Case-17 Compound-Cascade System

Case Background:

This case is for an installation for process gas mixture condensation for a hydrocarbon processing complex. One of the important requirements from the user is that the operating pressure of the refrigeration system is to be above atmospheric pressure no matter what refrigerant is used for the system.

Related Technical Data and Information for the Installation:

Refrigeration Capacity: 1,536,000 Btu/Hr (128 TR)
Evaporative temperature: -120℉

The evaporator is a Kettle type floating type sheet heat exchanger; it is designed and constructed by the user for the process stream.

Cooling water is available, 88℉ in and 98℉ out.

Cast steel casings for screw compressors.

Heat exchanger design and construction: TEMA-B and ASME, A516 Carbon silicon steel with impact test for temperature below -20℉ to -50℉ and 3-1/2% nickel steel with impact test for temperature below -50℉.

Fouling factor for all heat exchangers design is 0.001.

Electrical classification for the area is Class I, Group D, Division II.

Power supply: 4,160-3-60 for motors above 150 HP
460-3-60 for motors smaller than 150 HP
120-1-60 for controls

Refrigeration System Design Logic and Approach:

The evaporative temperature for the system is -120℉, it is beyond the capability of one refrigerant, particularly if the operating pressure is to be above the atmospheric pressure (14.7 Psia), therefore, a cascade system is to be used.

Cascade system uses two separate refrigerants. This installation is for hydrocarbon processing complex; therefore, it is logical to use hydrocarbon refrigerants such as R-290 (Propane) or R-1270 (Propylene) for the high stage and R-1150 (Ethylene) for the low stage. In this case, R-1270 is selected for the high stage instead of R-290; because the saturated temperature of R-1270 at atmospheric pressure is lower than R-290. R-1150 is used for the low stage; the saturated evaporative pressure of R-1150 for this refrigeration system at -120℉ is 40.33 Psia which is higher than the atmospheric pressure.

The lowest evaporative temperature allowed for the cascade condenser for the high stage system of this case is about -50℉ which is 16.2 Psia; allowing the suction pressure drops, the suction pressure to the high stage compressor would still higher than the 14.7 Psia permitted in accordance with the demand from the user.

The reasonable temperature difference between CT of the low stage system and ET of the high stage system for the cascade condenser might need about 14℉ for the heat transfer, fouling factor penalty and special tube material. If the ET of R-1270 is set to be -50℉, the CT of R-1150 low stage is to be designed for -36℉.

Therefore, the CT and ET for cascade condenser are fixed as the following:

The condensing temperature for the low stage R-1150 is -36℉

The evaporative temperature for the high stage R-1270 is -50℉

For the low stage R-1150 refrigerant circuit, the evaporative temperature is -120℉ and the condensing temperature is -36℉. If the low stage R-1150 refrigeration circuit is considered as a separate refrigeration system; the cascade condenser is the system condenser for the low stage.

For the low stage R-1150 System:

Condensing temperature:	-36℉ (224.92 Psia)
Evaporative temperature:	-120℉ (40.33 Psia)

The compression ratio for the low stage is about 5.58 without including the discharge and suction pressure drops for the low stage compressor. The low stage is with high pressure refrigerant, the refrigerant charge is to be as small as possible; therefore, a simple compression without economizing arrangement to keep the system and to keep the expansion tank small. However, because the evaporator is remote mounted, the liquid leaving the system is to be subcooled by the suction gas to avoid flash in the liquid line to the evaporator and a suction scrubber is provided to avoid any liquid slug over from the evaporator. The liquid and suction heat exchanger is to be placed before the suction scrubber; in case the suction gas carry a small amount of liquid, the liquid would help to subcool the liquid in the suction heat exchanger instead of accumulating in the suction scrubber.

The P-H diagram for this independent system is shown in Figure 17-1 as the following:

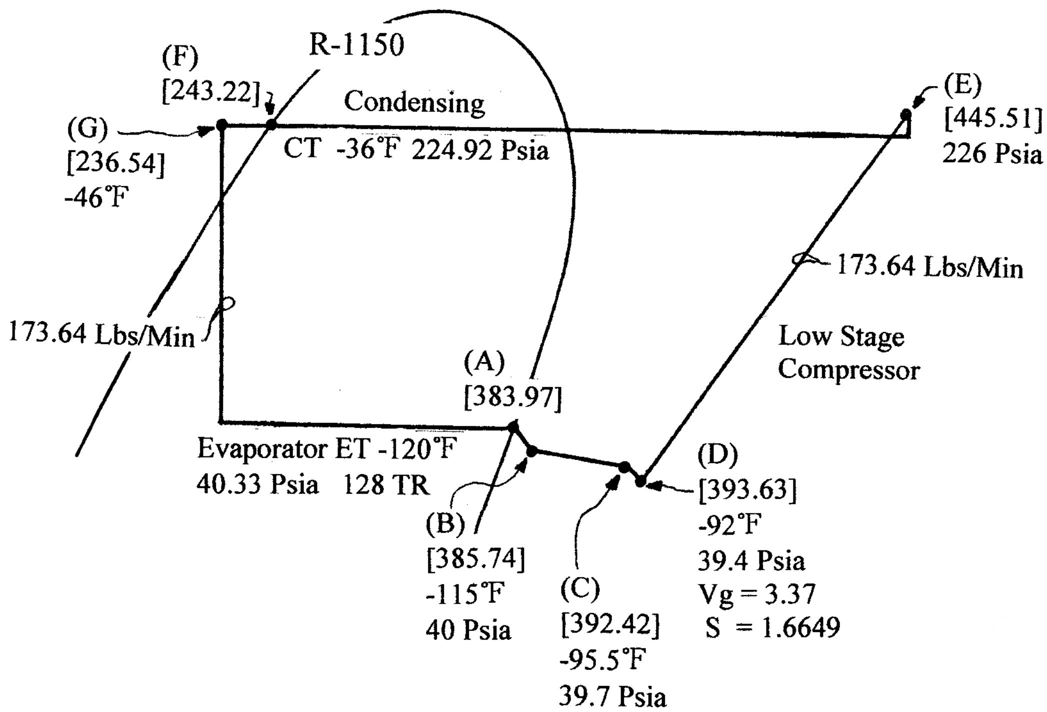

Figure 17-1 P-H Diagram for the R-1150 High Stage System

Assuming the liquid for the liquid to evaporator is to be subcooled for 10°F; the design condensing temperature for the low stage system is -36°F, therefore, the liquid leaving to evaporator is -46°F.

The enthalpy for point (F) which is the saturated liquid at CT of -36°F is [243.22].
The enthalpy for point (G) for liquid at subcooled temperature of -46°F is [236.54].
The enthalpy for point (A) for saturated gas leaving evaporator at -120°F is [383.97].

Net Refrigeration Effect (NRE) = 383.97 – 236.54
= 147.43

$$\text{Refrigerant Flow} = \frac{200}{383.97 - 236.54} \times 128$$

= 173.64 Lbs/Min

Suction and discharge penalties allowances for the design:
External Suction piping pressure drop from the evaporator to engine room: 0.33 Psi
External piping suction superheat from evaporator to engine room: 5℉
Compressor external discharge pressure drop: 1.08 Psi
Pressure drop through suction heat exchanger: 0.3 Psi
Pressure drop after heat exchanger to compressor suction: 0.3 Psi
Suction superheat after heat exchanger to compressor suction: 3.5℉.

Suction gas returning from evaporator, before the heat exchanger at point (B) is [385.74] at 40 Psia and -115℉.

The heat removal for the refrigerant flow of 173.64 Lbs/Min from point (F) to point (G)

$$= 173.64 \times (243.22 - 236.54)$$

$$= 1{,}160 \text{ Btu/Min.}$$

The enthalpy for point (C) for the suction gas:

$$= 385.74 + \frac{1{,}160}{173.64}$$

$$= 392.42$$

The temperature at point (C) at 39.7 Psia and h = 392.42 is -95.5℉.

Compressor suction conditions at point (D) are as the following:

Suction pressure:	39.4 Psia
Suction temperature:	-92℉
Enthalpy:	[393.63]
V_g:	3.372 Ft^3/Lb.
S:	1.6649

Liquid and Suction Gas Heat Exchanger:

Design and construction: Shell-and-tube, TEMA-B

Tube side:	To cool 173.64 Lbs/Min of R-1150 from -36℉ to -46℉.
Shell side:	Gas flow 173.64 Lbs/Min R-1150 from -115℉, 40 Psia to -92℉, Maximum pressure drop is 0.3 Psi.
DWP:	300 Psig.

