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The work reported here is being conducted as one part of the Lawrence Berkeley Laboratory program on the solar heating and cooling of buildings. This program presently includes three major efforts. First is the design, fabrication, and testing of a solid-state electronic controller for operating combined solar heating and cooling systems according to algorithms that minimize the use of auxiliary energy by such systems. To test this controller, an experimental solar heating and cooling system has been fabricated at Lawrence Berkeley Laboratory. A schematic of that experimental system is shown in Figure 1.

The second major part of the LBL program is the establishment of a network of insolation measurement stations in northern and central California. This work is being conducted in cooperation with Pacific Gas and Electric Company, whose service area includes most of California north of Los Angeles.

The third part of the program, and the subject of this paper, is the design, fabrication, and testing of a solar-driven air conditioner to provide the cooling for the experimental system. The generator coil at the right in Figure 1 is the point of connection to the remainder of the experimental system.

The design of this air conditioner has been guided by the operating parameters of the experimental system. First, the system is intended to test control algorithms for residential systems, so the cooling capacity of the air conditioner was chosen to be three tons. The heat source for the unit is water either directly from the PPG solar collectors or indirectly via the storage tank, so the temperature available to heat the generator is assumed to be less than 212°F. Actually, by slightly over-pressuring the system, this limit could be increased to about 230°F, but that is not feasible with the experimental system as now fabricated. We have decided to adopt as a further design constraint the assumption that only dry air cooling of the condenser and absorber (Figure 2) will be used. Thus significantly higher temperatures will occur at the condenser and absorber than if a wet cooling tower were used.

As has been discussed in other papers presented at this meeting, the combination of low generator temperature and high condenser/absorber temperatures can prevent operation of an absorption refrigeration cycle. For a given temperature, T_0, of the condenser and absorber, and a required temperature for the evaporator, T_E, there is a cut-off temperature for the generator below which operation ceases. This phenomena is represented in Figure 3, which shows the variation with generator temperature of the coefficient of performance of an ammonia-water absorption cycle as calculated with and without the assumption of heat recovery in the solution loop. An approximate expression for the generator cut-off temperature is $T_0T_E/(2T_E-T_0)$, which for the conditions shown (T_0 = 100°F, T_E = 45°F) has the value 168.3°F. It is seen that the conditions we have assumed for the design of the unit put us not far from the edge of this cut-off. Thus the performance of the unit depends sensitively upon the temperature of the solar heated water and the temperatures of the condenser and absorber.

The constraint on the temperature of the solar heated water supplied to the generator is well known to all those who have worked with flat-plate collectors. Performance is limited both by the declining efficiency of the collectors at high temperatures, and by the boiling point of water. The use of advanced technology collectors (such as the Corning or Owens-Illinois collectors) with a high boiling point working fluid would remove this constraint, but this is not now economically feasible. For the present-day state-of-the-art collectors, the temperature of the water to heat the generator is limited to about 230°F under the best possible conditions. Lower temperatures will be typical and must be designed for.

The constraint on the temperatures of the condenser and absorber is not as clear-cut as the generator constraint. The solar cooling demonstration projects now operating (or being planned) utilize wet evaporative cooling towers to remove heat from the condenser and absorber (or condensers, in the case of rankine units). At least for large commercial or industrial buildings, this is certainly the right thing to do because one is then dissipating heat against the wet bulb temperature of the air, which is usually well below the dry bulb temperature, and the constraint of the cut-off is significantly eased. However, as was discussed at length in the working session on absorption systems, it will probably never be possible to use wet cooling towers for widespread residential application. The reasons for this include the great demand for water that widespread use of wet towers would create, the problem of loading the urban atmosphere with water vapor, and, most important, the problem of maintenance of the wet cooling towers. Wet cooling towers demand significant routine maintenance, and while this is easy to provide in a large building that has a plant engineer already on the staff, this sort of maintenance is beyond what it can be expected that homeowners will perform themselves or will pay to have done for them. This leads to the conclusion that solar cooling units intended for residential use must use dry air cooling, even though this introduces difficult design problems.

What values for the temperatures of the condenser and absorber should be assumed for the design of an air cooled unit? A typical value used for the design point of a vapor compression unit that uses air cooling is a condensing temperature of 125°F, at an outside dry bulb temperature of 95°F (ARI standard condition). This value of T_0 = 125°F represents good design practice and is supported by decades of experience in the industry in the design of economically competitive air cooled units. However a value of T_0 this high makes the design of a solar driven unit essentially impossible, so this value must be reduced by some means. A few possibilities come to mind. First, we should reconsider how much heat exchange area for the air cooling we can afford to buy. Since increasing this area improves the cooling obtained from the unit for a certain heat input to the generator, there is a trade-off between the area of solar collectors in a system and the size of the air cooler. Thus the cost of collectors must be considered in deciding how large an air cooler we can afford and thus how close we can approach the ambient air temperature.

Even a close approach to ambient air temperature will not help on those days when the dry bulb air temperature goes well above 100°F. However, we may be able to design systems that use the auxiliary heat source of the solar heating and cooling system (perhaps a gas flame) to produce the high generator temperature required to keep the unit operating on those very hot days.

A further strategy might be to run the cooling unit only at night, when the dry bulb temperature of the ambient air is lower. One would have to store heat from the solar collectors during the day, run the cooling unit during the night with the stored heat, and store the cold in a cold water tank for use in cooling the residence during the following day. A disadvantage of such a scheme is the larger number of temperature drops at heat exchange surfaces.

