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AEC Research and
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UC-81, Reactors-Power
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**evaluation of
heat rejection systems
for PL-3**

Contract No. AT[30-1]-2900
with U. S. Atomic Energy Commission
New York Operations Office

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ALCO PRODUCTS, INC.
NUCLEAR POWER ENGINEERING DEPARTMENT

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AEC Research and
Development Report
UC-81 Reactors Power
(Special Distribution)

EVALUATION OF
HEAT REJECTION SYSTEMS
FOR PL-3

By
C. J. Thurnau

Approved by:
G. E. Humphries, Project Engineer

Issued: March 1, 1962

Contract No. AT(30-1)-2900
with U. S. Atomic Energy Commission
New York Operations Office

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ABSTRACT

This reports an investigation of heat rejection systems for use in the PL-3 nuclear power plant, designed for placement at Byrd Station, Antarctica. The study concludes that the glycol-coupled surface condenser and air blast cooler combination appears to be suited for PL-3 plant requirements and operating conditions.

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1.0 SUMMARY

Low and medium power nuclear plants built to date utilize dissimilar systems for the heat rejection portion of their thermal cycles. This indicates differences of opinion as to what constitutes the best heat rejection system for cold region application. During Phase I of the PL-3 contract, Alco investigated and evaluated the results of design studies, performance tests, operating experience, and manufacturer's data in conjunction with the heat rejection systems of these plants to determine the optimum system for use in the PL-3 nuclear power plant which will be installed at Byrd Station, Antarctica.

Data from certain reports published by manufacturers of other nuclear power plants has been compiled and studied. From a study of these data and information from various other sources, it was concluded that the correct heat rejection system for the PL-3 nuclear power plant is the glycol-coupled surface condenser and air blast cooler combination. Some of the advantages of the glycol-coupled air blast cooler and surface condenser are as follows:

1. The system is inherently free from failure due to freezing.
2. The system operates with no automatic controls and minimal operator attention.
3. The system is a proven design backed by field operation.
4. The system requires no provisions for startup and responds to load changes with no freezing danger.
5. Core life can be significantly improved by taking advantage of low ambient temperatures without danger of freezing.

The report shows that most of the advantages of the glycol system are correspondingly disadvantages for the other systems under consideration. On the basis of these, the conclusion in favor of glycol coupled air blast coolers and surface condenser was made.

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2.0 INTRODUCTION

This report presents an investigation of heat rejection systems for use in the PL 3 nuclear power plant being designed by Alco Products, Inc., under U. S. Atomic Energy Commission contract AT(30-1)-2900, for placement at Byrd Station, Antarctica. This plant will be air-transported from McMurdo Sound to the inland station.

The Phase I study of PL 3 has allowed Alco to determine the optimum heat rejection system for use in the plant. Initial efforts involved a literature search and vendor contacts to obtain data on standard manufactured items of continuous and finned fluid-to-air heat exchange surfaces. On receipt of the above material, sample calculations were made to obtain values for basic system parameters. These parameters included air and fluid velocity, air and fluid pressure drop, overall heat transfer coefficient and tube bank depth. At the same time, the reports of the various nuclear power plant manufacturers were obtained and their contents were discussed, studied and evaluated. Their systems were closely studied to note usable design features for PL-3 consideration. This, then, was Alco's general method of approach to the problem of selecting the optimum heat rejection system for the PL-3 nuclear power plant.

In the report that follows, various heat rejection systems will be discussed and the results and conclusions will be presented.

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3.0 INVESTIGATIONS AND DATA

3.1 INTRODUCTION

One of the more common steam driven power generating systems in use today utilizes the steam condensing cycle as its basis. It is composed basically of the following components, energy source, steam generator, steam turbine, electric generator, heat rejection system, and feed pump. A diagram of the basic system is seen in Fig. 1.

Figure 1. Steam Condensing Cycle

A feature of the steam condensing cycle is the great reduction in make-up water required by the system. It is necessary to provide some sort of condensing system to recover the steam used to drive the turbine. The commonest system found in use is the surface condenser coupled to a source of cool fluid. This system uses a flow of cool fluid being pumped through the tube banks over which the condensing steam is passed. This cool fluid normally comes from a lake, river or other source. The PL 3 environment dictates that all waste heat must be ultimately dissipated to the atmosphere. This requires a source of cool fluid utilizing the Antarctic air to remove the waste heat from the system.

