AMMONIA-WATER TRIPLE-EFFECT ABSORPTION CYCLE

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ABSTRACT

There are a number of known absorption cycles capable of "triple-effect" refrigeration. Among the basic triple-effect cycles only one particular cycle is able to use ammonia-water (NH3/H2O) as the absorption fluid pair. This cycle uses two condensers and two absorbers to achieve the "triple effect." This paper presents several basic triple-effect cycles superimposed on NH3/H2O pressure-temperature-concentration equilibrium diagrams (PTX) showing that only one particular cycle can use NH3/H2O. Calculations are presented showing the relative performance of a conventional double-effect cycle using NH3/H2O and the performance of this triple-effect cycle using NH3/H2O on a comparable basis. The triple-effect cycle is predicted to have 18% higher cooling efficiency (COP = 1.41 compared to COP = 1.2 for a double-effect), lower pressure (701 psi instead of 1000 psi), significantly reduced pumping power (less than one half that of the double-effect cycle), and potentially lower construction cost (33% less total heat exchange needed). Practical implications for this triple-effect cycle are discussed.

INTRODUCTION

All current gas-fired absorption air conditioners are based on well-known single-effect or double-effect cycles. Because these products are relatively "mature," the existing single and double-effect products are already (for all practical purposes) cost-performance "optimized." While there is room for additional efficiency gains for single and double-effect products, the potential performance improvements are incremental improvements which will likely not make a major difference in efficiency or in market share compared to electric equipment.

As an example, companies now engaged in manufacturing and sales of absorption equipment are conducting major programs to improve double-effect products. Published information from certain manufacturers (Kurosawa 1988) shows ambitious goals of coefficient of performance (COP) = 1.2 for small- and medium-sized machines and COP = 1.3 for large sizes (compared to COP = 1.0 to 1.07 as currently produced). If these goals for improved double-effect equipment are met successfully, the resulting products likely will be pushing the practical limits for double-effect equipment (Wilkinson 1987).

One approach to further improving the relatively inefficient cooling performance of even the best double-effect absorption equipment is to develop completely different more complex absorption cycles with significantly higher theoretical efficiency potentials in cooling (DeVault 1988a,b).

The double-effect cycle represents a significant step performance improvement over the basic single-effect cycle (COP = 1.2 for double-effect cycle compared to COP = 0.77 for the equivalent single-effect cycle). There are a variety of "triple-effect" cycles that could produce comparable significant step improvements in cooling efficiency compared to the equivalent double-effect cycles. Theoretically, a triple-effect cycle could be 50% better than a double-effect cycle in cooling performance.

Along with the potential significant performance improvements, increased technical challenges (risks?) are involved if a practical triple-effect cycle is to be developed. These technical challenges relate principally to the use of particular absorption fluids.

Almost all current absorption equipment is based on the use of either ammonia or water as the refrigerant. With some exceptions, ammonia refrigerant systems (such as ammonia with water as the absorbent) traditionally have been used in small residential equipment and water refrigerant systems (such as water with lithium bromide as the absorbent) have been used in large commercial equipment. Each absorption fluid system has well-known limitations that affect its potential use in a variety of theoretical triple-effect cycles. This paper focuses on triple-effect cycles suitable for ammonia/water (NH3/H2O) absorption fluids, and the constraints on the applicability of NH3/H2O for triple-effect cycles.

EVALUATION OF BASIC CYCLES

Every absorption cycle consists of certain basic components (ASHRAE 1985; Alefeld 1983; Raldow 1982), generally consisting of an evaporator, condenser, absorber, and generator, but also possibly including desorbers, resorbers, etc. Figure 1 shows the classic "elemental" single-effect absorption cycle. Figure 2 shows the two-condenser double-effect cycle, which is widely manufactured using water as the refrigerant. One ammonia refrigerant double-effect prototype has been built using this same cycle (Reid et al. 1987), and ammonia-water has been evaluated for use in this cycle (Phillips 1988; Modahl and Hayes 1988).

There are a number of known absorption cycles capable of "triple-effect" refrigeration. Rules have been established (Alefeld 1983, 1985) which allow the evaluation of complex cycles in terms of several equivalent single-effect cycles. These rules specify that one (or more) components of a single-effect cycle are combined with component(s) of a second single-effect cycle to obtain the more complex cycle. These combined components have a common absorption fluid stream and are in simultaneous heat and mass exchange with each other. These combined components of the elemental single-effect cycles are called "exchange units" (Alefeld 1983, 1985).

It is also possible to evaluate these same complex cycles in terms of basic single-effect cycles without having to use the combined heat and mass "exchange units" (Wilkinson 1987). Using single-effect cycles in which independent components are only in a heat exchange relationship with components of the other single-effect cycles also allows relatively simple evaluation of complex cycles.

SINGLE-EFFECT CYCLE

The basic single-effect cycle shown in Figure 1 will serve as the basis for calculation for each cycle evaluated in this paper. The basic cycle for ammonia-water, including internal heat recuperation currently practiced by the industry, is capable of a COP = 0.77 at the standard rating conditions. The evaporator (on the refrigerant side) is at 36° F (2.2° C) in order to cool air with a reasonable temperature drop across the heat exchanger. Both the absorber and condenser operate at or above 92° F (33.3° C) in order to reject heat to the atmosphere, which is at 82° F (27.8° C) for the standard rating test procedure (ARI 1981) for small air-cooled air conditioners. The condenser, operating at 92° F, will therefore be at a pressure of 184.8 psi. Under these conditions, the generator will operate over the range of 157.4° F to 240.3° F (69.7° C to 115.7° C). In other words, solution at the cold end of the generator will be at thermodynamic equilibrium at 157.4° F and then is heated by an external heat source to a temperature of 240.3° F before leaving the hot end of the generator. This cycle can be operated as the single-effect cycle with heat input to the generator from, for example, a natural gas flame.

For one "unit" of external heat input to the generator, one "unit" of refrigerant is produced. This refrigerant is then condensed (rejecting one "unit" of heat to the air) and evaporated (producing one "unit" of refrigeration). For one "unit" of external heat input, one "unit" of refrigeration effect is produced; hence the name "single effect." Ideally, this would be a COP = 1.0; however, because of real-world second-law thermodynamic losses, COP = 0.77 is typically achieved.

It is also possible to use heat from other processes to provide heat to the basic single effect in order to obtain the thermodynamic equivalent of other, more complex, configurations (Wilkinson 1987; Alefeld 1983,1985). The single effect discussed above is the "baseline" single effect for calculation of the more complex double and triple-effect cycles that follow.