These stratagems to obtain slightly lower values of T_0 for the operation of the cooling unit do not fully convince us that it is really possible to operate solar driven cooling units with air cooling in practical applications. However these considerations do motivate us to seek experimental data on the operation of absorption cycles operating close to cut-off. The data we seek should aid in deciding upon the feasibility or infeasibility of such air-cooled, solar-driven units.

An ammonia-water absorption cycle was chosen for our experiments for a number of reasons. Of the many absorption pairs that have been studied, only ammonia-water and water-lithium bromide have been widely used. There exist extensive operating experience and detailed thermodynamic data for these two pairs. Of these two pairs, ammonia-water is more suitable for an air-cooled unit. First, at the same condensing temperatures, the refrigerant vapor in an ammonia-water unit is 200 times more dense than the vapor in a water-lithium bromide unit. This makes possible the design of air-cooled components of reasonable size. Furthermore, the ammonia-water unit does not have the crystallization danger that must be avoided in operation of a water-lithium bromide unit. However it must be added that ammonia does have significant disadvantages. Ammonia is hazardous to health and must not be allowed in contact with the air system of the house. It is also corrosive to many materials that otherwise would be desirable for construction of the unit. Even though these drawbacks make it questionable whether ammonia-water units are likely to be widely used in residences, for the purposes of our experimental program ammonia-water seems the best choice for now.

It was decided to obtain a gas-fired, air cooled ammonia-water absorption chiller as a starting point for fabrication of a solar-driven unit. The unit obtained is an Arkla model ACB-60, which has a rated capacity of 5 tons.

The circuit of this unit in its gas-fired configuration is shown in Figure 4. The modifications that must be made to this unit to convert to solar operation are more drastic than would be the modifications of a water-lithium bromide unit. The gas-fired ammonia-water unit uses the high temperatures available with a gas flame to produce a temperature in the generator of about 325°F, which leads to a concentration of ammonia in the solution leaving the generator (the strong absorbent) of about 12%. Because of this very low concentration (relative to that produced in the solar driven unit), the gas-driven unit can use a solution-cooled absorber to preheat the solution (weak absorbent) entering the generator. This is not possible in the solar driven configuration.

Three major modifications were necessary to the gas-driven unit. Most obviously, the gas-fired generator had to be replaced by a water heated generator. This required replacement of the generator rather than just modification. Second, because the temperatures available in the generator do not allow large changes in the ammonia concentration of the solution passing through the generator, more solution must be pumped for each pound of refrigerant that is to be generated. Thus the solution pump in the unit must be replaced by a pump with three to five times the original capacity. Third, because the solution-cooled absorber will no longer be effective in preheating the solution entering the generator, a liquid-liquid heat exchanger must be added. When these modifications are made to the gas-fired unit, the unit shown in Figure 5 is obtained.

The state points shown for the solar-driven unit in Figure 5 have been calculated by a rather naive program that does not carefully treat all the temperature, pressure, and concentration drops that occur in the system. However, the values shown do indicate the regime of operation under which our experiments will be conducted. The solution-cooled absorber will be retained in the unit, even though we expect it will be rather ineffective. The use of the solution to cool the rectifier may not be necessary because the temperature of the top of the generator is low enough to produce a vapor of nearly pure ammonia without further rectification. Thus we may use the bypass shown by a dotted line. Note that the difference in concentrations of the strong and weak absorbents is rather small, from 52.1% to 47.5%. This is a symptom of operating close to the point of cut-off, and it is the behavior of the unit with these small concentration differences that will be investigated experimentally.

Most of our design effort thus far has been directed toward the generator. We have examined a number of possible designs, and have tried to select that design that offers the lowest possible concentration of ammonia in the solution leaving the generator (the strong absorbent) for a certain temperature of solar-heated water. This closeness of approach to the minimum possible concentration in the strong absorbent is needed to keep the cut-off point as low as is possible. We have decided upon a packed tower type of distillation column as the best means of achieving this low concentration. This type of column is commonly used for processing small flow streams in the chemical industry. The unit we have designed is shown in Figure 6. Solution entering the generator first goes to a distribution pan at the top of the column, through which the solution drips onto the packing. The packing extends throughout the height of the column and serves to break up downcoming streams of solution into drops, and to bring the solution into good contact with vapor rising up the column. The packing also aids in distributing the solution over the tubing that carries the solar-heated water through the generator. After passing through the packing and over the coils, the solution, which is now the strong absorbent, is collected and brought up through the column in a tube that serves to exchange some of the heat of the strong absorbent to the solution dripping down through the packing. The strong absorbent then leaves the generator. If necessary, the ammonia vapor generated is rectified in a solution-cooled unit mounted on the top of the generator, with gravity return of the condensate into the column.

To minimize the temperature drop from the solar-heated water to the solution passing through the packing, the coils are made from Linde Hi-Flux tubing. This tubing has a special porous outer surface that provides nucleation centers for bubble formation, and thus allows boiling to take place with a small temperature drop between the tubing surface and the bulk of the fluid. At a boiling heat flux of 2,200 Btu/ft^2-hr, the temperature drop with the Hi-Flux tubing is only 7°F, from the tubing to the fluid, rather than about 20°F with smooth surface tubing. The tubing was more difficult to bend than the uncoated tubing (SA 214, 0.75 inch O.D.) and a small amount of the coating flaked off. The coils wound from this tubing, and the generator shell, are shown in Figure 7.