The heat rejection systems of the various low and medium power nuclear plants have been studied and analyzed in the preparation of this report.

The low and medium power nuclear plants built to date have utilized various systems for the heat rejection portion of their thermal cycles. The fact that these systems utilize dissimilar approaches reflects that there are obvious differences of opinion as to what constitutes the best heat rejection system for cold region application. The initial phase of the PL-3 contract consisted of study

and evaluation of the characteristics of the various low and medium power nuclear plants in operation or in process of construction. Phase I, then, has allowed Alco to investigate and evaluate the results of design studies, performance tests, operating experience and manufacturer's data and information in conjunction with the heat rejection systems of these plants.

Five main systems of heat rejection were studied in conjunction with Phase I of the PL-3 project and will be discussed in turn. They are as follows:

1. Glycol-coupled air blast cooler and surface condenser.
2. Direct air-steam condenser.
3. Direct air-steam condenser with condensate subcooling.
4. Direct contact condenser with air blast cooler.
5. Water-coupled air blast cooler and surface condenser.

3.2 GLYCOL-COUPLED AIR BLAST COOLER AND SURFACE CONDENSER

This system consists of the air blast cooler, surge tank, surface condenser, ethylene glycol circulating pump and interconnecting piping. A schematic diagram of the system is presented as Fig. 2.

The glycol solution is pumped through the air blast cooler, where its temperature is lowered. It then flows through the condenser tubes, where it acquires the heat from the condensing steam. Temperature control and vacuum in the condenser is maintained by regulating the number of running air blast cooler fans.

This system has been designed and built by Alco for the PM-2A installation at Camp Century, Greenland. Thus far, it is the only system to operate successfully in an Arctic location. This glycol system requires a minimum of operator attention during plant operation as well as a minimum of operating instrumentation. The most important feature of the system is its inherent resistance to failure due to freezing. At the present time, a 60 percent solution of ethylene glycol is being utilized in PM-2A. This solution gives the required protection against any possibility of freezing due to plant shutdown or control system failure. Other features include the ability to use lower temperature ambient air than is possible with other systems, the ability to start-up with no special provisions and the ability to respond to sudden load changes with no freezing danger. Since the 60 percent glycol solution remains fluid to low temperatures the building does not have to be heated. The control of the system is simple, and requires only the running of those fans required to obtain proper condenser vacuum.

A disadvantage of this system is the possible problem of glycol leakage into the condenser and contamination of the condensate. This problem is easily resolved and can be overcome by proper tube and tube sheet design.

3.3 DIRECT AIR STEAM CONDENSER

This system consists of the air cooled condenser, condensate pump and interconnecting piping. The schematic diagram of the system is shown below.

Figure 3. Direct Air-Steam Condenser

The steam is piped from the turbine exhaust to the inlet of the air-steam condenser, where it is condensed within tubes by the passage of cold air over the finned surfaces of the condenser tubes. The condensate is then drained to an external hotwell. The condensate is then removed from the hotwell and returned to plant use. An offtake air cooler section is provided at one end of the air blast cooler unit. This section is separate from the main condenser and consists of a finned tube section with its own separate louver system. Steam jet air ejectors pull the non-condensibles and any remaining uncondensed steam into this section where the steam is condensed and the uncondensed steam and the non-condensibles are removed through the air ejector system.

This system was designed for installation in the PM-1 and PM-3A plants. The system is protected against freezing by limiting air intake to the heat exchanger core by movable louvers, which are controlled automatically to maintain a set condenser pressure. A separate louver system on the air cooler section is actuated by a pressure drop across an orifice which meters the amount of steam passing into the section. This keeps the air cooler section under enough heat load to prevent freezing the air removal section. This system requires more instrumentation than the glycol coupled system and is in danger of freeze-up in the event of control system failure or sudden loss of plant load. Studies have been made concerning the freeze-up problem of the steam-to-air condensers; calculations supporting these studies are presented in Appendix A of this report. The assumptions made in these calculations will be defined and supported in the calculations.

An analysis of the use of lower inlet air temperatures has been made using the direct air-to-steam condenser system compared to the ethylene glycol coupled air blast cooler and surface condenser. On a mean annual temperature basis, it has been established that the use of a glycol system results in a reduction of needed core output of approximately 12% of 0°F ambient air temperature or below. The analysis showed that with a glycol system having an inlet temperature of 0°F or lower, the condenser may be operating at 2 in. Hg absolute for approximately 265 days during the year. This is based on Antarctic weather data for the year 1959 which has been made available to Alco. At this operating point, the glycol solution will be leaving the air blast coolers at approximately +50°F.