DOUBLE-EFFECT CYCLE

The double-effect cycle shown in Figure 2 is commonly used in manufactured products. This cycle dominates sales of large absorption equipment. It differs from the baseline single effect in that there are two condensers and two generators instead of only one of each in the single effect. This "two-condenser, double-effect" cycle is thermodynamically equivalent to two basic single-effect cycles in which a "high-temperature condenser" single effect is combined with the baseline single effect discussed previously.

The "high-temperature condenser" single effect is defined as a single-effect cycle in which the condenser temperature is raised to a temperature greater than that of the generator of the baseline cycle. This means that the "high-temperature condenser" must operate at a temperature greater than 215.8° F so that all of the heat from this high-temperature condenser can be used to provide energy needed for the generator of the baseline single effect. The heat of rectification from the high temperature generator can be used to provide energy from 215.8° F to the 240.3° F peak temperature for the single effect generator. In this evaluation, a 10° F temperature difference is assumed for heat exchange, which results in the high-temperature condenser operating at 225.8° F (107.8° C). This condenser temperature corresponds to a pressure of 1000 psi (68.1 atm). Under these conditions, the high-temperature generator will have a maximum temperature of 391.3° F (199.6° C).

By combining the high-temperature condenser single-effect cycle with the baseline single-effect cycle, all of the condensation heat of the refrigerant in the high-temperature cycle can be used to "generate" additional refrigerant in the baseline cycle. One unit of refrigeration effect is produced in the high-temperature cycle with the addition of external energy. A "second" unit of refrigeration effect is produced in the baseline cycle by recovering the heat of condensation from the high-temperature cycle. Therefore, with the addition of external heat only to the generator of the high-temperature cycle, a total of two units of refrigeration is produced; hence the designation "double effect." Ideally, this would result in twice the efficiency of a single-effect cycle, or a COP = 2. When real second-law thermodynamic losses are included, COP = 1.20 is typically obtained. This represents a very significant 60% improvement in efficiency compared to the baseline single-effect cycle.

The "price" for this performance improvement is an increase in generator temperature from 240.3° F (115.7° C) to 391.3° F (199.6° C), an increase in pressure from 184.8 psi to 1000 psi, and a significant increase in complexity and heat transfer. As first approximations, these translate into increased corrosion rates, larger heat exchanger surface areas (and increased manufacturing costs), much higher pressures (also likely to increase manufacturing costs in order to maintain adequate safety margins in production), and increased control complexity.

TRIPLE-EFFECT CYCLES

Previous work has shown that there are theoretically a large number of cycles that fall into the category of "triple efficiency" (eg., "triple effect")(Alefeld 1983, 1985). By limiting the application to air conditioning of buildings, and by limiting the cycles to basic combinations of cycles using standard evaporator, condenser, absorber, and generator components, there are three basic triple-effect cycles possible.

These three cycles are shown schematically in Figures 3, 4, and 5. Each cycle will be discussed individually without regard to absorption fluid choice, and then the cycles will be evaluated for use with NH_3/H_2O.

Three-Condenser Triple-Effect Cycle

The first cycle, shown in Figure 3, uses three condensers and three generators to obtain the "triple-effect" cycle configuration. This cycle can be considered to be the traditional two-condenser, double-effect cycle with the addition of yet another condenser and generator. Principal considerations in applying this cycle are the much higher temperature of the third condenser and the resulting higher pressure compared to the double-effect cycle. This is the triple-effect cycle that has previously appeared in the literature, but has not been developed further with any existing absorption fluids.

Three-Absorber Triple-Effect Cycle

The second cycle, shown in Figure 4, uses three absorbers and three generators to achieve the triple effect. This cycle would operate at the same pressure as a single-effect cycle, but also requires extremely high temperature lift capability between the evaporator and the high-temperature absorber.

Two-Condenser, Two-Absorber Triple-Effect Cycle

The third basic triple-effect cycle, shown in Figure 5, uses two condensers and two absorbers to obtain the triple-effect cycle configuration. This cycle is equivalent to two independent single-effect cycles in which both the condenser and absorber of a "high-temperature, single-effect" cycle are hot enough to be used to supply heat to the baseline single-effect cycle. An interesting feature of this configuration is the ability to operate the high-temperature single-effect cycle at a lower pressure than is the case for the double-effect cycle. The reason for being able to operate at a lower pressure than the double-effect cycle will be discussed in a following section.

Triple-Effect Cycles With NH3/H2O

As a first step in evaluating any new complex cycle, it is essential to establish that a particular fluid is fundamentally suitable for the new cycle. For various reasons (for example, crystallization limits, inadequate solubility, etc.), some absorption fluids cannot be used to build and operate real machinery using a complex absorption cycle. For this reason, the first step in evaluating triple-effect cycles for use with NH3/H2O is to simply draw the particular triple-effect cycle on the NH3/H2O pressure-temperature-concentration (PTX) equilibrium diagram.

Figure 6 shows the three-condenser, triple-effect cycle superimposed on the NH3/H2O PTX diagram. As can be seen, this cycle would not be practically feasible with NH3/H2O, since the high-temperature condenser would have to operate well beyond the critical point of the ammonia refrigerant. Therefore, the three-condenser, triple-effect configuration is eliminated from further consideration.

Figure 7 shows the three-absorber, triple-effect cycle superimposed on the NH3/H2O PTX diagram. As can be seen from Figure 7, this cycle exceeds the solubility limit of NH3/H2O. It is not possible to operate this cycle with NH3/H2O, since the highest-temperature absorber and the highest-temperature generator would have to operate at temperatures higher than the solubility limits of

NH3/H2O (eg., beyond the pure H2O absorbent limit).

Figure 8 shows the two-condenser, two-absorber triple-effect cycle superimposed on the NH3/H2O PTX diagram. As can be seen, this cycle does fit completely within the solubility limits for NH3/H2O, with adequate margin for reasonable heat exchanger performance. Of the three basic triple-effect cycles, this configuration is the only cycle that can use NH3/H2O. This cycle will hereinafter be called the triple-effect cycle.

CALCULATED PERFORMANCE FOR THE NH3/H2O TRIPLE-EFFECT

Performance calculations for the triple-effect cycle have been made based on recent NH3/H2O data (Gillespie et al. 1985; Macriss et al. 1988).

Table 1 shows a summary comparison of single-effect, double-effect, and triple-effect absorption cycles using NH3/H2O. The refrigerant and absorbent operating conditions are included in Appendix 1. As can be seen, the triple-effect cycle does offer significant performance improvements compared to the double-effect cycle using NH3/H2O. At the standard rating condition, the triple-effect cycle is 18% more efficient than the equivalent double-effect cycle (COP = 1.41, compared to COP = 1.20).

