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PROGRAM PLAN

Submitted to

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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by

ALTAS CORPORATION

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for

INVESTIGATION OF METHODS
TO TRANSFER HEAT FROM SOLAR LIQUID-HEATING
COLLECTORS TO HEAT STORAGE TANKS

ERDA Contract No. E-(04-3)-1238

Budgeted Amount: \$64,314 Duration: 15 Months Authorized Start: March 15, 1976

Principal Investigator: Francis de Winter Telephone Number: (408) 246-9664

Endorsement of Principal Investigator

Francis de Winter

Isomtl ltr dtd. 6 Apr 1976.

Francis de Winter

President

ALTAS CORPORATION

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I SUMMARY

The reduction of the energy consumption in buildings probably is the greatest contribution that solar energy can make in the next few decades. In many cases, this will involve the use of a flat plate collector to collect solar energy in the form of heat, and the storage of this heat in a storage system using water. For domestic water heating, this water can then be used directly, with a temperature boost added should the solar energy have proved insufficient. For both the heating and air conditioning of buildings, water may also prove to be an ideal heat storage medium and heat transfer fluid. For the heating of buildings, the water can be used to heat an air stream, or piped around the buildings to radiators. For air conditioning, the hot water can serve as a heat source for absorption or adsorption air conditioners, for Rankine cycle units powering a compression cycle, or for similar hardware.

Unfortunately, water has two serious drawbacks in solar energy systems when used directly in flat plate collector:

- a) Although water is very cheap, it makes it necessary to use a collector which is corrosion resistant and which hence may be expensive.
- b) If water freezes, it may break the collector due to its expansion on freezing. In most of the U.S., one can expect significant freezing weather during at least some times of the year.

The corrosion problems with water makes it almost impossible to use aluminum, although from all other points of view aluminum would make an excellent collector material. Copper, a material which has essentially no corrosion problems with water, leads to a much more expensive collector.

The freezing problem is very serious. In virtually all areas of the U.S., with the exception of parts of Florida and California, and a very narrow coastal fringe in some southern states, one must be able to withstand frosts. The severity can be easily checked by checking horticultural reference sources for areas in which frost-susceptible tropical plants can be grown outdoors. There virtually are no such areas, except those mentioned above. Anyone who markets a solar water heating system without having examined this problem seriously is in for a lot of customer complaints.

There are a number of possible solutions to the problems of corrosion and freezing. These are listed and discussed briefly below. Specific considerations

involved in the choice and definition of these solutions are discussed in greater detail in later subsections.

a) Draining Systems One can solve the problem of freezing, but not of corrosion, by simply draining the collector and all other frost-susceptible parts of the system whenever frost threatens. Draining must be complete and foolproof. In the 1930's some of the thermosyphon solar water heating equipment used in California required the owner to do this manually (see Brooks, reference 10). The author designed and built a forced circulation solar swimming pool heating system which since March 1973 has done this automatically, whenever the circulation stops, by letting air into the collection system which is above pool level.

b) Separate Fluid Loop With Heat Exchanger The solar heat can be collected in a fluid which does not have freezing or corrosion problems, and then transferred to the water in the storage tank by using a heat exchanger which isolates the two fluids: heat transfer fluid and water. There can be several variations of this approach which are discussed below.

Boiling Collector. One can use the collector as a boiler, and heat the water in a condenser. The condensate is pumped back to the collector and vapor returned to the condenser. Such boiling collectors are also particularly useful for solar heat engines, and were used for such a purpose as long ago as the 1880's (see Molera and Cebrian, Ref. 11 or Tellier, Ref. 12).

"Sensible Heat" Collection. A liquid (single phase) can also be pumped through the collector and then through a heat exchanger which heats the water. If the storage tank is higher than the collector this can be done by thermosyphon, which can be particularly effective since many heat transfer fluids have high thermal expansion coefficients and can hence establish high circulation flow rates.