The packing used in the column is 5/8 inch Pall ring packing fabricated from mild steel, shown in Figure 8. This is a standard commercial packing. The design of holes and projections is intended to give a very high amount of surface area per unit volume, and to help break up streams of liquid to promote contact with the rising vapor.

Following final assembly of the absorption unit, we will undertake a program of measurement of the COP and cooling capacity as a function of temperatures of the solar-heated water and the ambient air temperature entering the air-cooled absorber and condenser. When the unit has achieved satisfactory operation, it will be used as part of the combined heating and cooling system.

ACKNOWLEDGEMENT

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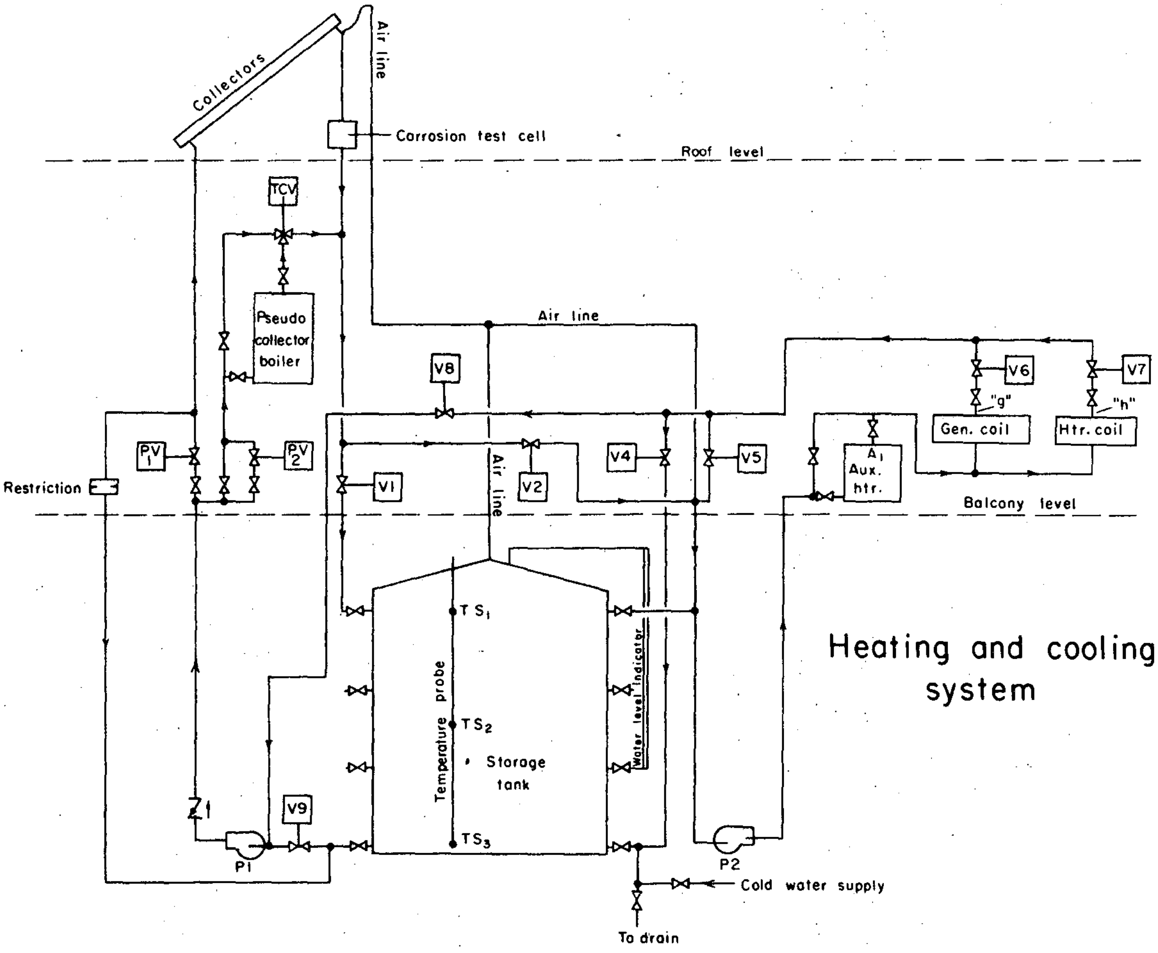

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Figure 1. The experimental solar heating and cooling system built at LBL to test the performance of solid-state control circuits. The ammonia-water air conditioner will provide the cooling function of this system.