Some of the calculated values in the summary table may at first appear to be surprising. For example, the triple-effect cycle is calculated to operate at lower pressure, to need less total heat exchange, and to have much lower pumping power requirements than the double-effect cycle. Each of these results will be discussed in the following sections.

High Pressure

As previously discussed under the double-effect cycle, the "high-temperature single-effect cycle" must reject heat at a higher temperature than the baseline single-effect generator (low-temperature generator) input temperatures. For the double-effect cycle, the high-temperature condenser is primarily used to provide energy to the low-temperature generator. For systems with a volatile absorbent, such as ammonia and water, some additional energy can also be recovered from the high temperature rectifier. The low-temperature generator can accept heat from 157.4° F up to 240.3° F. However, most of the energy available from the condenser is available from the heat of condensation of the refrigerant, with only a small quantity of energy being available from sensible cooling of the condensed refrigerant. This means that the high-temperature condenser must operate at 225.8° F (215.8° F generator temperature + 10° for heat exchange) in order to supply all of the available condenser energy to the low-temperature generator. The high-temperature rectifier can then provide the rest of the energy needed to heat the low-temperature generator to the 240.3° F peak temperature. For NH3/H2O, this means the double-effect cycle will operate at 1000 psi pressure, since the pressure is determined by the condenser operating conditions.

However, for the triple-effect cycle, both the high-temperature absorber and the high-temperature condenser are used to provide energy to the low-temperature generator. The absorber, rather than the condenser, can be used to provide energy to the hotter parts of the generator, so the condenser can operate at a lower temperature while still supplying energy to the cooler parts of the generator. This means that the high-temperature condenser can operate at about 190° F and reject all of the condenser energy to the low-temperature generator. Additionally, the high-temperature absorber can operate conveniently over a temperature range of 195° F to 230° F, thereby providing additional energy input to the low-temperature generator. Finally, as in the double effect, the high-temperature rectifier can be used to provide the rest of the energy needed to heat the low-temperature generator. This condenser operating condition for the triple-effect cycle corresponds to a pressure of 701 psi, rather than the 1000 psi for the double-effect cycle. Figure 9 shows schematically the heat exchange between the high-temperature condenser, the high-temperature absorber, the high-temperature rectifier, and the low-temperature generator.

A fundamental advantage of the triple-effect coupling of the high-temperature side to the low-temperature side compared to a double-effect cycle is the ability to operate at reduced pressure.

Solution Pumping

The triple-effect cycle has a substantially lower solution pumping power requirement than the double-effect cycle. The double-effect cycle would need 370 W of pumping power (ideal pumping power excluding pump or motor efficiency), whereas the triple-effect cycle would need only 151 W of pumping power. There are two reasons for the triple-effect cycle's reduced need for solution pumping power. The first is simply that the solution only needs to be pumped to 701 psi instead of 1000 psi, as discussed above. The second reason is that far less solution needs to be pumped to the high pressure generator in the triple-effect cycle configuration.

The refrigeration effect obtained from the high-temperature (eg., high-pressure) side of the double-effect cycle is about 57% of the capacity of the complete double-effect cycle. Therefore, as a first approximation, about 57% of the total absorption solution needs to be pumped to the high-pressure (1000 psi) generator. For the triple-effect cycle, the refrigeration effect obtained from the high-temperature part of the cycle is only 25.4% of the total refrigeration effect, with the remaining 74.6% being obtained from the lower-temperature part of the cycle. Therefore, substantially less absorption solution is pumped to the high-pressure generator in the triple-effect cycle.

Combining these two advantages for the triple-effect cycle results in a substantially lower solution pumping power requirement compared to the double-effect cycle.

Heat Transfer

The triple-effect cycle recovers more energy internally than the equivalent double-effect cycle, which means there is a substantial reduction in the total heat transfer needed for any given refrigeration capacity. This reduction in heat transfer is because the triple-effect cycle recovers the high-temperature absorber energy and substitutes this absorber energy for external energy that would be needed in the equivalent double-effect cycle. The double-effect cycle "throws away" this absorber energy to the outside air, adding to the total heat transfer taking place in the cycle. A second advantage of the triple-effect cycle using NH3/H2O is that less heat transfer is needed for rectification compared to the double-effect cycle (also due to the lower pressure, less solution flow advantages discussed above).

Therefore, as a first approximation, 33% less heat exchanger surface area is needed for the triple-effect cycle compared to the double-effect cycle. Since absorption machines are mostly heat exchangers, this means that it should cost less to construct a triple-effect NH3/H2O air conditioner than to construct a double-effect air conditioner of the same capacity.

Maximum Temperatures

A disadvantage of the triple-effect cycle compared to the double-effect cycle is the higher temperature necessary to operate it. For the same external conditions and equivalent heat exchangers, the triple-effect generator will operate at 425.7° F (218.7° C) compared to 391.3° F (199.6° C) for the double-effect cycle. If the same absorption fluids are used, along with equivalent heat exchangers, higher efficiency cycles can only be obtained by using higher driving temperatures for the absorption cycle.

These higher temperatures will increase potential corrosion rates, possibly affecting material choices and material costs. Reliability and maintenance requirements also could be affected.

HARDWARE IMPLICATIONS

Except for the higher temperatures, it would seem to be preferable to build NH3/H2O absorption air-conditioners using the triple-effect cycle rather than a two-condenser, double-effect cycle.

In the last few years, every individual component needed to build and operate the triple-effect cycle has been developed and tested, although all of the components have not been built or tested by a single organization. The basic evaporator, absorber, and condenser are the same components that have been manufactured for decades in single-effect NH3/H2O air-conditioners.

The high-temperature condenser, which supplies heat to the low-temperature generator, is the same for the double- and triple-effect cycles. This high-temperature condenser, using NH3 refrigerant, has been designed, built, and demonstrated for a double-effect cycle (Reid et al. 1987). In addition, it has been designed to operate as high as 1500 psi, and has been tested in operation to the design point. High-temperature condenser operation at conditions far beyond those needed for the triple-effect cycle has therefore been demonstrated.

The high-temperature absorber/low-temperature generator combination has also been designed, built, and tested (Modahl and Hayes 1988). The high-temperature absorber was built and tested for an NH3/H2O heat pump development project to obtain the equivalent of double-effect efficiency in a heating and cooling heat pump using a "generator-absorber heat exchange cycle." This high-temperature absorber, combined with a low-temperature generator, has also been demonstrated at operating conditions beyond those needed for the triple-effect cycle air conditioner.

The equivalent high-temperature generator needed for the NH3/H2O triple-effect cycle has also been developed and tested for a number of other applications (Phillips 1988; Modahl and Hayes 1988).