Low Stage Screw Compressor Unit:

The operating conditions for low stage screw compressor unit and computer selection input data:

Capacity:	128 TR
Refrigerant:	R-1150 (Ethylene)
Evaporative Temperature:	-120^{o} F
Condensing Temperature:	-36^{o} F
Suction pressure drop:	0.93 Psi
Suction superheat:	28^{o} F
Discharge pressure drop:	1.08 Psi
Compressor speed:	3,550 rpm
Oil pump:	Recycling
Oil cooling:	Water cooled

Compressor unit selected:

Model Number:	RW-134
Power consumption:	295.4 BHP
Oil cooling heat removal:	0 (Stand-by oil cooler to be recommended by maker.

Compressor construction:

Casing:	cast steel
Design working pressure:	300 Psig

Low Stage Suction Scrubber:

Suction scrubber is to be size for gravity liquid and gas separation for ACFM flow of 173.64 Lbs/Min. The pressure at the suction scrubber is 39.7 Psia; the saturated temperature is -120.61℉ at this pressure if liquid exists; the specific volume is 3.024 Ft^3/Lb; therefore, the ACFM flow for suction scrubber design is 173.64 x 3.024 = 525.1 CFM.

Expansion Tank:

The expansion tank is to be sized to provide additional space enough to hold the entire charge of the R-1150 at 110℉ maximum ambient temperature at a design DWP of 225 Psig. The specific volume of R-1150 at 225 Psig (239.7 Psia) and 110℉ is 0.8353 Ft^3/Lb.

Ethylene (R-1150) is relatively inexpensive and is easily obtainable in hydrocarbon processing industries. One of the advantage of using Ethylene as the refrigerant for the cascade system is to flare off the ethylene by using automatic pressure relief valve during the system shut down; the expensive expansion tank for the system could be eliminated all together from the system design.

Cascade Condenser:

Heat rejection for the cascade condenser for the R-1150 system:

$$= \quad 128 \text{ TR} + \frac{295.4 \times 2545}{12{,}000} = 128 + 62.6 = 190.6 \text{ TR}$$

Operating conditions and specifications for the cascade condenser:

Heat load:	190.6 TR
Heat Exchanger design:	Flooded, Full Bundle with surge drum.
Construction:	TEMA-B design
Tube Side, R-1150:	
Tubes:	14 BWG
Material:	3-1/2% 3-1/2% nickel steel
Gas:	R-1150
R-1150 flow:	173.64 Lbs/Min
Condensing temperature:	-36℉
Leaving R-1150 temperature:	-36℉
Inlet pressure:	225 Psia
Fouling factor:	0.001
Design working pressure:	300 Psig
Shell Side R-1270:	
Refrigerant:	R-1270
Refrigerant feed:	Flooded
Refrigerant flow:	242.1 Lbs/Min.
R-1270 Liquid inlet temperature:	5^{o} F
Liquid pressure to evaporator:	52.7 Psia
Evaporative temperature:	-50^{o} F
Design working pressure:	300 Psig

Liquid Seal Operating Receiver:

This receiver is just for the purpose of providing liquid seal to prevent gas mix with liquid going to the cascade condenser.

Low Side System Design Working Pressure:

The low stage system is to be designed for 300 Psig DWP.

Refrigerant Flow Diagram for the Low Stage Refrigeration System:

The refrigerant flow diagram for the low stage R-1150 refrigeration system is shown in Figure-17-2:

The R-1270 (Propylene) liquid from high stage is supplied to the cascade condenser; it evaporates in the shell side and condenses the R-1150 refrigerant gas in the tube side of the cascade condenser.

