31	0	17.342	0.03759
6	16.0	−17.99		17.342	0.03950
7	16.0	−17.99	0	4.664	0.01080
8	5.4090	−59.69		4.664	0.01192

M_I = 200/(70.727 − 4.664) = 3.0274 lb
M_{II} = $M_I(h_5 - h_7)/(h_3 - h_8)$
= 3.0274 (78.178 − 4.664)/(75.329 − 17.342)
= 3.8380 lb

Q_c = 3.8380 (83.977 − 17.342) = 255.75 Btu
W = 255.75 − 200 = 55.75 Btu
(CP) = 200/55.75 = 3.5875
ΔW = 55.75 − 50 = 5.75 Btu
ΔS_B = − 200/400 = − 0.5 Btu/R deg
ΔS_c = 255.75/500 = 0.51150 Btu/R deg
ΔS_{univ} = 0.51150 − 0.5 = 0.01150 Btu/R deg
$T_A\Delta S_{univ}$ = 500 × 0.01150 = 5.75 Btu
$(E_Q)_e$ = 500 × 3.8380 (0.17078 − 0.03759) = 255.59 Btu
$(E_A)_e$ = 255.75 − 255.59 = 0.16 Btu
$(E_{AA})_r$ = 500 × 0.01119 = 5.59 Btu
ΣE_{AA} = 5.59 + 0.16 = 5.75 Btu

Energy	Btu	Area
Q_i	200	d
Q_c	255.75	(a → d)
W	55.75	a + b + c
$(E_A)_i$	−50	− c
$(E_Q)_i$	250	c + d
$(E_A)_e$	0.16	a
$(E_Q)_e$	255.59	b + c + d
$(E_{AA})_r$	5.59	b

A summary of the important results of the Second-Law analyses presented in *Examples 1* to *9* is given in Table 1.

Second-Law analysis is an effective method for: (1) the establishment of the ideal refrigeration cycle and the work input therein, and (2) determination of the thermodynamic penalties which result from departures from the ideal cycle.

PART III: ABSORPTION REFRIGERATION CYCLES

Absorption refrigeration cycles are two-pressure, heat-operated cycles that make use of a vaporizable liquid as the refrigerant and a second liquid as the absorbent. The cycle can most easily be understood by comparing it to a conventional compression refrigeration cycle, Fig. 16, consisting of three basic components: compressor, condenser, and evaporator. In the compression cycle, a single fluid is used as the refrigerant; the liquid vaporizes in the evaporator, takes in heat at low temperature, and is compressed, by applying work through a mechanical device, to a pressure such that it condenses at a higher temperature in the condenser. The compression cycle is a two-pressure cycle, the condenser operating at a higher pressure than the evaporator, and the two pressure domains are separated by the compressor and a refrigerant flow control (expansion valve).

The absorption cycle, Fig. 17, consists of four basic components: absorber, generator, condenser, and evaporator (note that the condenser-evaporator portions of Figs. 16 and 17 are identical). The liquid refrigerant vaporizes in the evaporator, taking in heat at low temperature, and is *compressed by a heat-operated device* to a pressure such that it condenses at a higher temperature in the condenser. The absorption cycle is also a two-pressure cycle, and the two pressure domains are separated by the absorber-generator compression device and by a refrigerant flow control (expansion valve).

Thus, the only fundamental difference between the absorption cycle and the compression cycle is the substitution of the *absorber-generator compressor* operated by heat energy for the mechanical compressor operated by work energy.

BASIC ABSORPTION REFRIGERATION CYCLE

A more complete understanding of the basic absorption refrigeration cycle, and, in particular, an understanding of the function of the absorber-generator system, can be attained by discussing the steps in the cycle as depicted in Fig. 17. Two working fluids are involved; the refrigerant circulates from