FIGURE 4. PERCENTAGE INCREASE OR DECREASE IN REACTOR POWER VS. EXHAUST PRESSURE

3.4 DIRECT AIR STEAM CONDENSER WITH CONDENSATE SUB-COOLING

The system consists of the steam-to-air condenser, condensate pump and interconnecting piping. The schematic diagram of the system is shown below.

Figure 5. Direct Air-Steam Condenser with Condensate Sub-Cooling

Steam from the turbine enters the condensing section of the condenser through the interconnecting steam line. After passing through the condensing section of the cooler, the condensate is passed through the sub-cooling section, where its temperature is lowered below its condensing point. The condensate is then drained to an outside hotwell and returned to the plant through the plant auxiliary heat exchangers. Condenser vacuum is maintained by keeping the air inlet temperature to the heat exchanger core at some preset value. The louver system is designed so that the air exhaust louvers and the air recirculation louvers work in unison. This insures that sufficient hot exhaust air is mixed with the cold ambient air to hold the preset mixed air temperature at the core entrance. This control system must be adjusted so that the core inlet temperature is maintained at such a level that tube temperatures are kept safely above

freezing. As in similar systems, freezing is the major problem faced during operation in a cold region. Another disadvantage of this and the system previously described is the long turbine steam exhaust line, which results in flow distribution problems, and higher turbine exhaust pressures. This system has been tested at SL-1, and proposed for use in the PL-1 and PL-2 nuclear power plants.

3.5 DIRECT CONTACT CONDENSER AND AIR BLAST COOLERS

This system consists of a direct contact condenser coupled with an air blast water cooler which has a recirculation system. The schematic diagram of the system is shown below.

Figure 6. Direct Contact at Condenser and Air Blast Coolers

This system was investigated by the Martin Company in conjunction with certain parametric studies performed on the PM-1 project. Steam enters the condenser from the turbine exhaust line, where it comes in contact with the water spray and is condensed. A portion of the condensate is then pumped back to the plant, while the remainder is recirculated through the air blast cooler where it is cooled and begins the cycle again.

The system has a three way control valve which diverts condensate to between the condenser and the circulating pump inlet. The cooling coil is equipped with a louver system which is interlocked with a temperature sensing system and automatically opened and closed as required. Thus, freezing protection afforded this system is like the PL-1 and PL-2, which has recirculation of hot exhaust air inside a building so that air inlet temperature at the air blast cooler core is kept at some safe, predetermined level above freezing. This is extremely important, because the entire system is filled with water and can freeze extremely rapidly with sudden loss of plant load. At the present time, there is no utilization of the system in a nuclear power plant.

3.6 WATER-COUPLED SURFACE CONDENSER AND AIR BLAST COOLERS

This system consists of a surface condenser, an air blast cooler, circulating pump and louver system. The schematic diagram of the system appears below.

Figure 7. Water-Coupled Surface Condenser and Air Blast Coolers

Steam enters the surface condenser from the turbine exhaust and is condensed on the tubes. The water in the tubes, which absorbs the heat from the condensing steam, is circulated to the air blast cooler, where the heat is transferred to the air through a fluid-to-air heat exchanger. A louver system controls the temperature of the cooling water in the system by recirculating warm air to be mixed with the cold incoming air.

Again, the main disadvantage of this system is the freezing problem connected with an unprotected water system. A definite advantage to this system is the increased heat transfer efficiency realized when using water in place of ethylene glycol solution. Plant auxiliary cooling would be accomplished by placing the auxiliary cooling heat exchangers in parallel with the main condenser. At the present time, there is no utilization of this system in a nuclear power plant.

3.7 OPERATING EXPERIENCE

Presently, only the ethylene glycol system, used at the PM-2A plant at Camp Century, Greenland, has a record of operation under Arctic conditions. The PM-1 air cooled condenser has been operated in the Climatic Laboratory, Elgin Air Force Base, Florida, at temperatures as low as -70°F and encountered problems with steam and air distribution which required design modifications.

The modifications made were reported to include the addition of baffling to insure correct air distribution and hence eliminate localized cold spots, and modifications in the design of the air removal system. Field operational experience, however, has not been logged on these modified units to date.