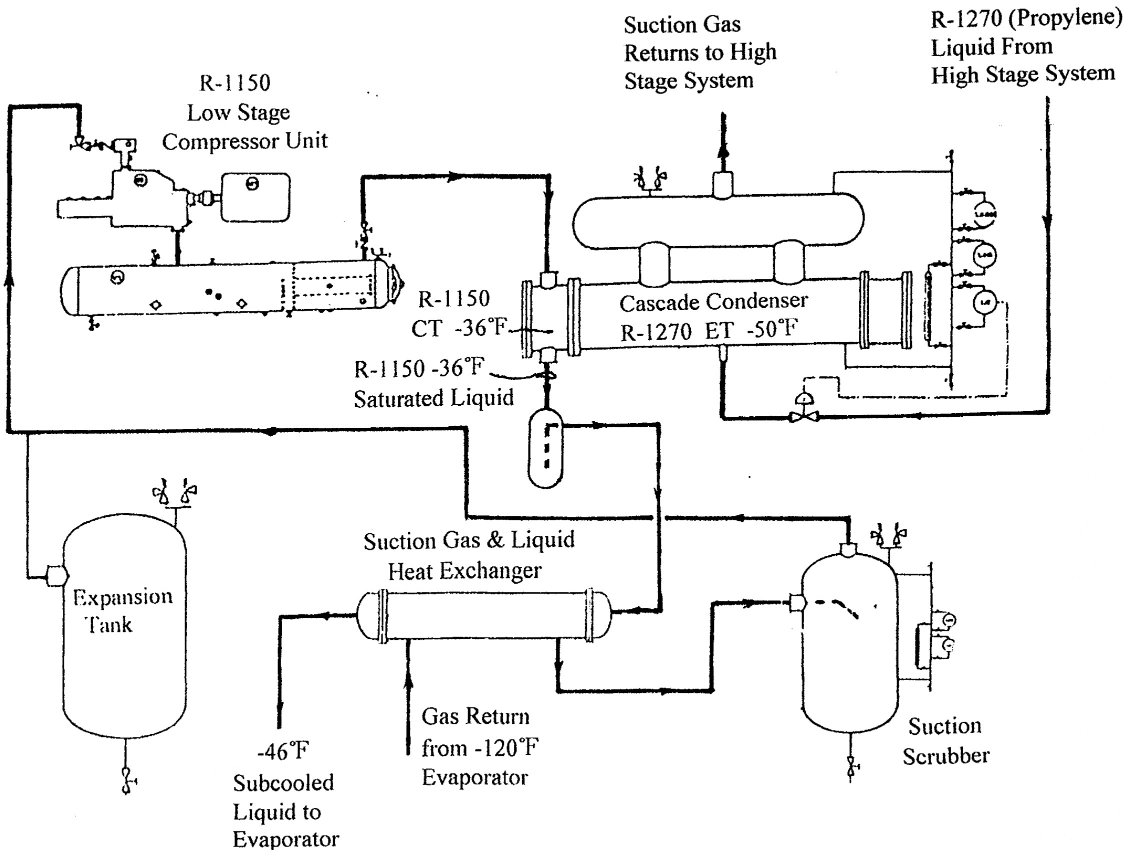

Figure 17-2 Refrigerant Flow Diagram for the Low Stage of the Cascade System

High Stage R-1270 Refrigeration System:

The high stage is a independent refrigeration system; the heat load for the high stage is 190.6 TR from the cascade condenser where the evaporative temperature is -50°F.

Cooling water for the high stage condenser is 88°F in and 98°F out; the reasonable temperature difference between CT and leaving water temperature for the condenser with the fouling factor penalty is about 12°F; therefore, the CT is to be designed for 110°F. In view of this, the high stage refrigeration system is to be designed for the following duty:

Refrigeration Capacity:	190.6 TR
Refrigerant:	R-1270 (Propylene)
Condensing temperature:	110˚F (257.9 Psia)
Evaporative temperature:	-50˚F (16.2 Psia)

The system compression ratio without counting the suction and discharge penalties is 15.92. For the purpose of improve power consumption and lower energy usage, it is suggested to use a compound system for the high stage of the cascade system; a booster is used and the high side screw compressor of the compound system is designed to be with a flash economizer. The intermediate temperature is fixed at 5˚F for this compound system.

The discharge and suction penalties for the design are as the following:

For Booster Compressor:

Suction pressure drop:	0.4 Psi
Suction super heat:	10 ˚F
Discharge pressure drop:	1.0 Psi

For the high side R-1270 compressor:

Suction pressure drop:	0.5 Psi
Suction super heat:	5 ˚F
Discharge pressure drop:	1.0 Psi
Economizer line pressure drop:	3.5 Psi

The Operating Conditions and Data for Computer Selection for Booster Screw Compressor Unit:

The operating conditions for high stage booster screw compressor unit and computer selection input data:

Capacity:	190.6 TR
Refrigerant:	R-1270 (Propylene)
Evaporative Temperature:	-50^{o} F
Intermediate Temperature:	5^{o} F
Suction pressure drop:	0.4 Psi
Suction superheat:	10^{o} F
Discharge pressure drop:	1.0 Psi
Compressor speed:	3,550 rpm
Oil pump:	Full lube
Oil cooling:	Water cooled

Booster Compressor unit selected:

Model Number:	RW-316
Power consumption:	243 BHP
Oil cooling heat removal:	0 (Stand-by oil cooler to be recommended by maker)

Compressor construction:

Casing:	cast steel
Design working pressure:	300 Psig

The Operating Conditions and Data for Computer Selection for the R-1270 High Stage Screw Compressor Unit:

Heat load for the high stage compressor:

$$= 190.6 \text{ TR} + \frac{243 \times 2{,}545}{12{,}000}$$

$$= 190.6 + 51.5 = 242.5$$

Say heat load for the high stage compressor is 243 TR at evaporative (Intermediate) temperature of 5˚F .

