DRY/WET COOLING TOWERS WITH AMMONIA AS INTERMEDIATE HEAT EXCHANGE MEDIUM

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ABSTRACT

Engineering conceptual studies were made of several dry cooling towers for a 500 MW_e power plant. The most economical method used ammonia as a heat exchange medium. The ammonia condenses the turbine steam in a condenser-reboiler while being evaporated itself. The ammonia vapor is condensed and then recycled from a dry cooling tower. The lowest cost approach utilized a water deluge on the tower during the hottest ambient conditions to effect water savings of 80% over an all evaporative system. The total capital, and capitalized operating cost saving for the deluged/ammonia cooling system over a conventional wet/dry tower is potentially 15 to 30% for a typically $30 million tower.

INTRODUCTION

Under the auspices of the Division of Nuclear Research of the United States Engergy Research and Development Administration (ERDA) studies have been performed of dry cooling of power generation plants, its feasibility, cost, and growth potential. As part of these studies cost projections were made for several "advanced concepts," i.e. ideas for dry cooling which are not state-of-the-art (currently marketed), nor evolutionary developments from the state-of-the-art. The cost studies showed that unless dry-cooling systems could be greatly improved, they would be more expensive than evaporative cooling and would never capture a significant share of steam power plant cooling as long as water was available for consumptive use.[1] However, the studies showed that significant reductions in dry cooling cost could be afforded by using some sort of wet cooling augmentation during the hottest weather periods.

In the course of evaluating various systems for power plant cooling two major points became recognized:

1. Wet cooling would probably be used to supplement dry cooling even at the sites with high water cost.

2. Potentially, an intermediate heat transfer fluid (specifically ammonia) could be used in a power plant cooling system at less cost for dry or wet/dry tower cooling than other systems evaluated.

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Water Augmentation

Let's discuss more fully the first point, that of using water to augment a dry cooling tower. The cost of dry cooling is in large measure assessed because of the loss of efficiency of the steam power plant when the condenser operates at higher back pressure on hot days. Fig. 1 shows a typical example of this effect. The dry bulb temperature is shown versus the cumulative number of hours at a given temperature or above. The dashed lines show the normalized power output under the temperature conditions for various size dry towers. Hence on hot days, either a larger dry tower must be built or less efficiency must be accepted for the power plant. If a larger tower is built, the cost of electricity produced is more even though it allows higher-than-rated plant output on the cold days.

If the dry cooled plant falls below its rated output during the extremely hot periods then the load must be made up by other base plants, auxiliary plants, or by designing a larger plant (i.e. shifting the design point) in the first place. The cost attributable to dry cooling can vary significantly depending on which of these methods of "capability penalty" (capacity and energy charges) is used. There is some variation in treatment among various dry cooling cost assessments in the literature. However, by any method, the cost for straight dry cooling is high, particularly for a summer peaking demand typical of nearly all utility systems in the United States.

The hot period penalty could be greatly reduced if some means were found to augment the cooling during that time. For example, a separate wet tower could be used, or as we are suggesting here the dry surface could be flooded with water, "deluged," in order to provide more heat transfer by virtue of the driving temperature differences of water evaporation tending toward the wet bulb rather than the dry bulb temperature. A power demand curve for this situation is shown in Fig. 2. Note that the sharp rise in the effective temperature of the heat sink is cut off and that the dry tower is large enough to handle the load for most of the cooling year. This approach is, of course, not a new idea. People pour water on their car radiators to gain extra cooling and separate wet sections or separate wet towers are currently manufactured as state-of-the-art. The deluging idea is suggested for use because it should cost less than the other methods.

Simply spraying the surfaces runs the risk of corroding or fouling the surfaces due to deposition of salts from the evaporated water. With the deluge approach, the surfaces are protected by the "delugeate." Some small-scale experience with this concept exists. Plate-fin tube surfaces have been tested in Hungary for an extended period through many cycles of wet and dry operation, and are to be used in a demonstration plant at Ivanivo, near Moscow in the Soviet Union. Fig. 3 shows a schematic view of the cross section of plate-fin tubes being deluged. The air is cross flow to the delugeate. Analytical evaluation and laboratory experiments show that heat transfer increases by a factor of two to five when deluge is used.