The PL-1 and PL-2 type condenser was tested at the Arco test site, but has had no extended operation or testing at extremely low temperatures. In view of this lack of operating experience at Arctic conditions, any system other than the glycol system will require extensive engineering analysis and testing to insure comparable reliability. Therefore, there is very limited assurance that these systems can be reliably operated in a plant with an environment similar to that anticipated for PL-3 where operator attention must be divided among other plant systems and cannot be concentrated on the condenser operation.

4.0 EVALUATION OF DATA AND CONCLUSIONS

The information gathered has been formalized as Table 1, which is found at the end of this section. For this study, Alco received information and data from various sources, many of which are manufacturers of this type of heat exchange equipment. The following is a list of vendors who were contacted and who responded with help for the project.

1. American-Standard, Inc.
2. Buffalo Forge Company
3. Trane Company
4. Griscom-Russell Company
5. Young Radiator Company

The information received from these concerns has been distributed throughout the report; no attempt to segregate each company's segment was made.

Evaluation of data in Table 1 shows these advantages for the glycol coupled condenser system:

1. The system is inherently free from failure due to freezing.
2. The system operates with no automatic controls and negligible operator attention.
3. The system is a proven design backed by field operation.
4. The system requires no provisions for startup and responds to load changes with no freezing danger.
5. Core life can be significantly improved by taking advantage of low ambient temperatures without danger of freezing.

These disadvantages are found in the glycol system.

1. Shipment of glycol is required.
2. Glycol leakage into condenser is possible, but the probability of this can be minimized by proper condenser tube and tube sheet construction.

Table 1 shows that most of the advantages for the glycol system are, correspondingly, disadvantages for the other systems studied. Based on the previous observations, it is concluded that a glycol system is the preferred system for application on the PL-3 nuclear power plant.

TABLE 1
COMPARISON OF HEAT REJECTION SYSTEMS

Item	System A	System B	System C	System D	System E
1. Description	Glycol-Coupled with Surface Condenser and Air Blast Coolers.	Direct Air-Cooled Condenser With No Subcooling.	Direct Air-Cooled Condenser With Subcooling.	Water-Coupled Direct Contact Condenser and Air Blast Coolers.	Water-Coupled Surface Condenser and Air Blast Coolers.
2. Present Application or Use	PM-2A	PM-1, PM-3A	PL-1, PL-2	None	None
3. Major Components	a)Surface Condenser b)Air Blast Coolers c)Glycol Circulating Pump d)Fans e)Condensate Pump	a)Air-Cooled Condensers b)Louver Assembly c)Fans d)Hotwell e)Condensate Pump	a)Air-Cooled Condensers b)Louver Assembly c)Fans d)Hotwell e)Condensate Pump	a)Direct Contact Condenser b)Air Blast Coolers c)Circulating Pump d)Fans e)Lower Assembly	a)Surface Condenser b)Air Blast Coolers c)Circulating Pump d)Fans e)Louver Assembly
4. Interconnecting Piping	a)Turbine Exhaust b)Glycol Coolant	a)Turbine Exhaust b)Vents and Drains	a)Turbine Exhaust b)Vents and Drains	a)Turbine Exhaust b)Water Coolant	a)Turbine Exhaust b)Water Coolant
5. Automatic Controls	None	Louver Controls	Louver Control	Louver Control	Louver Control
6. Manual Controls	Fan Operation	Fan Operation	Fan Operation	Fan Operation	Fan Operation
7. Danger of Condensate Contamination By Condenser Tube Leakage	Yes	No	No	No	No
8. Possibility of Excessive Air Leakage Into Condenser	Very Low	High	High	Very Low	Very Low
9. Requirements for Auxiliary Cooling	Intermediate Heat Exchanger	Separate Cooling Loop With Pumps and Heat Exchangers	None	None	None
10. Auxiliary Power	200 kw	160 kw	160 kw	200 kw	200 kw
11. Protection Against Freezing	None Required	a)Automatic Louver Controls b)Drainage	a)Automatic Louver Controls b)Drainage	a)Automatic Louver Controls b)Drainage	a)Automatic Louver Controls b)Drainage
12. Additional Protection Against Freezing Which Can Be Designed Into the System	a)Automatic Fan Shutoff at Very Low Glycol Temp. b)Automatic Pump Shutoff at Excessively Low Glycol Temp.	a)Automatic Fan Shutoff. b)Automatic Intake and Exhaust Louver Snap-Shut. c)Automatic Drainage. d)Automatic Heat Injection Into Building.	a)Automatic Fan Shutoff. b)Automatic Intake and Exhaust Louver Snap-Shut. c)Automatic Drainage. d)Automatic Heat Injection Into Building.	a)Automatic Fan Shutoff. b)Automatic Intake and Exhaust Louver Snap-Shut. c)Automatic Drainage. d)Automatic Heat Injection Into Building.	a)Automatic Fan Shutoff b)Automatic Intake and Exhaust Louver Snap-Shut. c)Automatic Drainage. d)Automatic Heat Injection Into Building.