The operating conditions for high stage screw compressor unit and computer selection input data:

Capacity:	243 TR
Refrigerant:	R-1270 (Propylene)
Evaporative Temperature:	5^{o} F
Intermediate Temperature:	5^{o} F
Suction pressure drop:	0.5 Psi
Suction superheat:	5^{o} F
Discharge pressure drop:	1.0 Psi
Compressor speed:	3,550 rpm
Oil pump:	Recycling
Oil cooling:	Water cooled

Booster Compressor unit selected:

Model Number:	RW-177 with flash economizer
Power consumption:	482.6 BHP
Oil cooling heat removal:	311,300 Btu/Hr.

Compressor construction:

Casing:	cast steel
Design working pressure:	300 Psig

The simplified P-H diagram for the independent R-1270 high stage refrigeration system is shown in Figure 17-3.

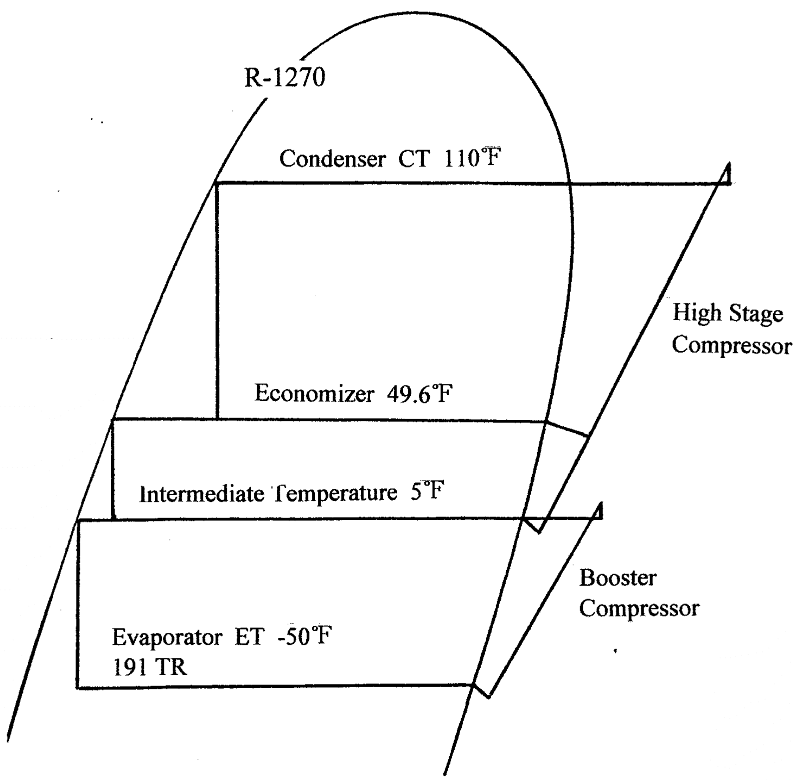

Figure 17-3 Simplified P-H Diagram for the High Stage Refrigeration System

The refrigerant flow diagram for the independent high stage R-1270 circuit refrigeration system is shown in Figure 17-4. As shown in the diagram, a flash type intercooler-economizer with internal built-in high pressure float valves is used instead of external float intercooler or economizer. Also, a liquid injection desuperheating arrangement controlled by a thermostatic expansion valve is used to desuperheat the discharge gas from the booster compressor instead of flash intermediate intercooler with external float valve. The intermediate intercooler-economizer is designed to serve as the combination system receiver. All the liquid condensed in the condenser is drained into the intermediate intercooler and receiver. Therefore, the combination receiver should be sized large enough to hold the refrigerant for surge operation. If the combination receiver is designed for storage, it shall be sized to hold entire R-1270 charge of the system.

A solenoid valve and a strainer and bypass service valves are usually provided together with the expansion valve. The expansion valve is to inject enough liquid to desuperheat the discharge gas which is from the booster compressor to saturated temperature of 5˚F.