The surface and arrangement just described can be used under license. It will be further evaluated in laboratory experiments in this country before a decision is made to use it in a large-scale demonstration. Other surfaces will also be tested in direct-augmentation arrangements.

Ammonia System

The second major point recognized was that use of an intermediate fluid could reduce the cost of dry cooling systems. The application of an intermediate fluid which undergoes a change of phase evolved from consideration of a binary cycle. In a binary cycle, work is extracted from the lower temperature portion of the Rankine cycle using a second fluid which is vaporized by condensing steam at a relatively high temperature (hence relatively high pressure) and is allowed to expand through a turbine to a low temperature and pressure, at which point it is condensed. The incentive for the use of the second fluid was that one could greatly reduce the equipment size of the low pressure turbine and thus save money by choosing a fluid which had a low specific volume and other favorable properties over the operating range. A study by the Franklin Institute[2] showed that the binary cycle would reduce plant cost under certain assumed conditions. However, for dry-cooled plants under the most likely set of conditions, the study concluded that one was further ahead to simply let the ammonia serve as a heat exchange fluid rather than a second "working fluid."

We continued such studies at PNL to critically compare the use of ammonia with other new concepts, such as the use of plastic tubes for the heat exchange surface. These studies led to the recommendation that the use of ammonia as an intermediate heat transfer medium together with the use of the deluge concept provides the best possibilities for markedly reducing the cost of dry (dry/wet) cooling systems.

System Description

The ammonia heat transport system for power plant heat rejection is functionally similar in many respects to the "direct" system in which the exhaust steam from the last stage of the turbine is ducted directly to an air-cooled condenser. The principal difference is the existence of a steam condenser/ammonia reboiler in which ammonia is "substituted" for steam as the medium for transporting heat from the turbine to the tower (heat sink). In all respects the ammonia system, with vapor moving from the reboiler to the air-cooled condenser and liquid returning to the reboiler, will function and respond to load changes in the same manner as the direct system.

Fig. 4 is the process flow sketch. Exhaust steam from the last stage of the turbine is condensed in the condenser/reboiler located directly below the turbine. Instead of water circulating through the tubes, liquid ammonia is boiled as it is pumped through the tubes underpressure, set by the operating temperature in the condenser. The flow rate of ammonia is set to yield a vapor quality emerging from the tube varying from 50% to

90%. This two-phase mixture is passed through a vapor-liquid separator from which the vapor is sent to the air-cooled condenser, while the liquid is combined with the ammonia condensate from the dry tower and recycled back through the condenser/reboiler.

The vapor from the vapor-liquid separator flows to the dry tower under the driving force of the pressure difference between these two components created by the temperature difference and the associated vapor pressure of the ammonia.

The vapor is condensed in the air-cooled (dry) tower. The ammonia vapor is condensed in a single pass cocurrent downflow arrangement, emerging at the bottom header as a saturated liquid at essentially the same pressure as at the inlet header. The liquid flows to a liquid receiver and then out through a vapor trap by gravity to a transfer line and thence back to the condenser/reboiler. Isolation valves at the inlet and outlet manifolds of a tower section will provide a means of removing sections of the tower from service as may be required for maintenance or reduced cooling capability.

Fig. 5 shows the temperature relationship of the ammonia system as compared to that of a conventional dry tower cooling system. The main difference is the relatively constant temperature difference in the condenser/reboiler between the condensing steam and the boiling ammonia and the increased mean temperature difference in the ammonia tower. This saves tower cost. The condenser/reboiler cost is not increased greatly despite the lower average temperature difference because of the high boiling-heat-transfer coefficient of ammonia. The vapor flows through the supply piping at near-saturation conditions. However, there is a pressure drop in the piping system from frictional effects. In this thermodynamic regime of ammonia vapor, this pressure drop is accompanied by a drop in temperature. At the tower, the vapor is condensed inside the metal finned tubes at constant temperature. The condensed ammonia is then collected and returned to the condenser/reboiler. The basic terminology is the same as for the state-of-the-art system except that the parameter, $RANGE_{Water}$, is eliminated and replaced by the vapor supply piping temperature drop, TTD2. Because of the economic trade-offs, the $RANGE_{Air}$ is somewhat larger for the ammonia system than for state-of-the-art systems.