Type of Exchanger. For both of these systems-boiling and single phase-there are still different types of heat exchangers one can use. For a large system, such as might be used for heating a building, there is no question but that it is wise to use a heat exchanger in which there is a circulation pump on the water side. For a small system such as might be used for heating domestic water for a single family dwelling, it is likely to be much more cost effective to dispense with one circulation pump, and

simply use the wall of the storage tank as the heat exchanger surface by using a double jacket or by using a coil fastened to the storage tank wall. This was done in the 1930's by the Day and Night Company in California (References 10, 13).

c) Separate Fluid Loop With "Liquid to Liquid" Heat Exchanger An imaginative way of using a second heat transfer fluid loop has been proposed by Drs. J.C. Ward and G.O.G. Löf at CSU (Ref.24). This involves using a fluid denser than water and immiscible in water, and exchanging heat in a direct contact "liquid-liquid spray tower" in which the hot heat transfer fluid is sprayed into the water storage at the top, and separated and withdrawn in the bottom of the tank. Much experience with these spray towers has been obtained by the Office of Saline Water of the U.S. Department of the Interior in the 1960's. All of this was with fluids lighter (rather than heavier) than water. Nevertheless much of it is applicable. A number of references on heat transfer, fluid flow, and separation in spray towers are given in the CSU proposal. A number of others are listed in the present proposal (references 14, 15, 17, 18, 19, 20, 21, 22, 23, 27).

d) Supplying Heat to the Collector A number of people have considered supplying moderate amounts of heat to exposed (collector) parts of a solar system during freezing weather. Some have considered doing this electrically. In some solar controllers (see Rho-Sigma Literature, Reference 26) there are models which will circulate water whenever the temperature drops below a given point at the control sensor (located at the collector exit). Such approaches may be acceptable as a stop-gap measure in areas of only occasional light frost. There are however unlikely to be effective from an energy conservation point of view in areas of frequent cold weather. Beyond that, another part of the circulation loop may freeze, due to defective insulation or other reason, before the sensor which controls the frost protection is activated.

Draining systems have a number of problems which can be considered by themselves. There are a number of other questions which affect more than one approach. Tank pressure is for example likely to affect tank cost seriously, and often the heat transfer approach is likely to establish the tank pressure. A number of the approaches require a second fluid, and the second fluid choice-criteria are similar in many cases. There are a number of heat exchanger considerations which cut across system boundaries, there are differences between "small" and "large" systems, there are collector design questions to be considered, and one must consider tank stratification questions. Such questions are discussed in more detail below.

A Draining System Considerations

In a swimming pool solar heater it is easy to arrange for the automatic draining of the collector if the collector is above the level of the pool. One merely has to install a one-way valve which can let air into the collector at a point above the pool level, but close enough to pool level so that during operation the normal system pressure drops hold the one-way valve closed. When the pump shuts off the system will fill with air, and if all the lines are sloped correctly no water will be left in the system. On startup the air charge is "burped" into the pool. A system such as this was developed and built by the author and is shown in Figures 1 and 2. It has operated with no problems since March 1973. The system has been presented at the 1973 Paris Conference (Reference 16) and described in detail in a technical report (Ref.3). The main difficulty in draining swimming pool heaters occurs when (as often happens) the circulation pump is above the level of the pool. In this case the pump can easily lose its "prime", and with the single check valve approach this will always happen. With more than one check valve and some extra plumbing one can perhaps solve the problem, but it must be considered that even a very minor air leak will be sufficient to make the pump lose its "prime". The check valve protecting the pump's "prime" must seat really tightly.

The same type of system can be installed in any "unpressurized" system in which there is a free surface in the storage tank so that the water has a place to drain to. One can also use it in a pressurized system (isolated from the city water supply) which has a free surface (i.e. with a pressurized gas charge). In this case the check valve instead of venting to the atmosphere should vent into the top of the storage tank. A typical arrangement is shown in Figure 3.

One can run into more difficult problems with a pressurized system tied directly into the city water supply. In this case the collector must not only be vented; it must also be isolated from the rest of the system, otherwise the city main pressure would fill it up with water. In this case one is faced with the need for multiple solenoid valves (not check valves or one-way valves). One probably needs two solenoid valves to isolate the collector from the pressurized parts of the system, and two to empty it (one to let in air, the other to let out the water). If one or more of these valves has a malfunction the system may be damaged by frost. Even during proper operation

FIGURE 1. PHOTOGRAPH OF THE CDA SWIMMING POOL HEATER PROTOTYPE, SHOWING DRAINING CHECK VALVE ABOVE POOL LEVEL.