The remaining step, not yet taken, would be to design, construct, and test a complete triple-effect machine using NH3/H2O.

CONCLUSION

It is technically feasible to build and operate a two-condenser, two-absorber triple-effect cycle using ammonia-water (NH3/H2O) as the absorption fluid. This particular triple-effect cycle offers a number of significant advantages compared to the equivalent two-condenser, double-effect cycle. These advantages are substantially higher efficiency (COP = 1.41 about 18% higher), lower pressure (701 psi instead of 1000 psi), significantly reduced pumping power (less than one half that of the double-effect cycle), and potentially lower construction costs (33% less total heat exchange needed). In order to achieve the triple-effect levels of performance, peak generator temperatures are higher than for the equivalent double-effect cycle, adding technical risk due to potentially higher corrosion rates.

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TABLE 1: CYCLE COMPARISON
BASIC AMMONIA-WATER CYCLES

CYCLE	SINGLE EFFECT	DOUBLE EFFECT	TRIPLE EFFECT
COP	0.77	1.20	1.41
HEAT TRANSFER (Btuh)	250,000	390,000	260,790
HIGH PRESSURE	185 psi (12.6 atm)	1000 psi (68.1 atm)	701 psi (47.7 atm)
NO. PUMPS	1	2	2
PUMPING POWER	35 W	370 W	151 W
NO. MAJOR COMPONENTS	5	7 (8)	7 (10)
PEAK GENERATOR TEMPERATURE	240.3° F (115.7° C)	391.3° F (199.6° C)	425.7° F (218.7° C)

Note: The calculations are at the standard rating conditions for unitary air-conditioners (ARI standard 210-81) and assumes commercially achievable heat exchanger performance (approximately 10° F).

APPENDIX 1

Standard Rating Conditions for SEER (82 degrees F)
Indoor Air: 80° F return, 67° F supply
10° degrees F for heat exchangers

Refrigerant/absorbent conditions:

Lower Loop:

Evaporator: 36° F; 66.7 psi; 99% NH_3 purity

Absorber: 92° F; 66.7 psi; 52.0% conc.
167.4° F; 66.7 psi; 29.1% conc.

Condenser: 92 F; 184.8 psi; 99% conc.

Generator: 157.4° F; 184.8 psi; 52.0% conc.
240.3° F; 184.8 psi; 29.1% conc.

Upper Loop:

Evaporator: 47° F; 86.2 psi; 99% conc. (the evaporators are staged
to keep temperatures & pressures as low as possible)

Condenser: 190° F; 701 psi; 99% conc.

Absorber: 195° F; 83.1 psi; 25.6% conc.
230° F; 83.1 psi; 17.0% conc.

Rectifier: 221.6° F; 701 psi; 99% conc. (vapor to condenser)
374.5° F; 701 psi; 78.4% conc. (vapor from generator)

Generator: 364.5° F; 701 psi; 25.6% conc. (rich liquid)
425.7° F; 701 psi; 17.0% conc. (weak liquid)

Other Notes:

For the above conditions, the upper loop supplies 25.4% of cooling capacity and lower loop supplies the remaining 74.6% of capacity.
The lower loop generator receives heat input from the upper loop condenser (190° F), absorber (195° to 230° F), and rectifier (221° to 374° F).

This calculation is for an air-conditioner only, temperatures for lower loop would not work for a reversible heat pump configuration.