The effect of deluge or water augmentation on these diagrams is to make the air range from the wet bulb temperature to the saturation temperature (hence less airflow is needed) and larger heat transfer driving temperature differences will exist. The deluge water would be at an intermediate temperature below the ammonia condensing temperature. Another possibility is to augment condensation of the ammonia with a separate loop wet tower rather than to deluge. The deluge has the mass transfer driving force of high temperature water throughout whereas the augmenting wet tower would have a range of water temperature. We are looking closely at this idea.

Choice of Heat Transfer Fluid

Early studies considered a variety of fluids, particularly refrigerants, which could be used in the phase-change mode to transport heat from the turbine to the air-cooled heat rejection system. Selection of the best fluid was based on a number of factors including the size of the ducts required to transport the fluid. A large heat of vaporization (h_{fg}) and a low specific volume of vapor (V_g) contribute to a large heat flux and small transport lines. However, the allowable vapor velocity ($U_{allowable}$) in the transfer line is also related to the specific volume (V_g) by the relationship

$$\frac{U^2_{allowable}}{V_g} = \text{constant}, \qquad \text{or} \qquad U_{allowable} \sim \sqrt{V_g} \quad .$$

Hence a "figure of merit" from the standpoint of duct size is $h_{fg}/\sqrt{V_g}$.

TABLE I shows the properties and figure of merit of several heat transfer fluids considered.

The advantage of ammonia in this respect is clear. Consideration must also be given to the operating pressure and the impact on equipment cost. The temperature on which the above table is based (150°F) is somewhat higher than will probably be experienced. 135°F (equivalent to about 5 in. Hg back pressure) is more representative, at which temperature the ammonia pressure is approximately 350 psi.

The freezing point of anhydrous ammonia is -108°F. Thus no concern for freezing need be considred in design, which eliminates the need of louvers and quick-drain provisions in the cooling tower.

The relatively high operating pressure required with the use of ammonia necessitates the use of heavier, more expensive piping, but it has the ameliorating feature that a relatively large pressure drop can occur between the plant and the dry tower with little change in temperature because of the steep slope of the vapor pressure temperature curve. Thus vapor is easily transported to the tower with little degradation of the available ITD (initial temperature difference) at the tower. If a "direct" steam system were used, the pressure drop between the turbine and condenser would have to be kept very low since low pressure steam at the same temperature is much more sensitive to pressure drop in the steam ducts than ammonia.

The significant advantages of the ammonia system include the following:

a. Isothermal condensation in the dry tower and consequently a larger temperature driving force for heat transfer than an indirect system. Hence less surface area is required.

b. Much lower volumetric flow rate and specific volume of the vapor result in smaller transfer lines between the plant and the tower, and in the tower.

c. No problems with freezing in the dry tower and consequently no requirement for louvers, drain valves or other low temperature safety systems.

d. No pumping required to move vapor to the tower and very little pumping required to move liquid back to the plant because of its low viscosity.

Available Technology for Ammonia Use

The use of ammonia is very general in the chemical process industry and agriculture. Consequently, criteria for design of production processes, the practices for handling large quantities, the codes and standards for storage and use, and for maintenance and safety are very extensive.

Considerable information is available on the questions of materials selection and corrosion performance. A PNL report[3] concludes:

"Candidate materials for use in the cooling cycle of a power plant ammonia heat rejection system are aluminum, carbon steel and stainless steel. Other materials are rejected as candidates on the basis of incompatibility with ammonia (e.g., copper-base alloys).

"Corrosion of aluminum alloys 1100 and 3003 is negligible in anhydrous ammonia and these would be satisfactory for service in both the condenser/reboiler and the air-cooled ammonia condenser. However, aluminum is susceptible to impingement attack by saturated, high-velocity steam. Thus if aluminum is used in the condenser/reboiler, the first several rows of tubes must be either constructed of stainless steel or protected with stainless steel sleeves.

"Carbon steel is a satisfactory construction material for relatively pure ammonia. High strength carbon steel is susceptible to stress-corrosion cracking in air-contaminated ammonia. Susceptibility increases with the yield strength of the steel. Cracking is caused by levels of oxygen and nitrogen as low as 1 to 2 ppm. Water added to a concentration of 0.1% to 0.2% is effective in inhibiting stress-corrosion cracking of susceptible steels in air-contaminated ammonia. Water added to liquid ammonia is effective in inhibiting stress-corrosion cracking of steel in contact with the vapor phase. Stainless steels of all types are resistant to corrosion in liquid and gaseous ammonia.