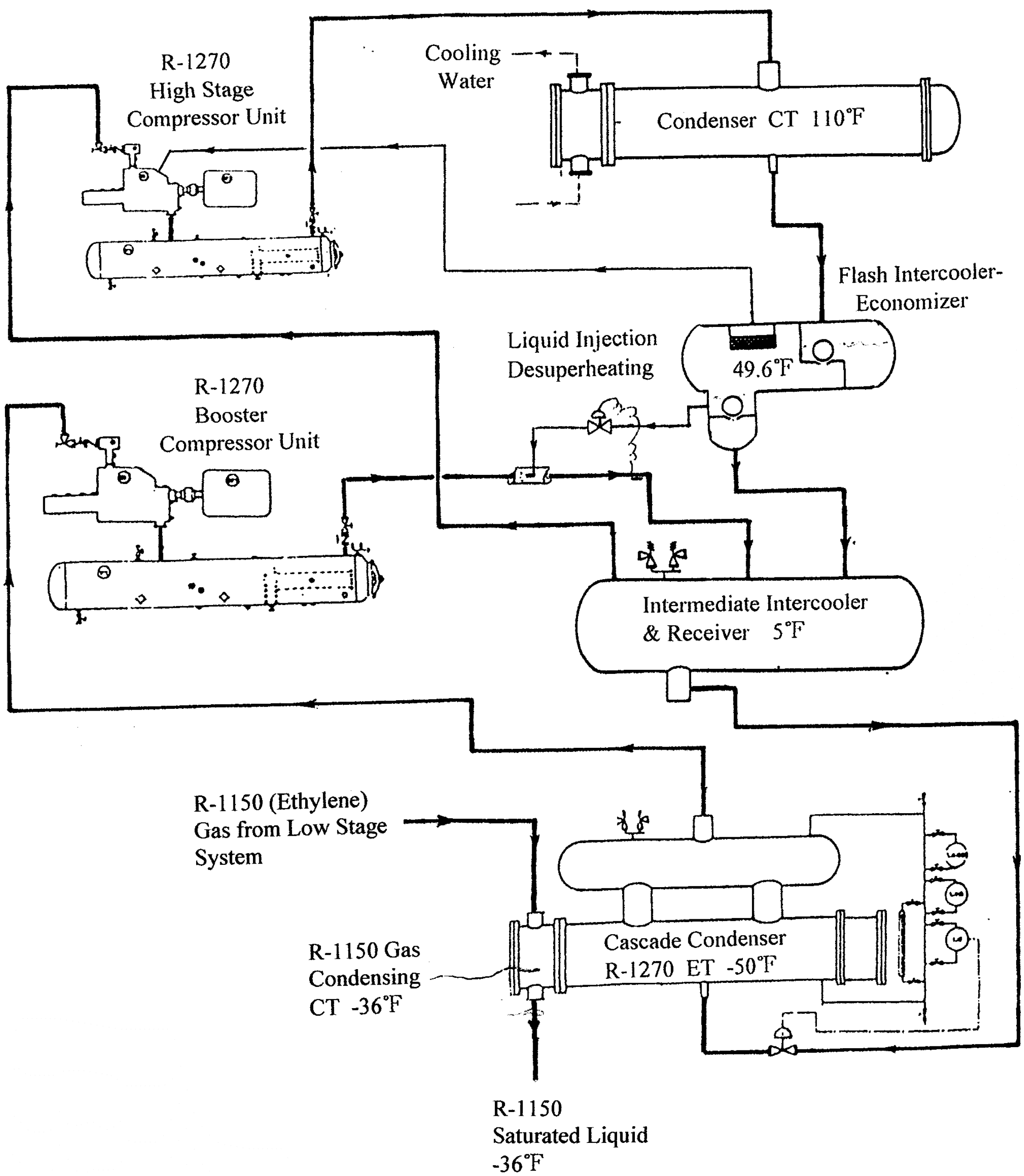

Figure 17-4 Refrigerant Flow Diagram for the High Stage R-1270 System

Heat Load for Water Cooled Condenser:

$= 243 \times 12{,}000 + 482.6 \times 2{,}545 - 311{,}300$

$= 3{,}832{,}917$ Btu/Hr or 3,833 MBH

Cooling water 88°F in and 98°F out.