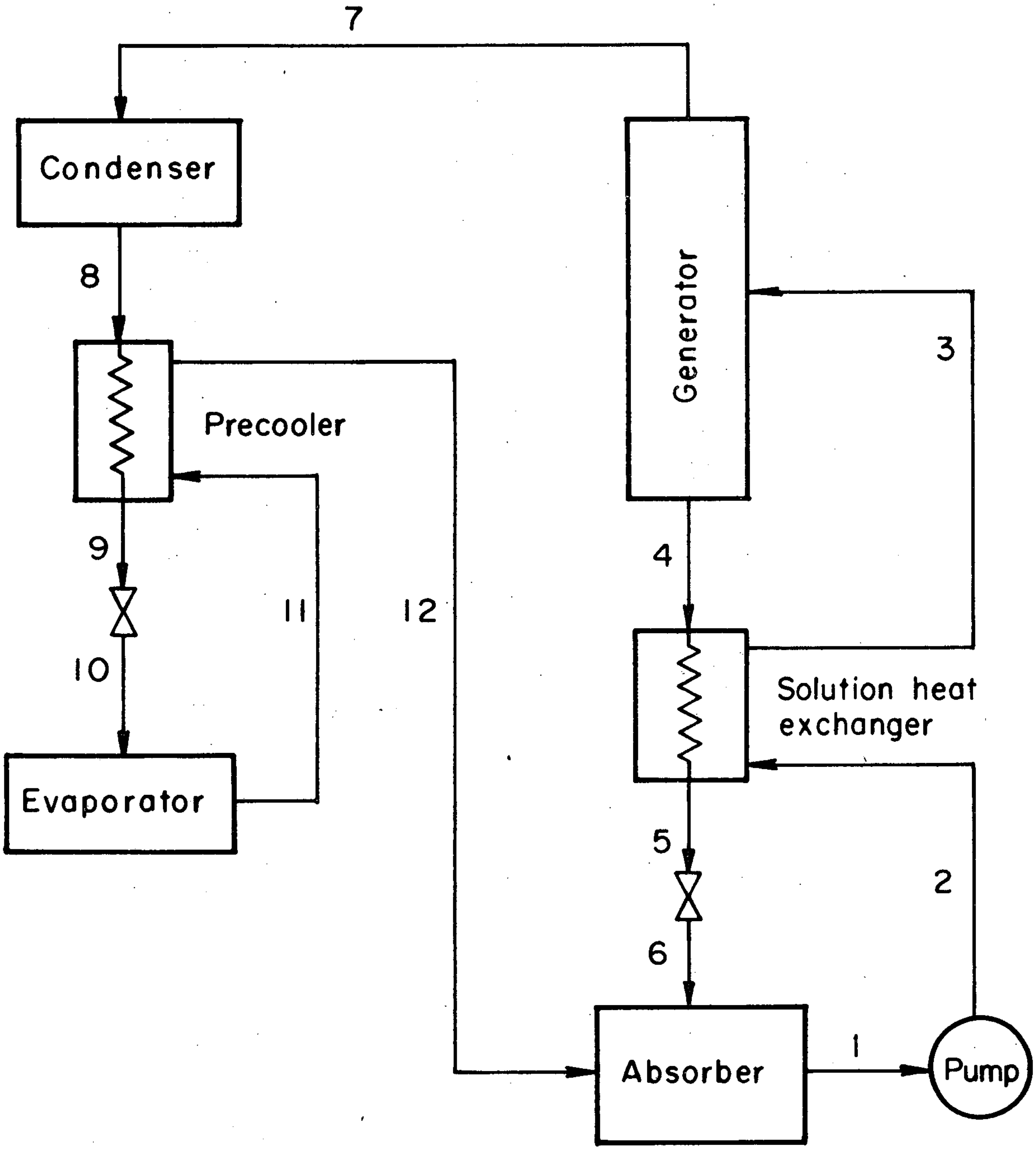

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Figure 2. Simple schematic of a single-stage, continuous-operation ammonia-water absorption air conditioner.