Small "leakages of ammonia through the condenser/reboiler should not have an adverse effect on condensate chemistry. In fossil-fuel plants and pressurized-water reactors, leaks of ammonia into the condensate can be easily detected and will not cause accelerated corrosion of materials in the condensate/feedwater cycle. In boiling-water reactors, ammonia is rapidly decomposed radiolytically; the only problem caused by an ammonia leak would be an increased volume of condensable gases (H_2 and N_2) in the condenser."

General Design Criteria

Aside from the applicable codes for pressure systems operating in the range of 350 to 400 psi and the selection of construction materials which avoids the use of any copper-containing alloys in contact with ammonia, the design criteria associated with the anticipated application of ammonia will have few restrictions.

Double tube sheets and/or welding of tubing to tube sheets and headers in the condenser/reboiler and in the dry tower will probably be a requirement, both because of the pressure and because of the ammonia characteristics (reactions with copper, toxicity). However, the construction practice is well established and should not introduce a large premium on construction costs. Inspection of a small representative sample of welded joints (perhaps 5%) rather than complete radiographic inspection is believed to be sufficient.

Heat transfer coefficients can be predicted to essentially the same degree of reliability as in a water system. However, no tube-side fouling resistance factor is required in the design of an ammonia system because of the purity of the fluid and the small likelihood for the continuing introduction of noncondensibles once they are initially removed from the system following startup (due to the high operating pressure).

Safety and Maintenance Experience

Ammonia plant safety has been the subject of considerable attention in the chemical process industry and a number of professional society symposia. American Standard Safety Requirements for the storage and handling of anhydrous ammonia have been established by the American Standards Association under the sponsorship of the Compressed Gas Association.

The construction of ammonia plants has become somewhat routine; we understand for example, that a major chemical company which normally carries out all its own plant design and construction, contracts out all ammonia plant construction on a turn-key basis to one of several firms who construct such plants. During several visits to industrial operations which included ammonia manufacturing plants, the comment was heard repeatedly that the operation and maintenance of the ammonia unit is routine and its portion of plant maintenance cost is very low. Repairs of leaking valves and other similar packing can generally be done without deactivating the component.

It is not possible to accurately project the maintenance and operations (M&O) performance of an ammonia heat rejection system from the M&O performance of an ammonia manufacturing plant. Since the ammonia tends not to foul or corrode the condenser and the condenser is the major source of present downtime in fossil and nuclear fueled power plants, there is a rationale for projecting a greater reliability for the ammonia system than for the conventional. The impact of plant availability on power cost is very significant; but the anticipated availability of commercial ammonia dry cooled systems can only be developed after demonstration experience has been obtained.

Economic Evaluation

An economic study was made to see if there is incentive to solve the technical aspects or demonstrate the technical feasibility of an ammonia cooling system, i.e. even if a wet/dry ammonia system can be made to work will it be economical enough to use? A computer optimization study on dry towers alone[4] suggested that the ammonia intermediate cooling system was a lower cost method of dry cooling than other methods (under the typical conditions of fuel pricing, penalties and demand chosen). For the wet/dry system, since no optimization was available, the method of comparison was to write design criteria for several different concepts (named in TABLE II) for the same site and for the same annual water use (about 20% of a fully evaporative system).[5] This study was based on the San Juan site in New Mexico, with fixed demand. Using these criteria, a design and cost estimate was performed by an independent architect engineering firm to obtain the estimated capital cost of a 500 MW_e plant cooling system.

TABLE II shows the capital cost estimates with escalation and contingency. The capital costs include the steam condenser, piping, fill and drain system, water quality control, cover gas, cooling towers, buildings, electrical, overhead and profit, and management.

TABLE III gives the operating costs of the cooling system. Credit is taken for the fuel savings when the system can be run more efficiently at less than the design back pressure. To make a comparison for the cost of the cooling system, the operating costs were capitalized on the basis of a fixed charge rate of 18% and added to the basic capital cost (neglecting escalation and contingency) and are shown in TABLE IV. This comparison shows that there is potential for producing a lower cost we/dry cooling system than current state-of-the-art systems. The one with the greatest potential cost savings is the metal-finned-tube tower with deluge using ammonia as an intermediate heat transfer fluid. The six million dollars difference between the baseline (integrated dry/wet) system and the ammonia cooling system represents a savings of approximately 18%.