FIGURE 2. EXPLODED VIEW OF THE CDA SWIMMING POOL HEATER PROTOTYPE, SHOWING DRAINING CHECK VALVE ABOVE POOL LEVEL.

Figure 3. Typical Draining System for a Pressurized Solar Energy System Isolated from the City Water Supply. (System can also be unpressurized.)

there may be drawbacks. In some areas water main pressures are very high (the author gets city water at 98 Psig) and one must consider the noise and damage potential of the water hammer effects involved in filling up the collection system each morning.

It should not be assumed that there are no serious problems with systems so long as they have draining provisions. According to Dr. Löf (in reference 4), however, many installations which had this provision have had a catastrophic failure at some time when the draining system did not drain. As a result of these problems, many investigators and developers are using other fluids in their collectors. Dr. Löf's company is working almost exclusively with air collectors (Dr. Löf has some 30 years experience with solar air heating systems). Many people are working with ethylene or propylene glycol solutions with suitable corrosion inhibitors, some are considering other fluids such as Dowtherm J.

In the present program many different plumbing diagrams such as those shown in Figures 1, 2, and 3, and those involving solenoid valves as discussed in the text will be considered. Plausible hardware will be selected, to determine the costs involved in equipment likely to work. Large solenoid valves are for example likely to be quite expensive. So are large diameter checkvalves which do not impose large pressure drops, yet which are likely to seal tightly and reliably during a long lifetime. Plumbing diagrams and specifications most likely to be workable and cost effective will be made for many types and sizes of systems. In some systems widespread

usage may only be desirable after an extended testing program with real or simulated hardware. Necessary testing work of this type will be identified.

B Tank Pressure Considerations

It must be kept in mind that in many solar heating systems the collector may be on a roof while the storage tank is buried underground or in a basement. A liquid column directly connecting the two will produce a hydrostatic pressure in the tank. This may be decreased by operating the collector at less than atmospheric pressure, but one may run into column height and fluid boiling point limitations and a special suction pump sometimes may be needed to keep the "syphon" filled. In Figure 3 such a suction pump is not shown. If a large storage tank must be constructed to withstand a significant pressure, it is bound to be much more expensive than one which operates at atmospheric pressure. Any scheme which uses a heat exchanger to isolate the collector fluid from the storage fluid can also keep the hydrostatic head from pressurizing the storage tank. In a liquid-liquid spray tower scheme there is however full pressure transmission.

C Heat Transfer Fluid Choice Considerations

The use of a second heat transfer fluid produces a number of problems. The choice of fluid is quite difficult because of a number of factors:

- a) Many of the fluids are toxic.
- b) Most are expensive.
- c) Most are combustible.
- d) Most have a very high coefficient of thermal expansion, compared to water, so that expansion tanks are required (see Figure 5 below).
- e) Many are highly volatile, and require leaktight systems to avoid loss, or to avoid problems with toxic vapors.
- f) Most have poor heat transfer properties compared to water: low thermal conductivity, high viscosity, low specific heats.

It may not be possible to use toxic fluids even with a heat exchanger wall separating it from potable water, because of code limitations. A spray-tower liquid-liquid scheme may be out of the question in potable water systems, except if the

storage-water is isolated from the potable water.

In the liquid-liquid spray tower system, the fluid must be denser than water and must be immiscible in water. At CSU some 24 plausible fluid candidates have been identified (Reference 24), and a significant effort is likely to be made to narrow this down to a best choice. There seems to be no need to duplicate this effort.

In systems in which the water and heat transfer fluids are kept separated a significant amount of work is also going on. Despite much discussion to the contrary, it seems that propylene glycol is nearly as toxic as ethylene glycol (Reference 28). Dowtherm J seems to be an interesting fluid candidate (it was used in the sample calculations performed in Reference 1), but at present the question as to whether its toxicity, volatility, and combustibility properties are acceptable is not clear. It again does not seem desirable to duplicate on-going work.

It is probable that over the next year or two, there will develop a consensus as to which fluids make the most sense. Afterwards, particularly when collector manufacturers make a specific recommendation, there should no longer be any significant problem of choice on the part of the user.