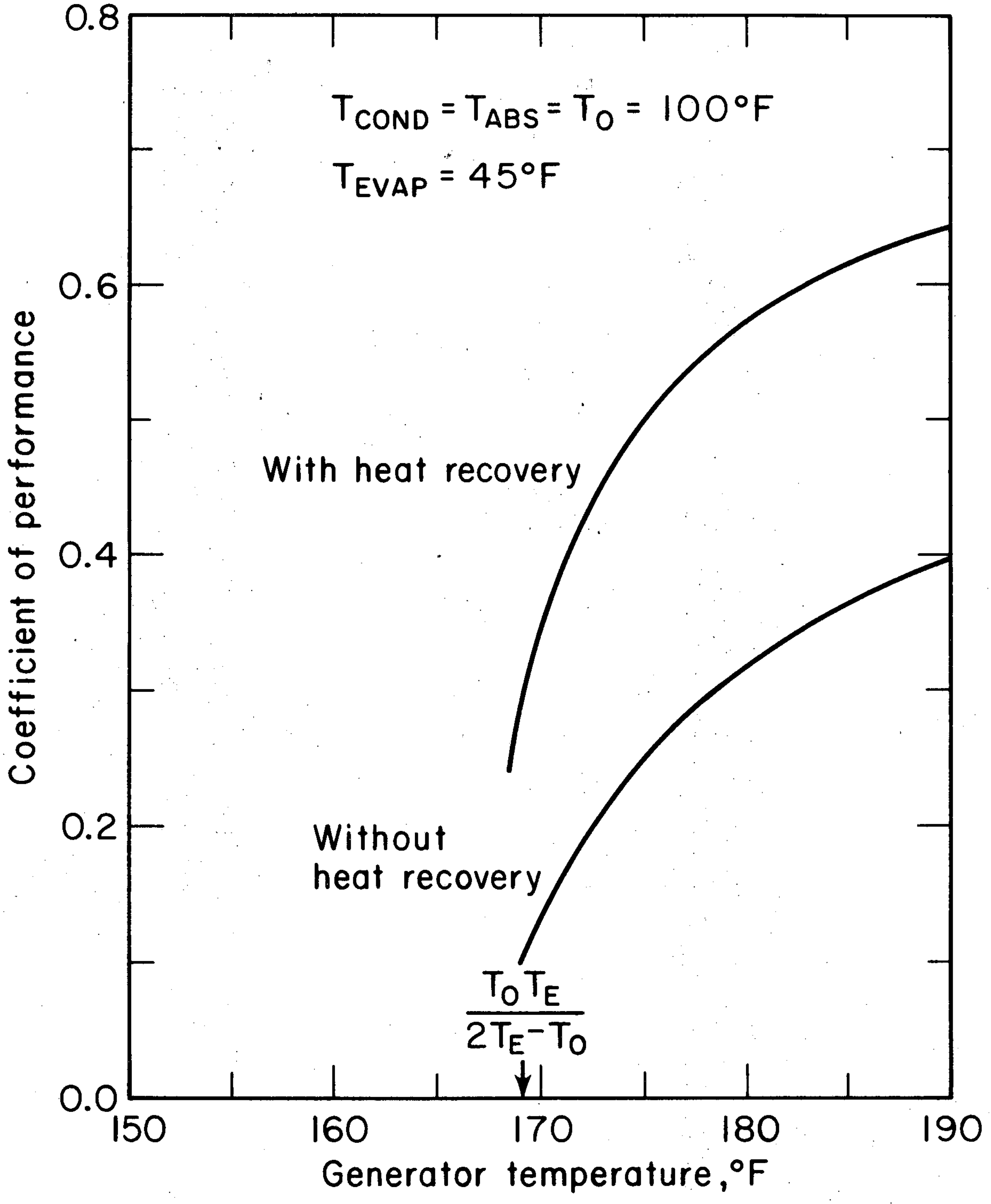

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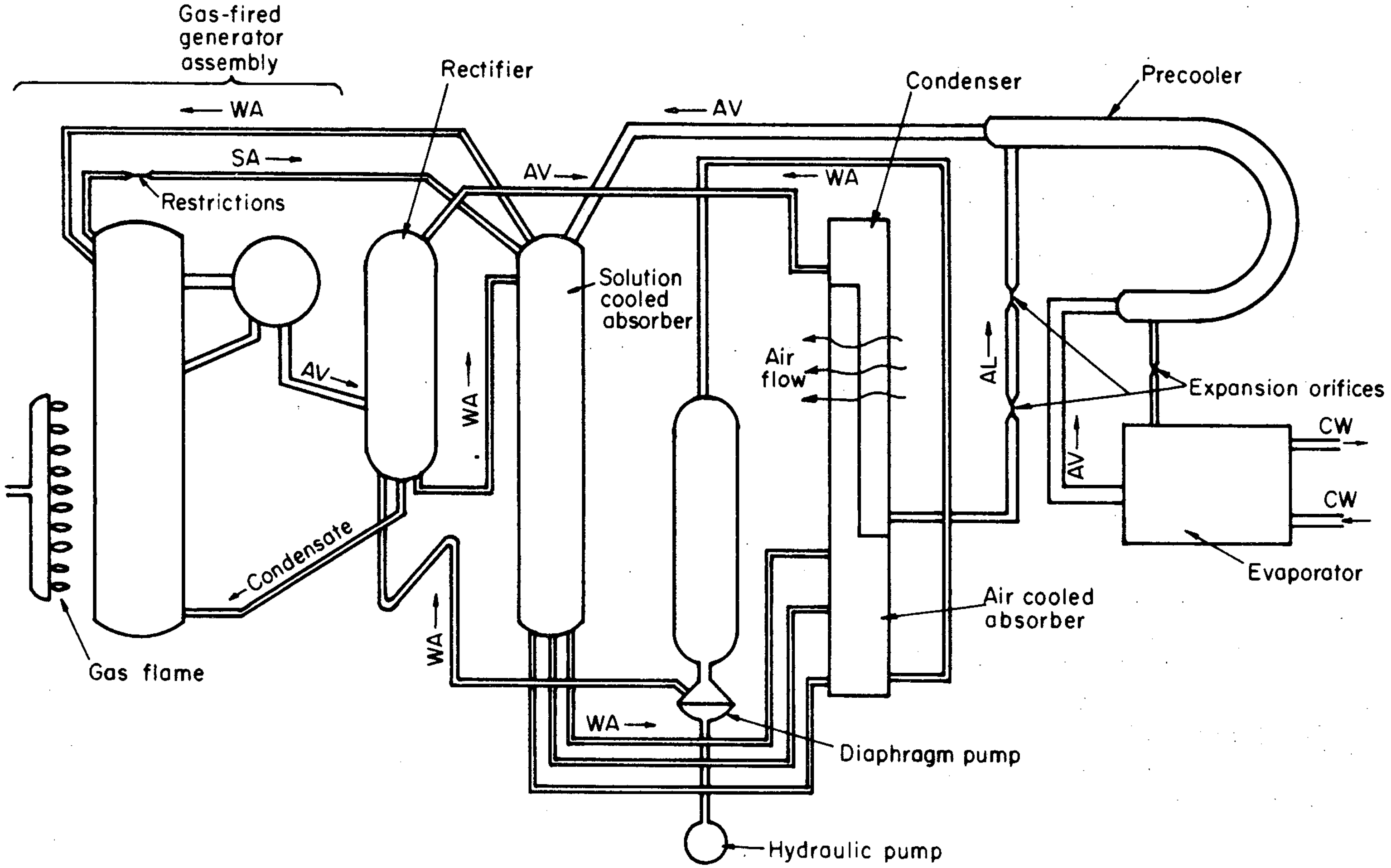
Figure 3. Calculated performance of an ammonia-water absorption cycle as a function of generator temperature, with and without heat recovery in the solution loop by heat exchangers.