Summary

Studies have been carried out on the feasibility and economic incentive to develop an advanced concept of wet/dry cooling for power plants. This advanced concept uses ammonia as an intermediate heat transport medium between the turbine exhaust steam and the cooling tower air, and uses water for augmentation by directly deluging the heat transfer surface in the tower during periods of high ambient temperature. For the selected coal-fired-plant-study-site, total capitalized (including operations costs) savings could be 12 dollars per installed kW. With this type of incentive, further technological development of the ammonia concept is warranted.

References

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TABLE I

Physical Properties of Selected Refrigerants at 150°F

ASHRAE Refrigerant Number	Chemical Name/ Formula	Saturation Pressure PSIG	Specific Vol. of Vapor V_g ft^3/lb	h_{fg}-Heat of Vaporization Btu/lb	$h_{fg}/\sqrt{V_g}$
R-717	Ammonia	420	0.675	416	506
R-22	$CHClF_2$	382	0.124	56.6	160
R-600a	Isobutane	128	0.619	119	151
R-114	$CClF_2$ $CClF_2$	94.9	0.293	45.9	85
R-718	Water (vapor)	-11.0	97.1	1010	102
R-718	Water (liq.)	0	0.0163	25(i.e. a temp. range of 25°F)	196

TABLE II

RESULTS OF CAPITAL COST ESTIMATES OF ALTERNATIVE HEAT REJECTION CONCEPTS FOR SAN JUAN UNIT 3 ($ THOUSANDS, 1976)

	Estimated Capital Cost	Escalation	Contingency	Total
Integrated Dry/Wet (Baseline)	$22,789	$5,638	$ 8,573	$37,000
Separate Dry/Wet	29,276	7,243	10,981	47,500
Metal Fin-Tube/Deluge	28,882	7,145	10,773	46,800
Plastic Tube/Deluge	24,311	6,014	9,075	39,400
Deluge/Ammonia Heat Transport	23,128	5,721	8,651	37,500

TABLE III

ESTIMATED ANNUAL OPERATING COSTS ($/YEAR)

	Circulation Pump Cost	Induced Draft Fan Cost	Reduced Back Pressure Savings	Water Treatment Cost	Deluge Pump Cost	Total Cost
Integrated Dry/Wet	628,000	1,228,000	-56,000	330,000	-0-	2,130,000
Separate Dry/Wet	967,000	1,312,000	-56,000	356,000	-0-	2,579,000
Deluge/Finned Tube	783,000	1,017,000	-230,000	130,000	13,000	1,712,000
Plastic Tube	650,000	598,000	-235,000	131,000	8,000	1,152,000
Ammonia	34,000	1,047,000	-220,000	75,000	25,000	962,000

TABLE IV

SUMMARY OF COMPARATIVE CAPITAL COSTS

	Basic Capital Cost	Capitalized Operating Cost	Comparable Capital Cost
Integrated dry/wet	$22,789,000	$11,836,000	$34,625,000
Separate dry/wet	29,276,000	14,330,000	43,606,000
Metal fin-tube/deluge	28,882,000	9,512,000	38,394,000
Plastic tube/deluge	24,344,000	6,400,000	30,744,000
Metal fin-tube/deluge/ammonia	23,152,000	5,342,000	28,494,000