For evaporating collectors feeding condensing heat exchangers, the situation is different, and a significant study seems to be required. The fluid must have high enough vapor pressures to produce good vapor mass flow rates in reasonably sized diameter tubes. The vapor pressure should not be so high as to impose unacceptable strength requirements on the collector and the rest of the plumbing at expectable system temperatures. The molecular weight should be relatively small so as to have high sonic velocities. Toxicity, combustibility, corrosiveness, cost and other factors must be considered. The use of Freons seems undesirable until the problems of Freon interactions with atmospheric ozone are resolved. Liquid viscosity must be low and thermal conductivity high for good condensation heat transfer. Latent heat should

be high. The final choice should be a compromise based on these and other factors. This involves mostly a straightforward literature search, but it must be quite thorough. This does not need to require a large engineering effort. There are unlikely to be more than perhaps 100 possible candidates, and in a few weeks of effort it should be possible to narrow the choice down to perhaps 5 or 10. Whether it is possible (or even desirable) to narrow down the choice much further in this program remains to be seen.

D. Heat Exchanger Considerations

A heat exchanger required to transfer the collected heat to the water in storage must be carefully optimized. If it is not optimized, there are two possibilities:

- a) If the heat exchanger used is too large, then it is too expensive.
- b) If the heat exchanger is too small, then too large a temperature difference will be imposed between the two fluid streams. The collector temperature will be forced up excessively, and collection efficiency will suffer as a result. The collection efficiency penalty can be understood more easily by examining Figure 4.

Every job will be different depending on collector size and usage. It will be desirable to use a heat exchanger of the right type and to use a cost-optimized heat exchanger: large enough so as to yield a small temperature boost to the collector (so as not to decrease collection efficiencies excessively), yet small enough so it does not cost too much.

A preliminary study has already been completed by the Altas Corporation on internal funding, and optimization criteria and techniques have been developed. The results of this study are discussed in reference 1, which has already been published in Solar Energy. This paper (Reference 1) is entitled: "Heat Exchanger Penalties in Double

Figure 4 Heat Collection Decrease Due to a Double-Loop Heat Exchanger.

Loop Solar Water Heating Systems", and has been published in the "Solar Energy" Journal in the December 1975 issue. It was presented at the International Solar Energy Society Conference at UCLA in July and August, 1975.

A full-fledged heat exchanger, with two circulation pumps (one for each loop) can of course only be considered for large (house-heating) systems. For a small system such as might be used for heating domestic water, one only has a collector of perhaps 50 ft² and a tank of some 80-100 gallons. In this type of system the best (i.e. most cost-effective) heat exchanger is a storage tank with a coil soldered or welded to it, or with a double jacket. This is not new. It was used back in the 1930's in California in the Day and Night commercial solar water heating systems (References 10, 13). Figure 5 shows such a system as depicted in 1936 by Brooks (Reference 10).

The differences between "large" and "small" systems in this regard are due to a combination of the following factors:

Fig. 23.—Commercial type nonfreezing solar-heater-system tank.

Figure 5 Jacketed Tank-Heat-Exchanger System of the 1930's, as Shown by Brooks (Reference 10).

- a) In a small system the storage tank (surface area)-to-(volume) ratio is large, in a large system it is small. In a small system one can hence get a reasonable rate of heat transfer by using the tank walls as a heating surface. In a large tank this becomes a questionable proposition.
- b) In a large system a heat exchanger and extra circulation pump only constitute a small part of the system cost, whereas in a small system a heat exchanger and extra circulation pump would make a sizable cost addition. In a large system it is hence much cheaper to add a heat exchanger and circulation pump than it is to penalize the efficiency of the large collector investment by relying on an inefficient heat transfer mechanism such as a coil in or on a tank. In a small system, the heat exchanger and circulation pump costs are much higher than the cost of the penalties imposed on the collector through the use of coils on a tank.

The above is of course purely qualitative. It is however not adequate to say that a 50 ft² system is small and a 1000 ft² system is large; one must develop a good understanding of the ranges over which each solution makes more sense. This involves not only a study of the heat transfer mechanisms in the "jacketed tank" or "traced tank" type system, and of the heat exchanger penalties in the larger systems. One must also examine the heat exchangers available on the market, particularly the heat exchangers of a small size. It is the performance and cost of small heat exchanger-pump combinations which are going to lead one to the decision not to go to a still smaller heat exchanger-pump combination, but to a jacketed or traced tank approach.