FIGURE 1

Single-Effect Cycles

ORNL-DWG 89-15422

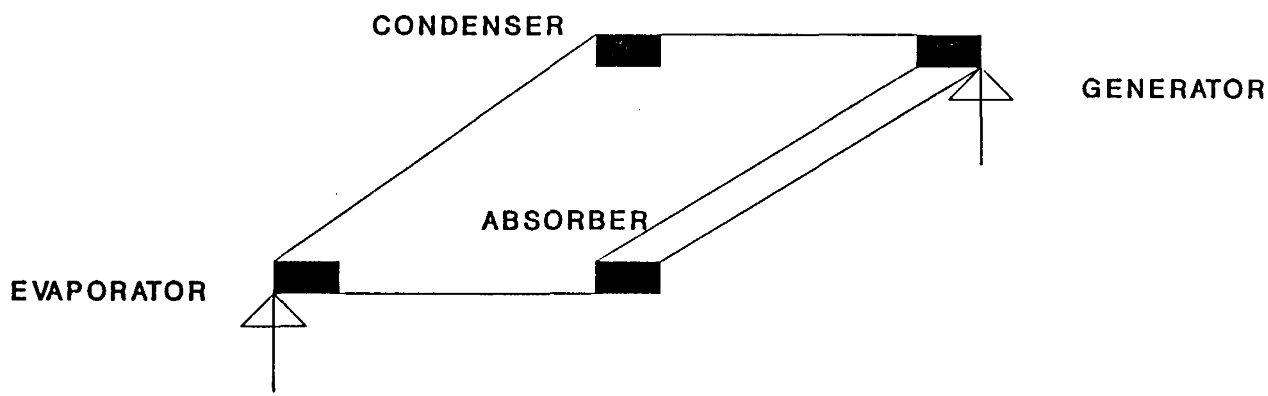

FIGURE 2

Double-Effect Cycle

ORNL-DWG 89-15428

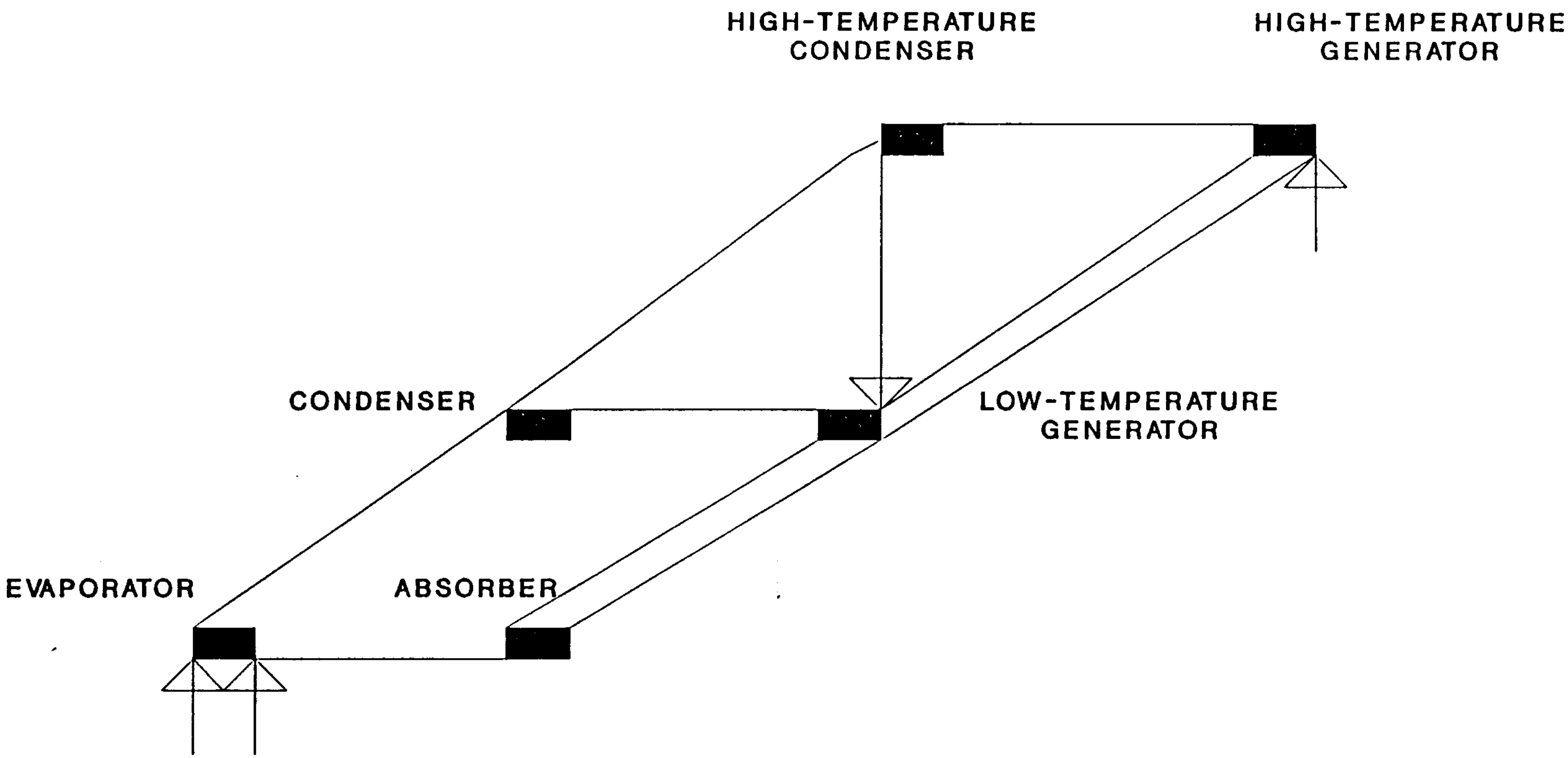

FIGURE 3

Three-Condenser Triple-Effect Cycle