XBL753-2463

Figure 4. Schematic of the absorption chiller (Arkla ACB-60) in its original, gas-fired configuration. WA = Weak Absorbent, SA = Strong Absorbent, AV = Ammonia Vapor, AL = Ammonia Liquid, CW = Chilled Water.

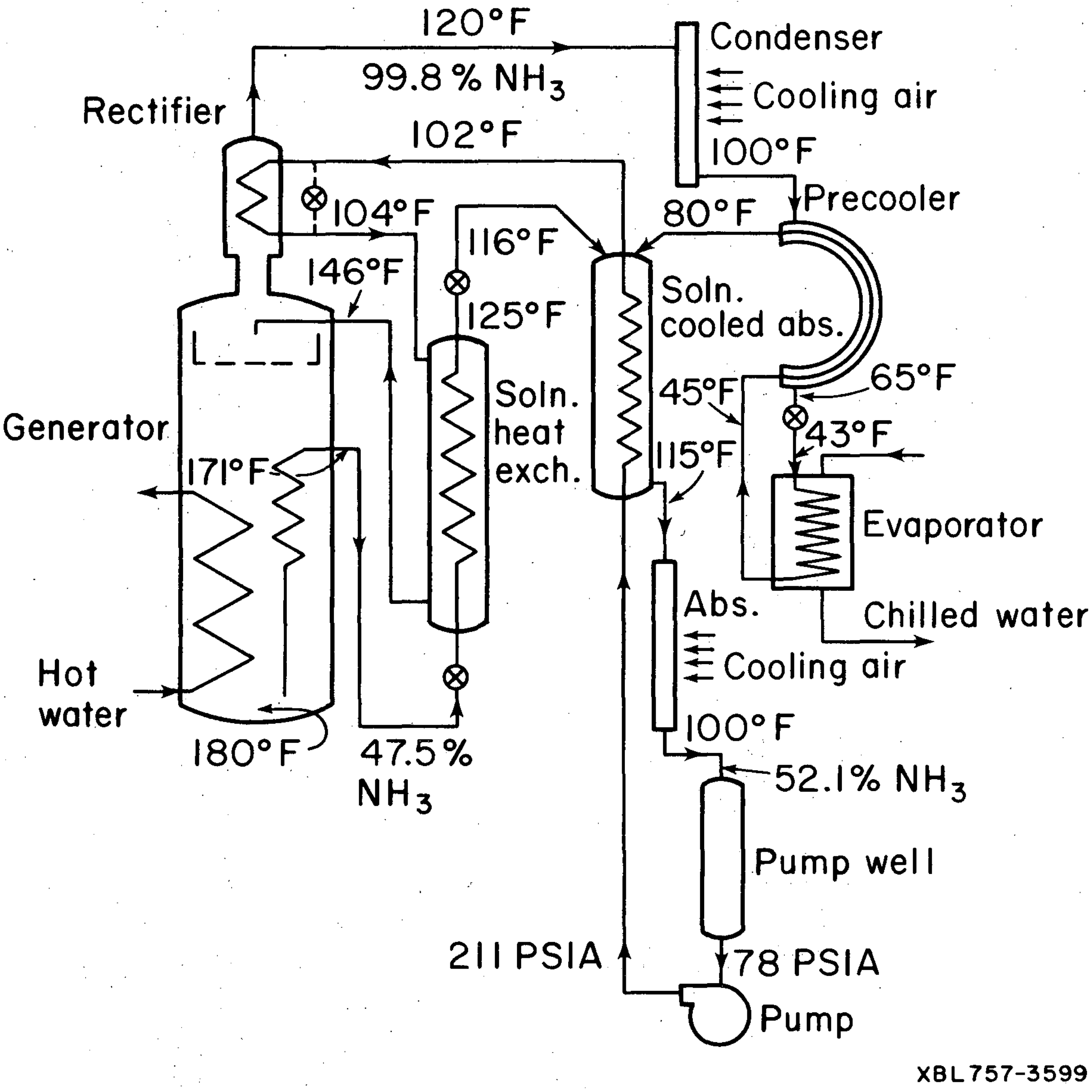


Figure 5. Schematic of the absorption chiller as modified for solar operation. The state points are given as calculated by the program COPER.