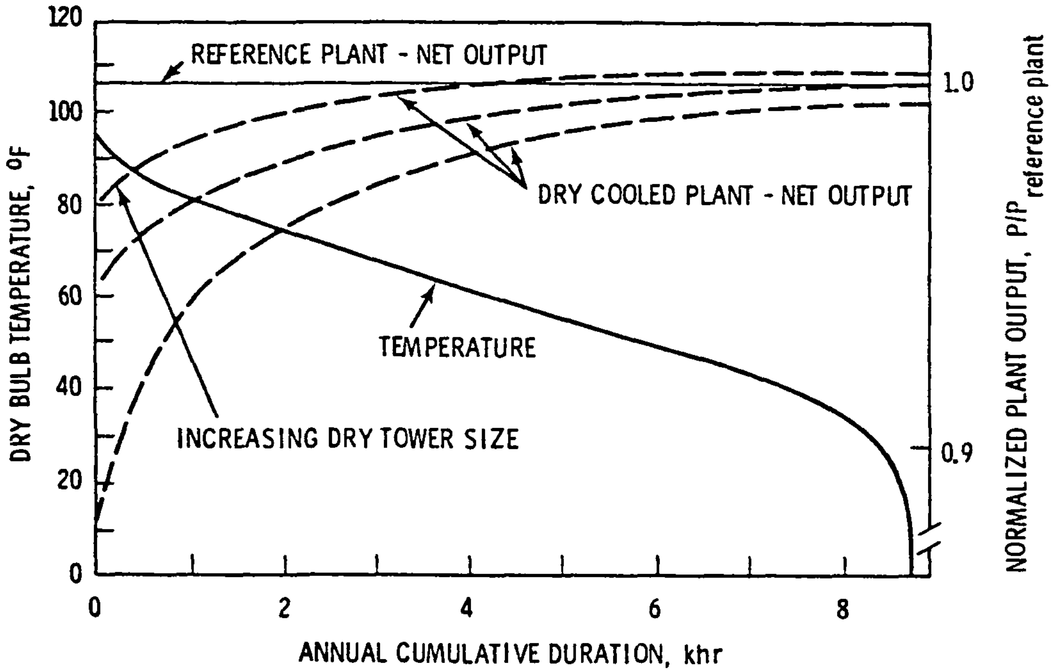

Figure 1. Relative Performance of a Dry Cooled Plant with Fixed Steam Source

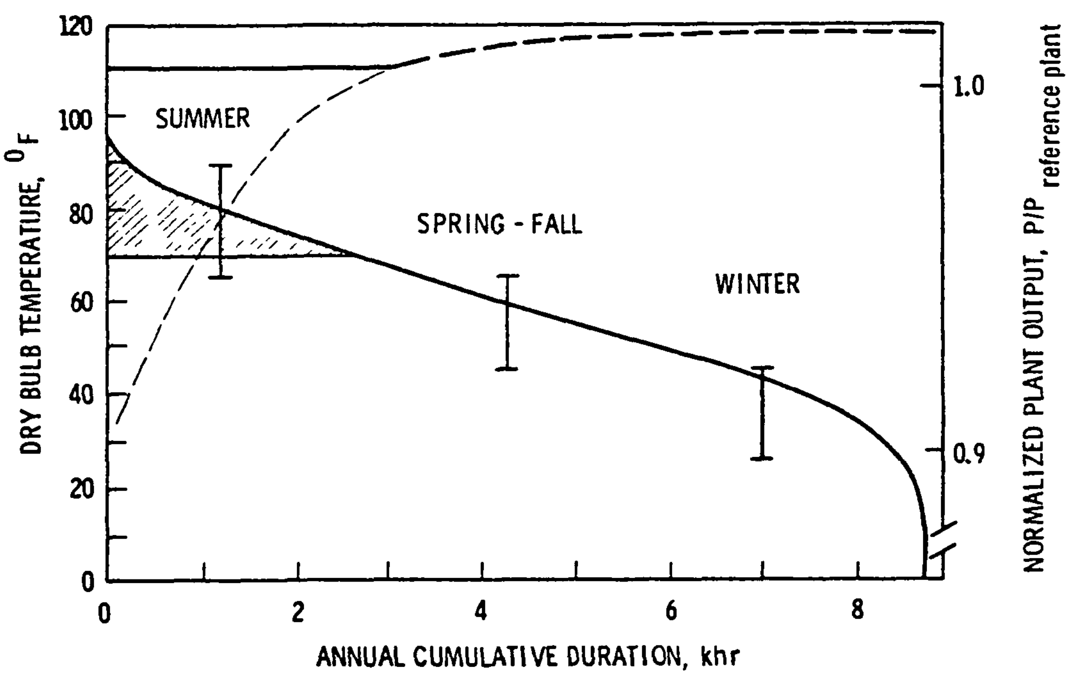