$$\text{Cooling Water Flow} = \frac{\text{Btu/Hr.}}{499.8 \times \Delta T}$$

$$= \frac{3{,}833{,}000}{499.8 \times 10}$$

$$= 766.9 \text{ GPM} \qquad \text{Say } 767 \text{ GPM}$$

Operating conditions and specifications for the water cooled condenser for the R-1270 high stage refrigeration system:

Heat load:	3,833,000 Btu/Hr
Construction:	TEMA-B
Tube Side:	
Tubes:	16 BWG
Material:	Carbon steel
Water flow:	767 GPM
Water inlet & outlet temperature:	88°F to 98°F
Design working pressure:	150 Psig
Shell Side:	
Refrigerant:	R-1270
condensing temperature:	110° F
Design working pressure:	300 Psig

The Compound-Cascade System:

Figure 17-5 is the P-H diagram of the compound-cascade refrigeration system which is the combination of the Figure 17-1 and Figure 17-3.

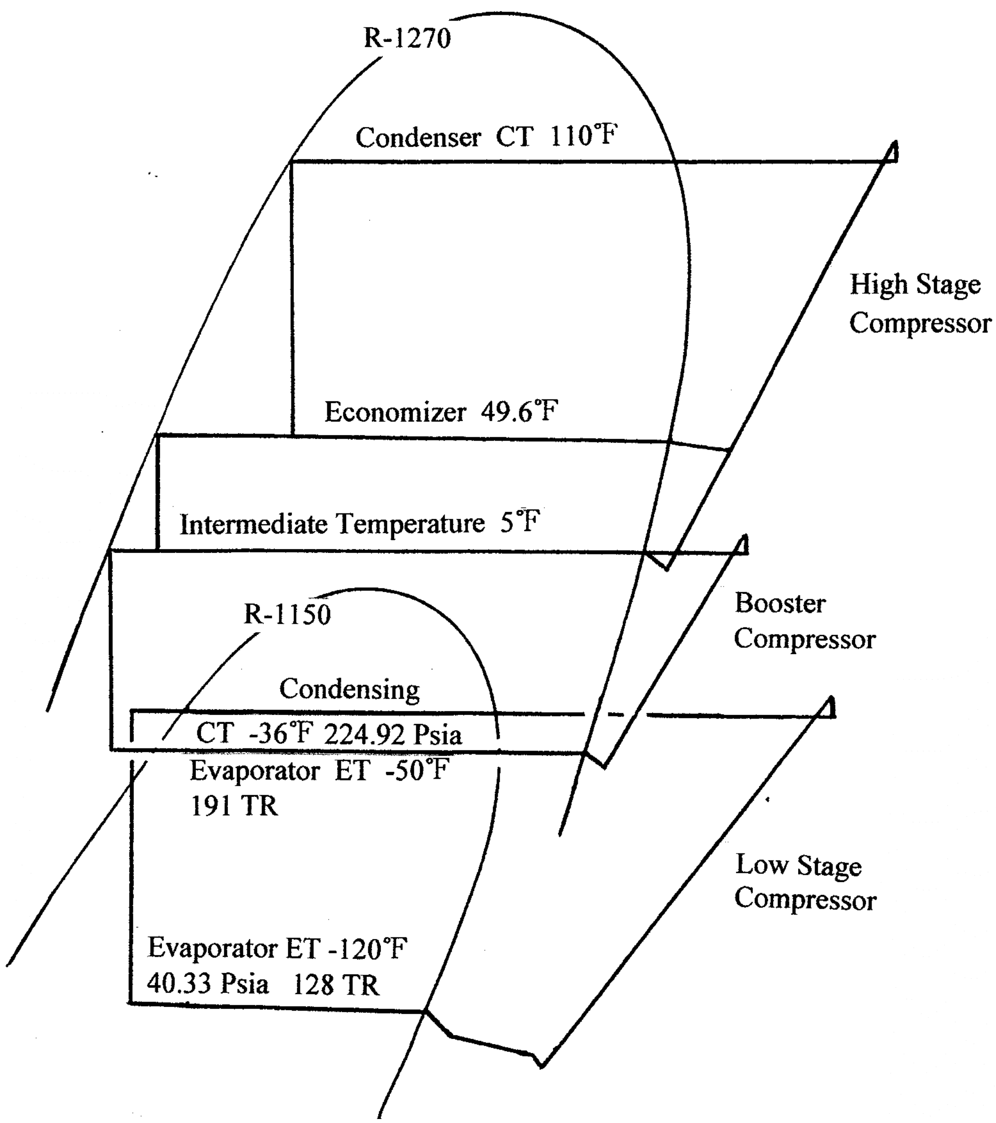

Figure 17-5 P-H Diagram for the Cascade Refrigeration System

Figure 17-6 is the refrigerant flow diagram of the compound-cascade refrigeration system which is the combination of the Figure 17-2 and Figure 17-4.