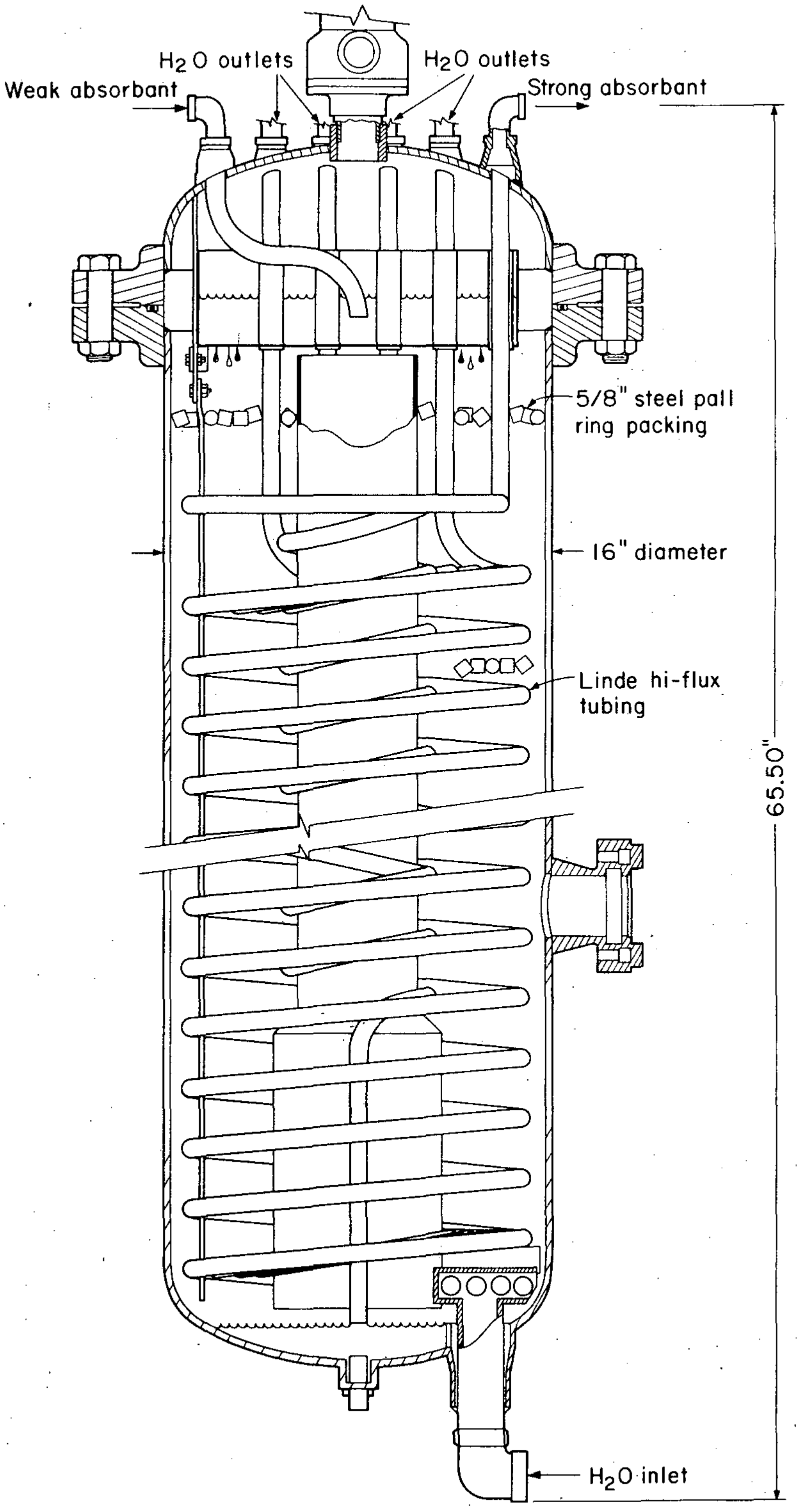


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Figure 6. The generator designed for operation with solar heated water. The Pall ring packing extends from the liquid distribution pan to the bottom layer of coils.