It is likely the same switch in design approach will obtain in the liquid-liquid spray-tower approach. This approach is likely to be useful also only for "large" systems. For "small" systems, particularly since these will generally be potable water systems, it is unlikely that the spray-tower approach will be desirable or even acceptable. A jacketed or traced storage tank system will again be best, and it is also necessary to determine at what size one switches from one solution to the other.

The results of the Altas Corporation study reported in Reference I are relatively simple, and a heat transfer engineer should have no problem in applying them. The results are in fact already being used. Prof. J.A. Duffie, Program Committee Chairman for the ISES Conference at UCLA, received a first draft of the paper in November 1974.

In February of 1975 he wrote to the Altas Corporation (Reference 29) that portions of the paper had already been incorporated into the University of Wisconsin solar system simulation computer programs, and indeed the Wisconsin group has already published a paper (Reference 30) incorporating the work. There are, however, few people in the building industry who are highly versed in heat transfer or in solar energy.* If solar energy is to be applied on a significant scale, then design tools which must be used by the practitioner must be simplified to the handbook or "cookbook" level, and one must have the certainty that in producing the simplified material, the validity has not been lost or compromised.

Because of the work already completed, the planned work in the heat exchanger area is aimed at much more definitive results than the work planned in the area of draining systems, evaporating collector-condenser combinations, or liquid-liquid spray-tower exchanger. It is planned to extend the work reported in the paper (Reference 1) already published, so as to make it possible for the ultimate solar energy HVAC system practitioner to choose the right heat exchanger for his specific application. Limits of usefulness of the traced tank approach would be established, and preliminary design criteria for traced tanks would be formulated. It should be noted that this will not include an exhaustive and definitive study of stratification effects and devices - such as suggested by the 1936 illustration shown in Figure 5, but a number of such tanks will be built at Altas on in-house R&D funds, and testing results may be available. Stratification considerations are discussed further in subsection G below.

E Liquid-Liquid Spray Tower Heat Exchanger Considerations

It is assumed that a significant program in this area will be performed at CSU as a follow-on to their preliminary study, and no attempts will be made to duplicate this work. A good collection of literature in this field will be established, and the literature search to accomplish this end has already been started (see References 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 31). This is essential if one is to have a thorough understanding of the significance of new work.

Design and performance criteria for liquid-liquid spray towers will be obtained from the CSU work and from the literature, to evaluate the status and potential of this scheme. It will be attempted to determine the system size at which the spray tower

* It is quite likely that most people specifying heat exchangers for this application in solar HVAC systems will have no other contact with heat exchangers.

approach ceases to be a useful concept, and at which one should switch to the traced tank approach.

It will be attempted to evaluate the liquid-liquid system on a basis similar to that used in the heat exchanger work shown in the Appendix. Two cost items were included in this work: the equipment cost and the cost penalty imposed on the solar heat collection. In addition there are other effects to be considered. One must examine de-stratification effects of spray tower operation, as compared to that produced by a heat exchanger setup (see subsection G below). Operating costs should be estimated, and compared with other approaches.

F Condensing Heat Exchanger Considerations

If the heat transfer fluid is evaporated in the solar heat collector the heat exchanger used to transfer heat to the storage water will have to be a condenser. This complicates heat exchanger design and evaluation, since most heat exchanger analysis is based on the use of constant heat transfer coefficients. In condensation heat transfer in a condenser, condensation heat transfer coefficients are not constant throughout the exchanger since there is a variation in the temperature difference which causes condensation and which determines the condensation heat transfer coefficient. As a result, the differential equation of the heat exchanger is not linear, and it is not possible to get the usual heat exchanger performance versus "Number of Transfer Units" relationship.

It might seem necessary to evaluate the performance of a condenser either on the basis of some average condensation heat transfer coefficient which is then assumed uniform in the condenser, or on the basis of a numerical integration performed on a computer (the first approach might be inaccurate, the second very costly). This is however not the case. One can obtain integrated forms of the non-linear differential equations describing condenser performance, using essentially the same types of assumptions used in general heat exchanger analysis. The end results of this analysis is not a closed-form equation describing a type of performance versus NTU relationship, but instead several relatively simple equations which can lead to condenser performance in a simple iteration routine.

Mr. de Winter derived these equations in the early 1960's for use in the design and evaluation of Freon condensers used in aircraft air conditioning equipment. It

is mentioned in subsection H that heat transfer behavior in the condenser might limit the advantages obtainable from evaporating collectors in water heating systems. It is clear that careful work in this area is necessary.