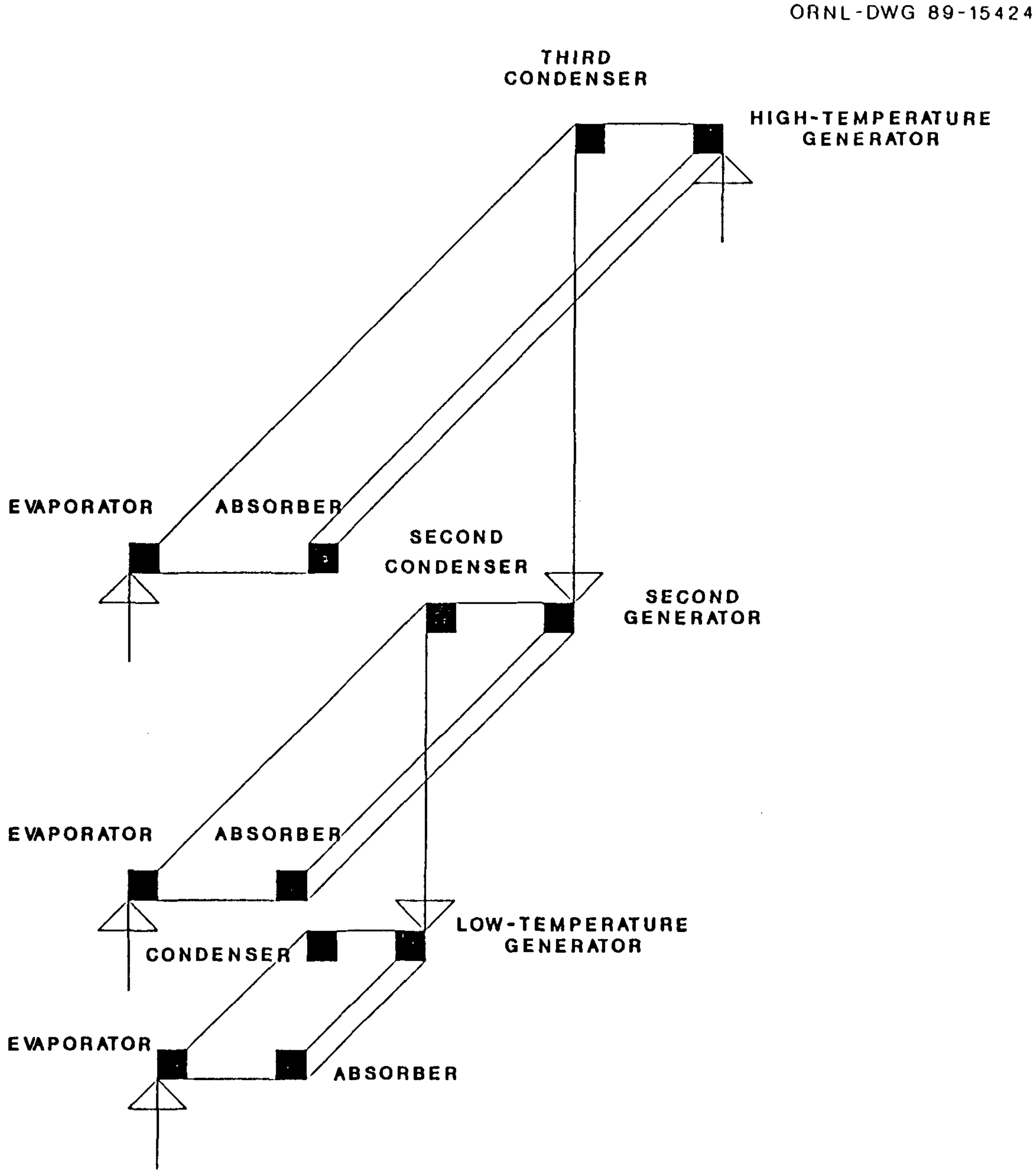

FIGURE 4

Three-Absorber Triple-Effect Cycle

ORNL-DWG 89-15425

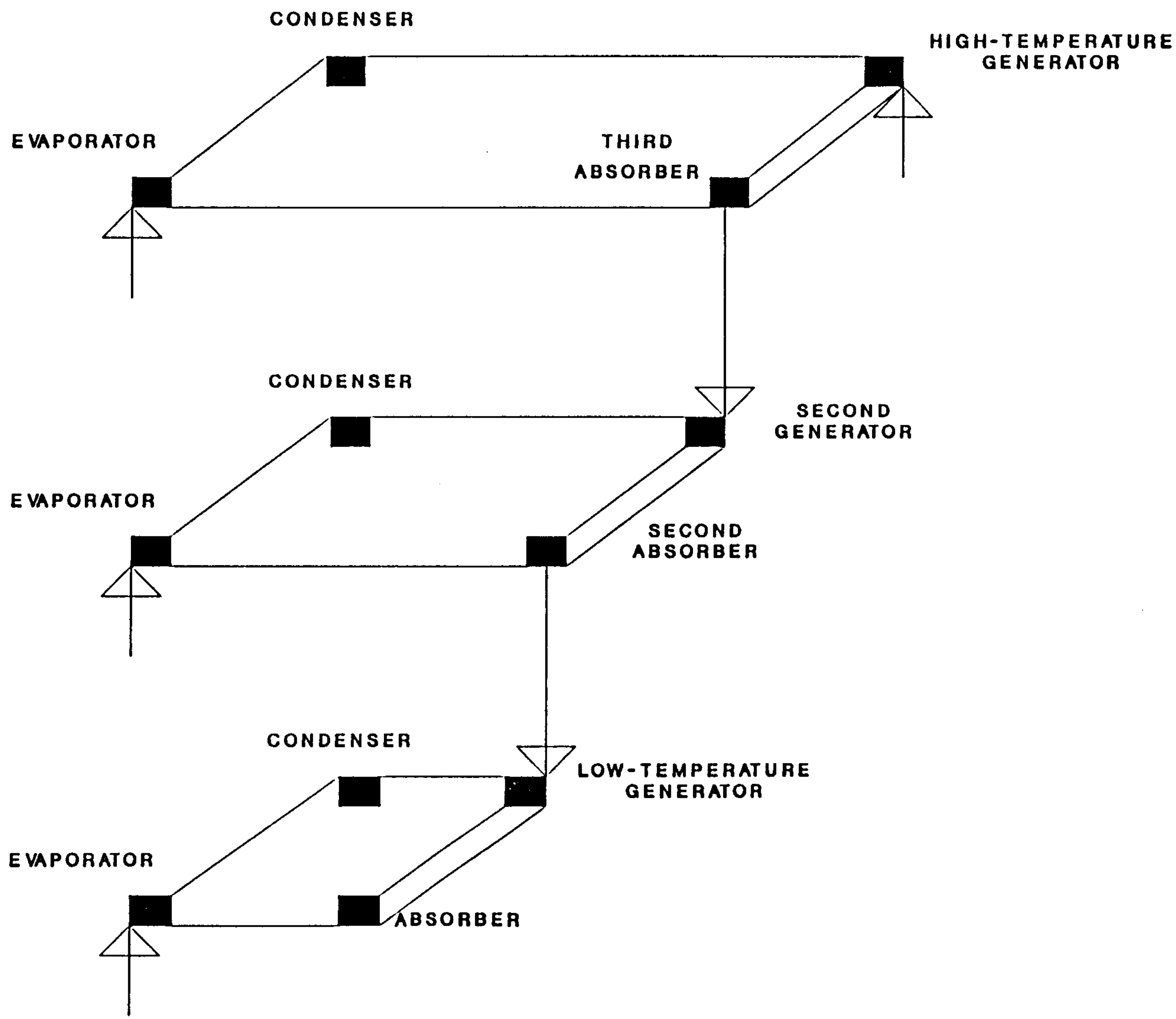

FIGURE 5

Two-Condenser, Two-Absorber Triple-Effect Cycle

ORNL-DWG 89-15426