Table 1 .... Summary of Results from *Examples 1* to *9*

Example	Cycle	Irreversibilities*	W	ΔS_{univ}	$(E_{AA})_r$	$(E_{AA})_{\Delta Q}$	ΔW, $T_A\Delta S_{univ}$ ΣE_{AA}	(CP)
1	reversed Carnot	none	50	0	0	0	0	4
2	reversed Carnot	Δt_{Q_c}	60	0.02	0	10	10	3.33
3	modified reversed Carnot	adiabatic compression friction	75	0.05	25	0	25	2.67
4	modified reversed Carnot	friction (Q_f)	75	0.05	25	0	25	2.67
5	modified reversed Carnot	Δt_{Q_c}, Δt_{Q_i}, friction in all 4 processes	177.69	0.25538	100	27.69	127.69	1.1256
6	ideal basic vapor	Δt_{Q_c}, exp. valve	62.07	0.02414	11.29	0.78	12.07	3.2222
7	actual basic vapor	Δt_{Q_c}, Δt_{Q_i}, exp. valve, evaporator friction	71.98	0.04396	20.38	1.60	21.98	2.7785
8	actual basic vapor	Δt_{Q_c}, Δt_{Q_i}, exp. valve, friction in all 4 processes	115.16	0.13032	47.17	17.99	65.16	1.7367
9	vapor, 2 stage comp., flash intercooler	Δt_{Q_c}, exp. valves, flash intercooler	55.75	0.01150	5.59	0.16	5.75	3.5875

* Δt_Q = irreversibility due to heat transfer through a finite temperature difference. Friction (Q) = fluid friction during process of heat flow.

the condenser to the evaporator, to the absorber, to the generator, and back to the condenser, while the second fluid, the absorbent, circulates from the generator to the absorber and back to the generator, etc. At the condenser, heat is removed from the refrigerant vapor coming from the generator, and the vapor condenses. The liquid refrigerant then flows through an expansion valve, or its equivalent, into the evaporator, where the pressure is maintained at a sufficiently low level so that the refrigerant will evaporate at the desired temperature, the heat of evaporation being taken from the material which is to be cooled. The refrigerant vapor then flows through an unrestricted passage to the absorber.

It is the function of the absorber to (1) maintain the desired pressure in the low side, and (2) dissolve the vapor in the absorbent so that the refrigerant can be returned to the high side without expending a large amount of mechanical work to compress the vapor. Both functions are accomplished because the absorbent has a high affinity for the refrigerant vapor, i.e., the absorbent must have a strong tendency to absorb or dissolve the vapor. The pressure maintained will be that fixed by the nature of the absorbent, its concentration, and its temperature. These factors are selected by the designer in order to obtain the desired results. In the absorber, the absorbent and the refrigerant vapor are brought into intimate contact to facilitate the dissolving of the vapor. The absorption process is exothermic, and the heat released is known as the heat of absorption. This heat quantity is numerically equal to the sum of the heat of condensation of the vapor and the heat of dilution of the absorbent. Thus, in order for the absorber to continue its functions, the heat of absorption must be continuously removed. Furthermore, this heat must be released at a temperature high enough so that the heat can flow to the available heat sink. Generally, the same heat sink will be available for both the condenser and the absorber.

It is significant to note the degree of *compression* that is apparently brought about when the refrigerant vapor is dissolved in the absorbent. For example, if two pounds of a 10 percent aqueous-ammonia solution at 120 F (volume equals 0.034 cu ft) is allowed to absorb one pound of ammonia vapor saturated at 38 F (volume equals 4.13 cu ft), the resulting three pounds of 40 percent solution cooled to 120 F will have a volume of 0.057 cu ft. The increase of liquid volume is thus 0.023 cu ft, and the compression ratio is therefore 4.13/0.023 ≃ 180. This very high compression ratio demonstrates the

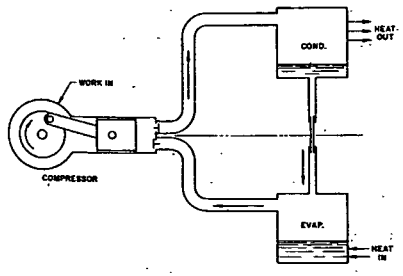

Fig. 16 .... Basic Compression Refrigeration Cycle

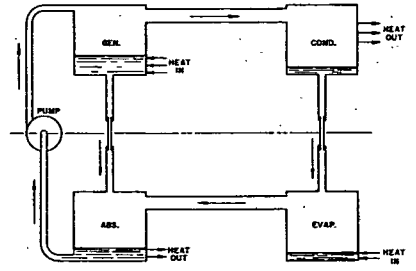

Fig. 17 .... Basic Absorption Refrigeration Cycle