TABLE 1 (CONT'D)

Item	System A	System B	System C	System D	System E
	Glycol-Coupled with Surface Condenser and Air Blast Coolers.	Direct Air-Cooled Condenser With No Subcooling.	Direct Air-Cooled Condenser With Subcooling	Water-Coupled Direct Contact Condenser and Air Blast Coolers.	Water-Coupled Surface Condenser and Air Blast Coolers.
13. Start-up Facilities Required	None	Bldg. Heating to Above 32°F.	Bldg. Heating to Above 32°F.	Bldg. Heating to Above 32°F.	Bldg. Heating to Above 32°F.
14. Auxiliary Start-up Power	60 kw	20 kw	20 kw	60 kw	60 kw
15. Ability to Operate at Low Condenser Pressure to Improve Annual Mean Cycle Efficiency	Can Operate Safely to -100°F and Condenser Pressure to 2" Hg absolute.	Limited to 8" Hg Absolute.	Limited to 32°F Ambient or 8" Hg Absolute	Limited to 32°F Ambient or 8" Hg Absolute.	Limited to 32°F Ambient or 8" Hg Absolute.
16. Reactor Power Based on 34°F Ambient	7.98 tMW	7.84 tMW	7.34 tMW	7.98 tMW	7.98 tMW
17. Estimated Reactor Power Based On Mean Annual Temperature	7.0 tMW	7.5 tMW	7.3 tMW	7.9 tMW	7.9 tMW
18. Equipment Cost Estimate	\$170,000	\$160,000	\$150,000	\$170,000	\$190,000
19. Equipment Weight Estimate, Tons	35	30	25	30	30
20. Air Lifts	3-1/2	3	2-1/2	3	3
21. Core Cost Savings Per Core	\$10,000	\$4,000	\$5,000	0	0
22. Ability To Absorb Load Transients With No Danger of Freezing	No Operator Attention Required	Depends On Proper Operation of Automatic Controls.	Depends on Proper Operation of Automatic Controls.	Depends on Proper Operation of Automatic Controls.	Depends on Proper Operation of Automatic Controls.
23. Engineering Effort Required to Develop Reliable System	Requires Optimization of Glycol Coupling, Heat Transfer Surfaces, and Fan Power.	a) Requires Optimization of Heat Transfer Surfaces and Fan Power. b) Requires careful analysis For Good Steam and Air Distribution. c) Requires Development for Fail-Safe Louver Control System. d) Requires Development of Automatic Building Heating System.	Same as System B.	Same as System B and, in Addition Requires Development of Direct Contact Condenser.	a) Requires Optimization of Water Coupling, Heat Transfer Surfaces, and Fan Power. b) Requires Development of Fail-Safe Louver System.

5.0 REFERENCES

1. "PM-1 Air-Cooled Condenser Test," Martin Nuclear Division, MND-M-2575, 1959.
2. "PL Condenser Evaluating Report," Combustion Engineering, Inc., CEND-139, June, 1961.

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APPENDIX A

CONDENSER COOLDOWN TIME

Condenser Cooldown Time

One of the areas of investigation during this study was that of the problem of air-steam condenser cooldown and freeze-up time. We have assumed a situation of a direct air-to-steam condenser with condensate subcooling for the theoretical analysis of the problem. The condenser is also assumed to be in an insulated building located in a polar region.

In making the following analysis, two conditions have been assumed. They are the following:

1. The cooler fans stop instantly and have no coast down time lag.
2. The louver system on the intake and outlet ductwork close instantly and seal with zero leakage of air.

The various values used in the equations which follow are:

θ_1 = Temperature of core in $^{\circ}\text{R}$.

C_1 = Heat capacitance of core which is a summation of the metal and water in the core.

U_1 = Heat transfer coefficient of the condenser.

Q_1 = Heat transferred from core to building.