G Storage Tank Stratification Considerations

There are three different situations which can be imposed on the storage tank by the heat supply mechanisms. These are discussed below:

a) If one has an external heat exchanger, one can without great difficulty withdraw the lowest temperature water from the storage tank. The return of heated water can lead to destratification due to "jetting" or due to insertion at a "wrong" level, i.e. one at which the temperature of tank water and heated water does not match. The "right" level depends on water supply temperature, and on the past solar energy supply and demand history. There are many people studying optimum methods of laying down heated water return to maximize stratification, and considerable work has been done and is continuing on what the penalties are for less than optimum stratification, ranging anywhere to the fully stirred tank model.

b) If one has a spray tower then there is a destratification mechanism due to the local droplet drag. It is conceivable that in large systems there might be local instabilities caused by spray irregularities which might produce variations in gross (water plus fluid) local densities. Perhaps a fully stirred tank model is inevitable. It remains to be seen how much stratification can be achieved.

c) If one has a jacketed tank then one has still another situation. By not jacketing the upper part of the tank (an approach possible if the lower part has enough heat transfer surface) one can perhaps conserve partial stratification. Internal shields such as the 1930's model shown in Figure 5 may be necessary to minimize the constant stirring produced by natural convection boundary layer chimney effects.

It is clear that in each of these three different types of systems one has exceedingly complex problems meriting significant study. The proposed program can perhaps not have much significance unless there is a continuing awareness of these problems, and of the studies being undertaken elsewhere (Lockheed in Palo Alto, CSU, University of Wisconsin, etc.) in solving them. Independent and in-depth work in this area is however not contemplated in the proposed program.

H Evaporating Collector Considerations

It was mentioned earlier that evaporating flat plate solar heat collectors were used and patented as long back as the 1880's as boilers for heat engines. In such an application the advantages are obvious. One is able to avoid a "heat exchanger penalty" such as discussed in the Appendix, and in those collector areas in which boiling is going on the collector temperature is uniform so that collector heat losses are minimized. * One can also easily make a vapor separation section and a superheating section if one is powering a heat engine, but for simple heating systems superheating is probably unnecessary. Any liquid separated from the vapor can be returned directly to the collector input manifold.

Apparently at the University of Florida some work with boiling collectors is going on for heat engines. The Barber Nichols Corp. has not used them in their Rankine engine work for fear of possible refrigerant leakage problems (Reference 32).

If one uses such an evaporating collector in a heating system, one must transfer the heat to water in a condenser. The advantages of the flow factor of unity (mentioned earlier) disappear unless one uses a large water flowrate in the condenser. A flow factor very close to unity could also have been obtained by using a large water (or other single-phase liquid) flowrate through the collector directly, and it is not clear that the use of a boiling fluid in the collector is advantageous on the basis of such simple reasoning.

There are some potential advantages in the use of boiling evaporators in heating systems. For most heat transfer fluids boiling and condensation heat transfer coefficients are much easier to get to high levels than forced convection heat transfer coefficients. Since liquid specific heats are low but heats of evaporation are reasonable, fluid circulation rates (and hence pumping power requirements) are minimized.

It seems that careful engineering design work is needed to evaluate evaporating collectors. Some details of the necessary work are discussed below.

* The Whillier "flow factor" is unity in these areas.

Candidate fluids should be examined, and selection criteria are discussed elsewhere in this proposal.

Fluid maldistribution should be avoided. If some channels run dry and the collector starts superheating locally, local efficiency will drop. If the superheated vapor is then mixed with wet vapor coming out of other channels and is brought back to saturation, one will end up with a collector less efficient than one which has saturated vapor coming out of all channels. Evaporators of the early jet passenger planes (DC-8 and B-707) air conditioning systems had refrigerant maldistribution problems of this nature, and as a result early systems could only get to 60% of design capacity. The author was involved in a significant engineering study in the early 1960's to correct such problems. It is likely a significant amount of design work will be needed to determine the correct fluid passage diameter, required liquid holdup in the collector, and manifold arrangement for a successful design with no maldistribution problems.