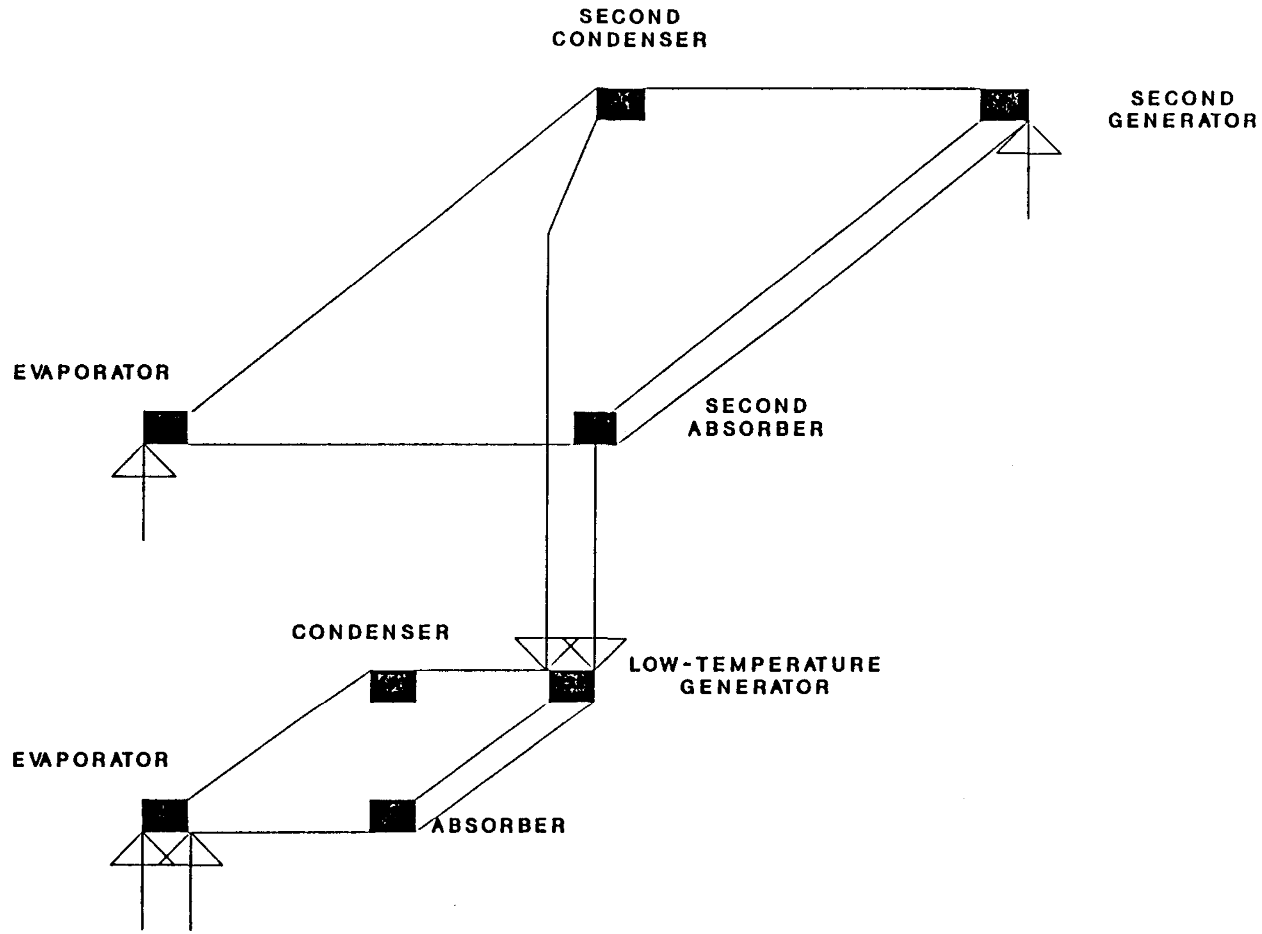

FIGURE 6

NH3/H2O PTX With Three-Condenser Triple-Effect Cycle

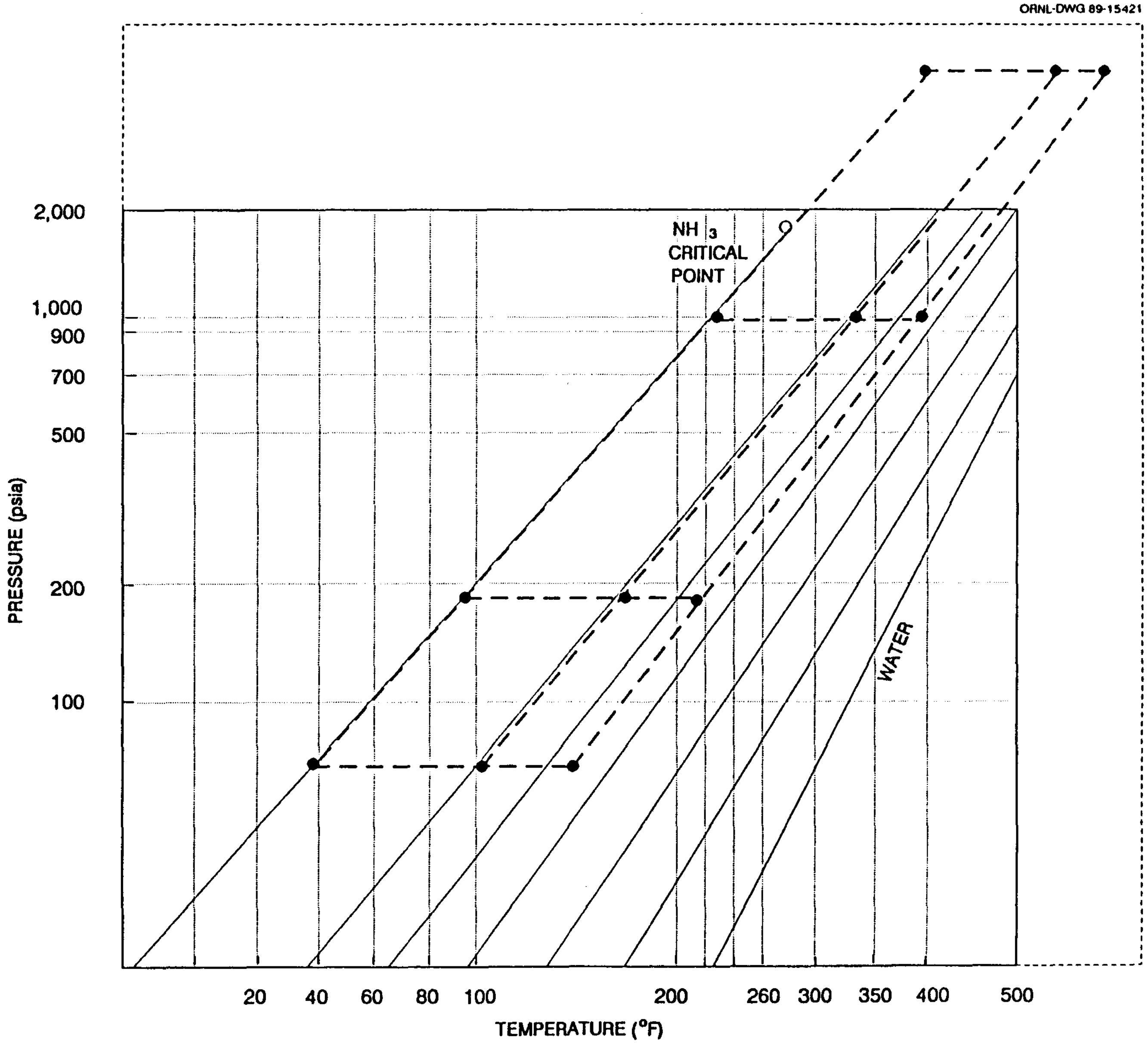

FIGURE 7

NH3/H2O PTX With Three-Absorber Triple-Effect Cycle