θ_2 = Temperature of the room in $^{\circ}\text{R}$.

C_2 = Heat capacitance of the air in the building.

K = Rate of heat losses from the building. K includes the heat losses due to heat transport through closed louvers and conduction through building walls.

The derivation of the applicable equation is shown on the following pages. Figure 7, Condenser Cooldown Time, plots the results of this equation under three conditions; zero leakage, 250,000 Btu/hr louver leakage and 2,500,000 Btu/hr louver leakage.

In making the following analysis, certain assumptions are made. They are the following:

1. Fans stop circulating instantly.
2. Louvers are completely sealed.

Writing equations for the system

$$-C_1 \frac{d\theta_1}{dt} = Q_1 = U_1 (\theta_1 - \theta_2)$$

$$C_2 \frac{d\theta_2}{dt} = Q_1 - K = U_1 (\theta_1 - \theta_2) - K$$

Rewriting the equations

$$\frac{d\theta_1}{dt} + \frac{U_1}{C_1} \theta_1 - \frac{U_1}{C_1} \theta_2 = 0$$

$$\frac{d\theta_2}{dt} - \frac{U_1}{C_2} \theta_1 + \frac{U_1}{C_2} \theta_2 = \frac{-K}{C_2}$$

Using the integral transform method for solutions we write the equations as follows:

$$s \theta_1 - \theta_{1_0} + \frac{U_1}{C_1} \theta_1 - \frac{U_1}{C_1} \theta_2 = 0$$

$$s \theta_2 - \theta_{2o} - \frac{U_1}{C_2} \theta_1 + \frac{U_1}{C_2} \theta_2 = \frac{-K}{C_2 s}$$

$$(s + \frac{U_1}{C_1}) \theta_1 - \frac{U_1}{C_1} \theta_2 = \theta_{1o}$$

$$-\frac{U_1}{C_2} \theta_1 + (s + \frac{U_1}{C_2}) \theta_2 = \theta_{2o} - \frac{K}{C_2 s}$$

Solving for θ_2 and substituting

$$\theta_2 = \frac{\theta_{2o} - \frac{K}{C_2 s} + \frac{U_1}{C_2} \theta_1}{(s + \frac{U_1}{C_2})}$$

$$(s + \frac{U_1}{C_1}) \theta_1 - \frac{\frac{U_1^2}{C_1 C_2} \theta_1}{(s + \frac{U_1}{C_2})} - \frac{\frac{U_1}{C_1} \theta_{2o}}{(s + \frac{U_1}{C_2})} + \frac{\frac{U_1}{C_1} K}{C_2 s (s + \frac{U_1}{C_2})} = \theta_{1o}$$

Solving for θ_1

$$\theta_1 = \frac{\theta_{1o}}{[s + (\frac{U_1}{C_1} + \frac{U_1}{C_2})]} + \frac{\frac{U_1}{C_2} \theta_{1o} + \frac{U_1}{C_2} \theta_{2o}}{s [s + (\frac{U_1}{C_1} + \frac{U_1}{C_2})]} - \frac{\frac{U_1}{C_1} K}{C_2 s^2 [s + (\frac{U_1}{C_1} + \frac{U_1}{C_2})]}$$

For simplicity

$$\text{Let } \frac{U_1}{C_1} + \frac{U_1}{C_2} = \alpha$$

$$\theta_{1o} = a$$

$$\frac{U_1}{C_2} \theta_{1o} + \frac{U_1}{C_1} \theta_{2o} = b$$

$$-\frac{U_1 K}{C_1 C_2} = c$$

$$\theta_1 = \frac{a}{s + \alpha} + \frac{b}{s (s + \alpha)} + \frac{c}{s^2 (s + \alpha)}$$

Through manipulation this becomes

$$\theta_1 = (a - \frac{b}{\alpha} + \frac{c}{\alpha^2}) \frac{1}{s + \alpha} + (\frac{b}{\alpha} - \frac{c}{\alpha^2}) \frac{1}{s} + \frac{c}{\alpha} (\frac{1}{s^2})$$

This reduces to

$$\theta_1 = e^{-\alpha t} (a - \frac{b}{\alpha} + \frac{c}{\alpha^2}) + \frac{c}{\alpha} t + (\frac{b}{\alpha} + \frac{c}{\alpha^2})$$