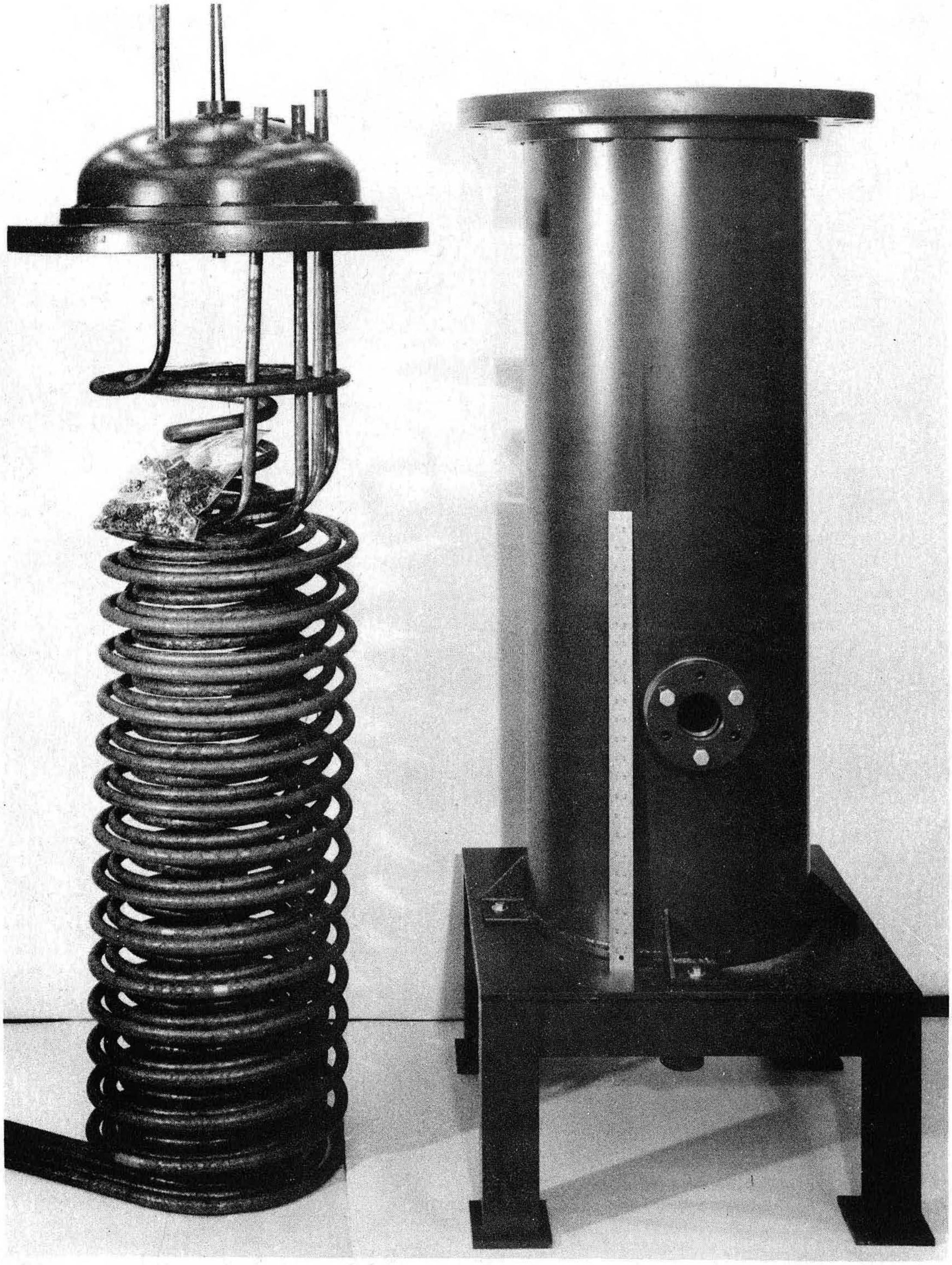

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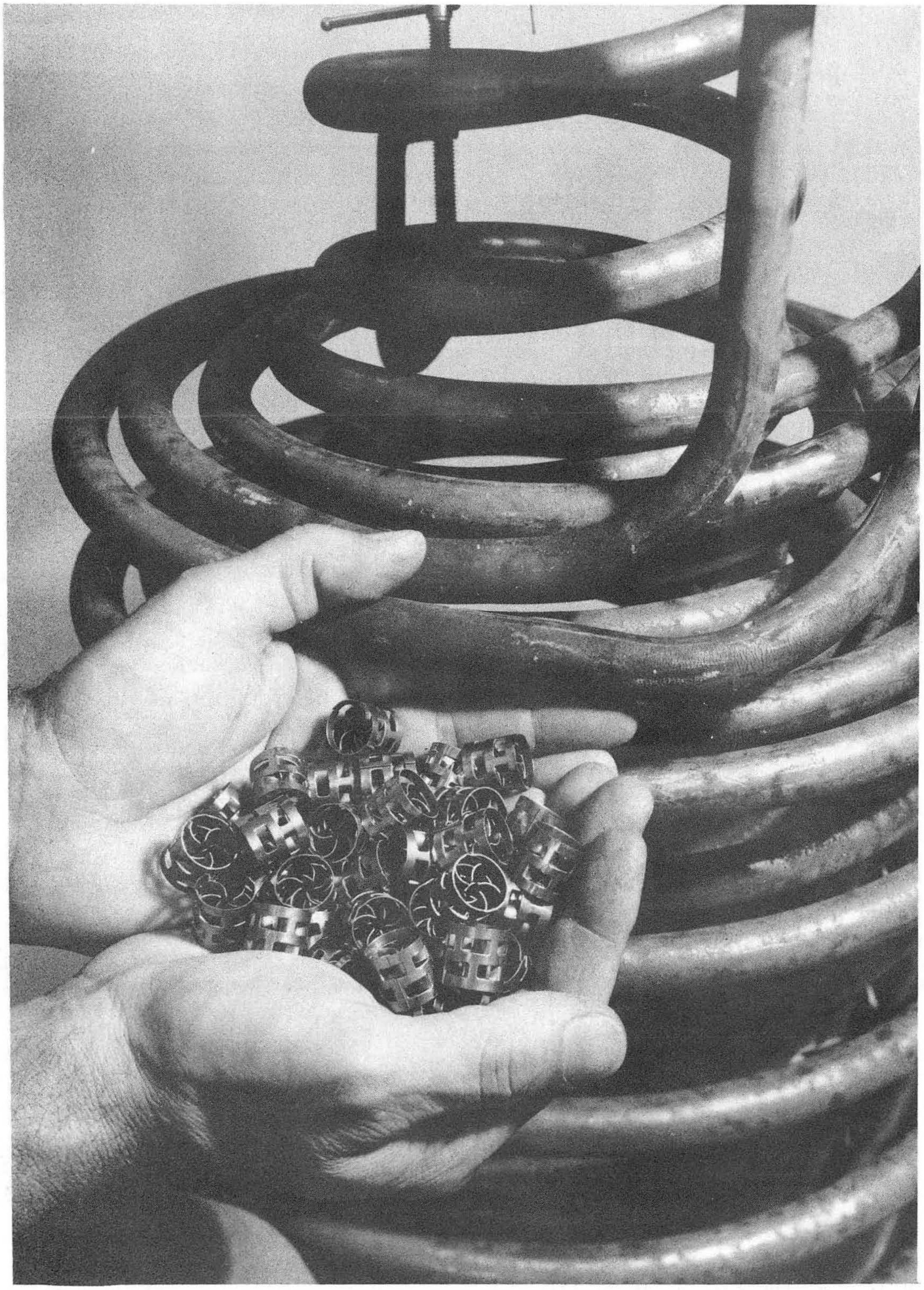
Figure 7. The coils wound from Linde Hi-Flux tubing and the generator shell.



CBB 757-5476

Figure 8. Close-up view of the packing and the coils.

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