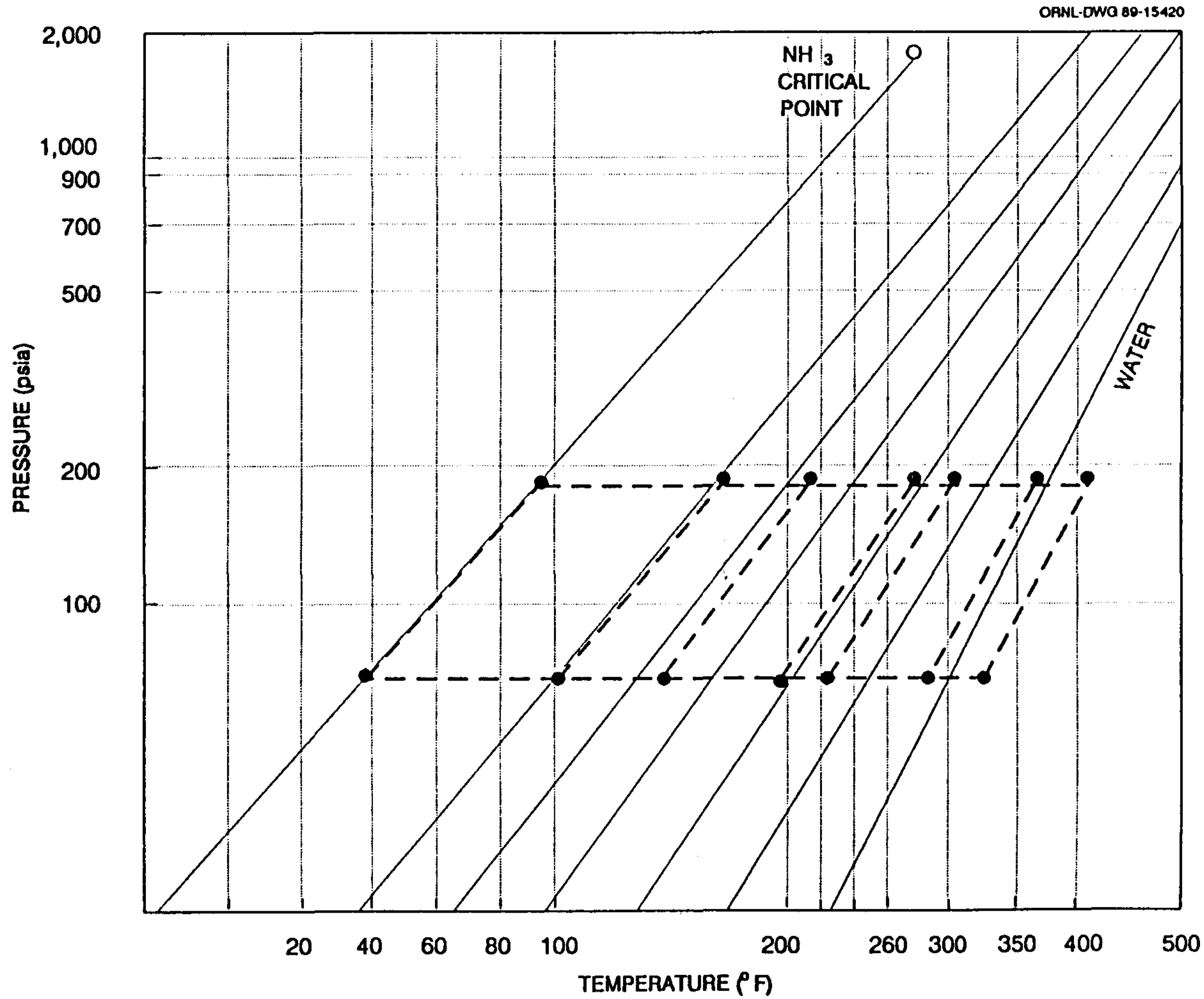

FIGURE 8

NH3/H2O PTX With Two-Condenser,
Two-Absorber Triple-Effect Cycle

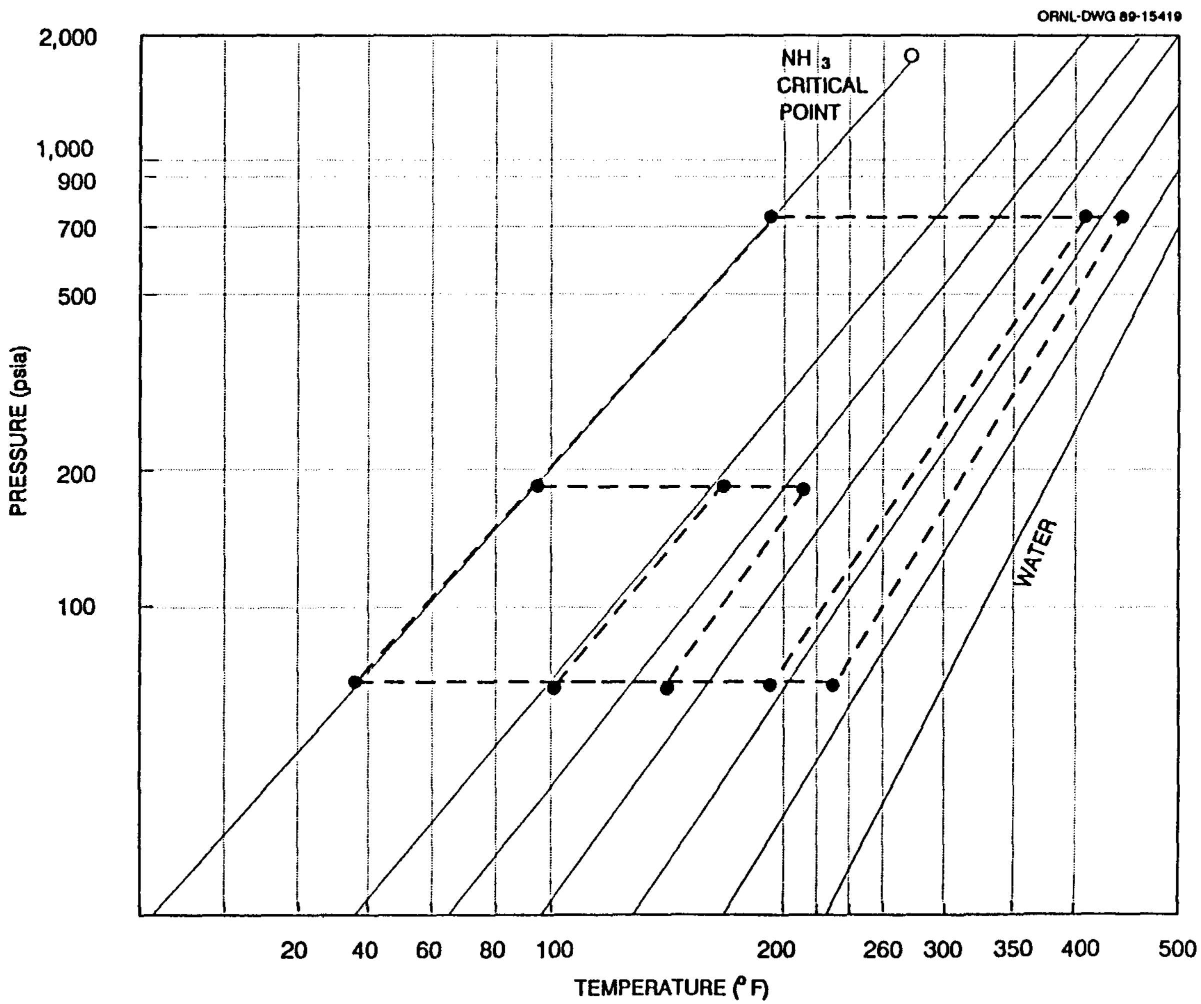

FIGURE 9

High-Temperature Heat Exchange
For NH3/H2O Triple-Effect Cycle

ORNL-DWG 89-15427