Evaluation of Constants

The constants were evaluated using available data and are as follows.
(Numerical work is shown on following sheet)

$$C_1 = 2380 \text{ Btu/}^\circ\text{F}$$

$$U_1 = 94800 \text{ Btu/hr } ^\circ\text{F}$$

$$C_2 = 500 \text{ Btu/}^\circ\text{F}$$

$$K = 23100 \text{ Btu/hr}$$

$$\alpha = 237 \text{ 1/hr}$$

$$\therefore a - \frac{b}{\alpha} + \frac{c}{\alpha^2} = 14 \text{ } ^\circ\text{R}$$

$$\frac{c}{\alpha} = 10 \text{ } ^\circ\text{R/hr}$$

$$\frac{b}{\alpha} - \frac{c}{\alpha^2} = 586 \text{ } ^\circ\text{R}$$

$$\therefore \theta_1 = 14 e^{-237t} = 10t + 586$$

The results are plotted on Fig. 7.

1. Heat capacity of 2 air blast cooler skids (PL-2 design)

- a) Weight of steel = 3000 lb
- b) Weight of aluminum = 3000 lb
- c) Weight of water = 200 lb

a) Heat capacity of steel = $6000 \times 0.11 = 660 \text{ Btu/}^{\circ}\text{F}$

b) Heat capacity of aluminum = $6000 \times 0.22 = 1320 \text{ Btu/}^{\circ}\text{F}$

c) Heat capacity of water = $400 \text{ Btu/}^{\circ}\text{F}$
Total $= \frac{2380 \text{ Btu/}^{\circ}\text{F}}$

$C_1 = 2380 \text{ Btu/}^{\circ}\text{F}$

2. Area of Tubes and Fins

4 ft² per linear foot

linear feet = $245 \times 25 = 5900 \text{ ft/skid}$

area = $11800 \times 4 = 47,200 \text{ ft}^2$

assume $U \approx 2 \text{ Btu/hr ft}^2 \text{ }^{\circ}\text{F}$

$U_1 = 2 \times 47,200 = 94800 \text{ Btu/hr }^{\circ}\text{F}$

$U_1 = 94800 \text{ Btu/hr }^{\circ}\text{F}$

3. Capacitance of Air Volume in Building

Building = $20 \times 70 \times 14 = 29600 \text{ ft}^3$

$\rho_{\text{air}} = .07 \text{ lb/ft}^3$

$C_2 = (.24) (.07) (29600) \approx 500 \text{ Btu/}^{\circ}\text{F}$

$C_2 = 500 \text{ Btu/}^{\circ}\text{F}$

4. Heat Loss From Building

$$\text{Area of building} = 2 (20 \times 70) + 2 (14 \times 70)$$

$$\text{Area} = 4620 \text{ ft}^2$$

$$u = 0.1 \text{ Btu/hr } ^\circ\text{F ft}^2$$

$$UA = 462 \text{ Btu/hr } ^\circ\text{F}$$

$$K = UA \quad t = 462 \times 50 = 23100 \text{ Btu/hr}$$

$K = 23,100 \text{ Btu/hr}$

Interpretation of Results

Air-steam systems require that up to 70% of the air to be recirculated to avoid freezing during actual operation. This analysis is based on a 70% recirculation of air during operation.

Figure 7, Condenser Cooldown Time, has three graphs plotted on it. The first, zero leakage, shows that for an assumption of zero leakage of air through the closed louver system it will require approximately 9-1/2 hr to freeze the condensate in the condenser. Looking at a more reasonable assumption, that of 250,000 Btu/hr leakage, it is shown that freeze-up time will occur at about 1 hr from start. The assumption here is that the louvers will not close perfectly tight. Our last assumption is that there is a 2,500,000 Btu/hr leakage rate. Evaluation of the equation shows that for this rate of air loss freeze-up will occur in about 8 minutes. This assumption takes into consideration the fact that the louvers may leak excessively. Calculations, then, show that the freeze-up time of the condenser is actually between 8 min and 1 hr for normal operation and small louver gaps in the closed position. Louver leakage may be defined as that air leakage past the sealing strips on each edge of mating louvers.

In the event of a louver control system malfunction, assuming 70% recirculation of air and fan coast down, it has been calculated that freeze-up would occur within 1 min during actual operation.

Therefore, it cannot be assumed that any reasonable degree of reliability exists, even with a high percentage of recirculation of air, for any system which requires regulation of air flow by control equipment.

FIGURE 8. CONDENSER COOLDOWN TIME TEMPERATURE VS. TIME