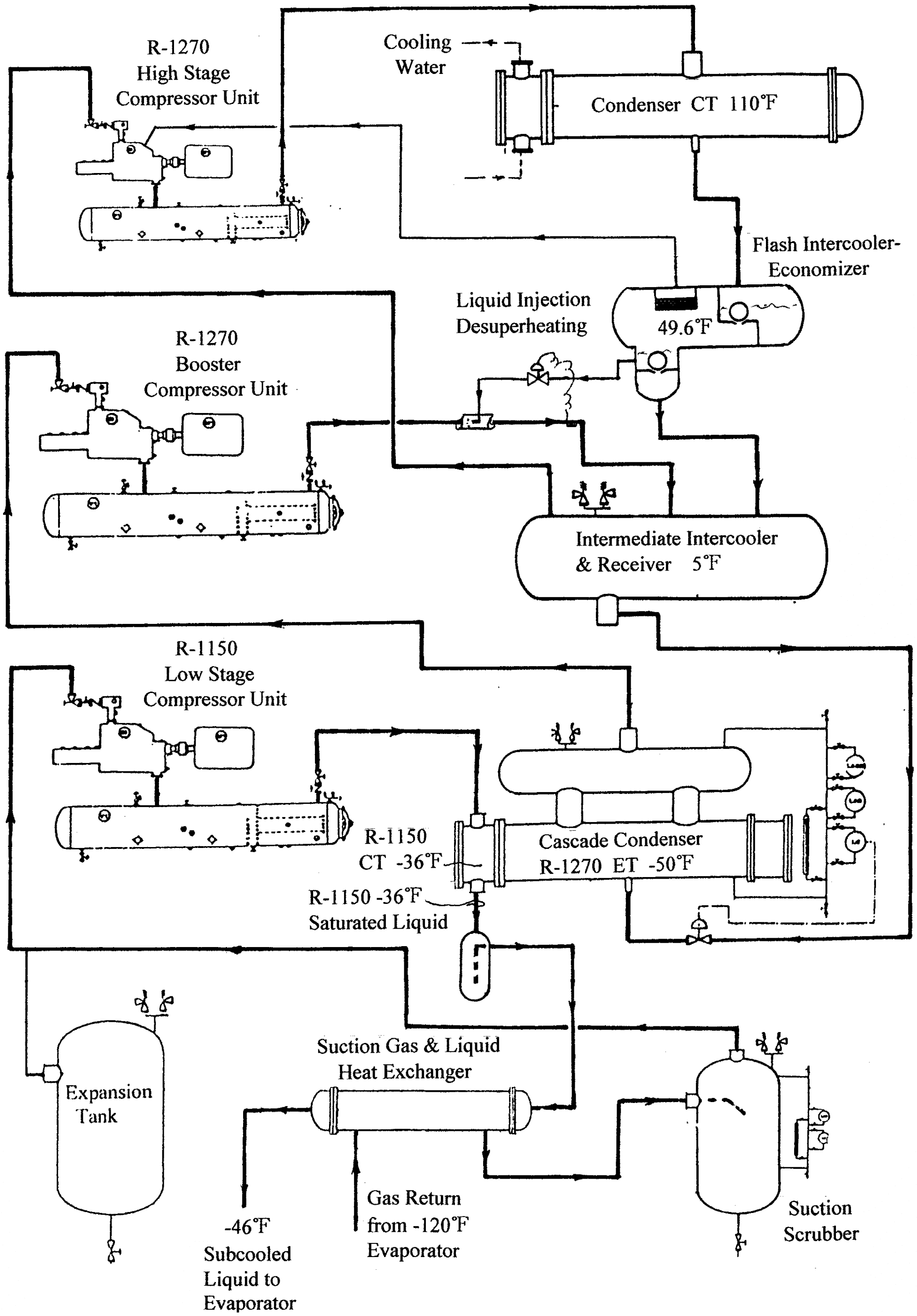

Figure 17-6 Refrigerant Flow Diagram
For the Cascade Refrigeration System