Figure 2. Wet Augmentation of Dry Cooling

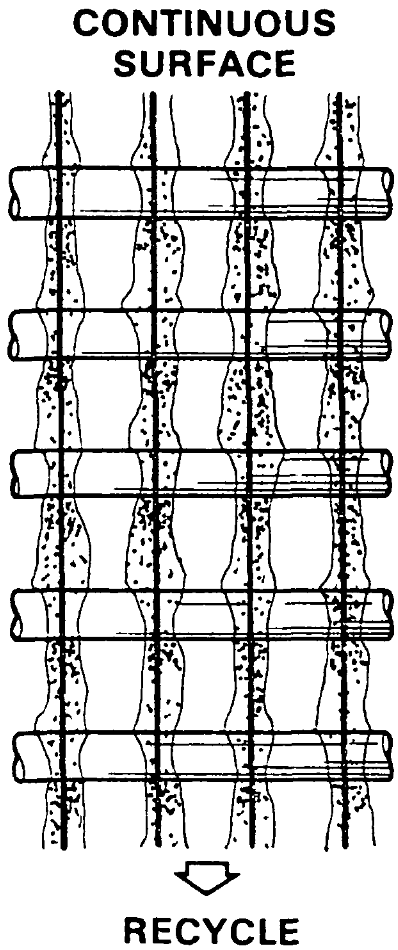

Figure 3. Deluge on Plate Fin

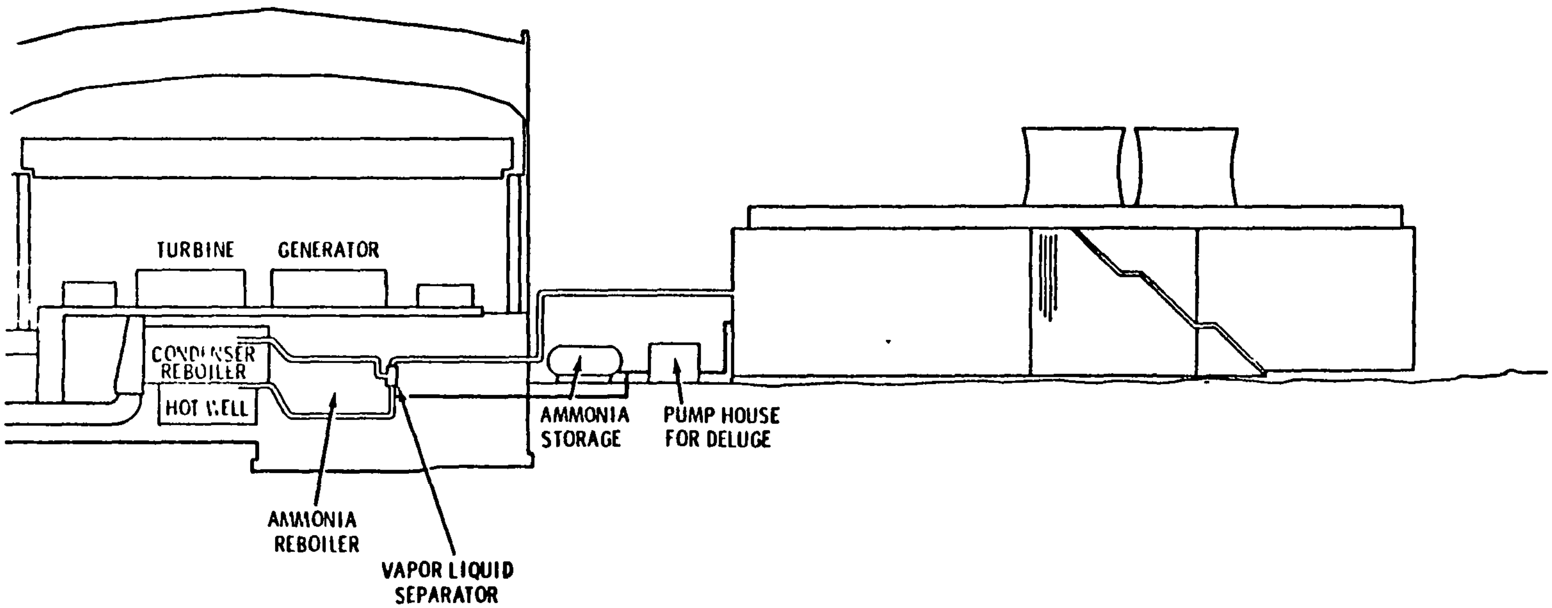

Figure 4. Layout of Steam Plant with Ammonia

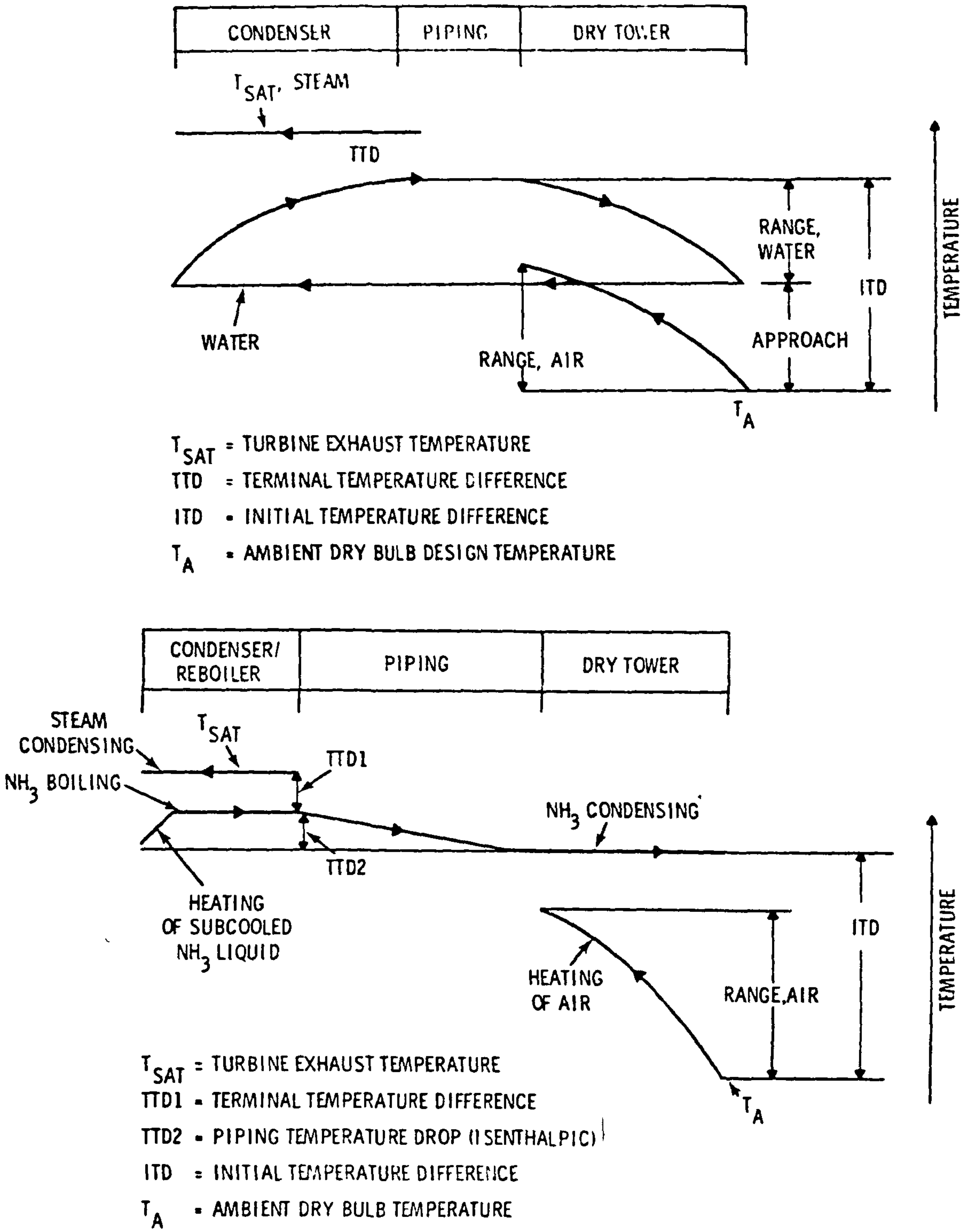

Figure 5. Comparison of Temperature Relationship for Conventional and Ammonia Coolant Dry Cooling Systems