Many other questions must be considered in order to generate a plausible design which can be evaluated properly for comparison with other concepts. Fluid leakage problems must be considered. Passages must be sized for fluid throughput. The very large literature in heat pipes in two phase flow and in boiling coefficients in refrigerants must be used to determine heat transfer and fluid flow requirements. It is desirable to avoid the use of capillary (e.g. mesh) liquid-distributing provisions inside of the collector flow passages. Such design features of a heat pipe nature are bound to be expensive. Tubing walls must be made strong enough for service at maximum temperature conditions. Condensate pumping and pump requirements must be determined. Finally, the collector must be coupled to the condenser, and this to the storage water loop and tank (a traced or jacketed tank condenser is also possible).

The final objective of this study is the answer to a simple question. For heat engines an evaporating collector has some obvious advantages. The question to be answered for a water storage heating application is: Does a plausible and realistic system package involving an evaporating collector--as opposed to a single phase collector--have any significant advantages which appear to justify its development? If the answer to the question is in doubt or if the answer is positive, necessary research areas should be identified.

I Traced or Jacketed Tank Design Considerations

One can transfer heat to water in a storage tank with either a double jacket or a tube fastened to the tank in regularly spaced coils. In designing such a device the objective is the same as in the technical paper shown in the Appendix. It is to maximize the solar heat collection per dollar at some tank (water) temperature. This involves investing enough in heat transfer equipment (in this case bonded coils or a jacket) so that the collector is not forced to operate at an excessively high temperature with a resulting loss in efficiency. One should however not invest too much money in the exchanger, or one will pass the optimum design point. Figure 2 in the Appendix shows this very clearly.

The tank wall would ordinarily be steel, with a thickness determined by the strength requirements following normal pressure vessel or boiler codes. Coils must be spaced closely enough so that the "fin-efficiency" of the intervening tank wall is sufficiently high. This fin efficiency is a function of the spacing and wall thickness. An optimum exists, since when the tubes are too close together the tube plus bonding cost is too high. An optimum coiled tube approach can be compared to an optimum jacketed approach to see which is more cost-effective. In order to determine reliable optima one must estimate manufacturing costs.

Natural convection coefficients must be determined for the inside of the tank and of the jacket, following standard heat transfer correlations. Inside of a coil fastened to the tank surface one must determine the forced convection coefficients.

To avoid excessive destratification of the water in the tank it may be desirable not to have any coils or double jacket in perhaps the top third of the tank. One may also require a baffle such as shown in Figure 5 in order to minimize stirring effects, but it will be difficult to develop reliable criteria on this without extensive testing. Some testing is planned on such tanks on in-house Altas funding, but probably not sufficient to develop really definitive results applicable to many different tank configurations and sizes.

Jacketed and traced tank designs will have to be made and evaluated for a number of different tank sizes. The cost and cost effectiveness will be compared to that of similar size tanks using a full fledged heat exchanger with pumped water and

heat transfer fluid loops following the approach used in the Appendix. At some tank size the heat exchanger approach will become more cost effective.

It should be noted that the natural convection heat transfer picture inside of the tank will depend on the stratification, i.e. on the vertical temperature profile of the water in the tank. In the present work it will be assumed the tank water temperature is uniform, but calculations will be performed for several temperature levels.

II PLANNED PROGRAM

The scheduled program will be aimed at establishing design guidelines, cost estimates, performance descriptions, and cost-effectiveness estimates for the different systems which can be used to transfer heat in a reliable and trouble-free manner from a liquid-heating solar collector to a water storage system. Comparisons will be made on a basis as definitive as appears to be possible within current understanding, and areas of required and promising research and development will be identified.

For each of the systems to be studied a series of tasks are defined and a work statement is presented and discussed. The headings are shown below in the order in which they are arranged:

- A Study on Draining Systems..
- B Study on Evaporating Collector with Condensing Heat Exchanger.
- C Study on Double Loop Heat Exchanger Systems.
- D Study on Liquid-Liquid Spray Tower Systems.
- E Study on Traced Tank Systems.
- F Study of Other Relevant Questions.

The interrelation of the various tasks and subtasks, and the importance of other associated questions can be understood in more detail by reading the Summary Section.

A Study on Draining Systems

The study on draining systems is the simplest one of all. A significant amount of experience has been obtained with draining systems by ALTAS personnel. There are likely to be relatively few plumbing diagrams which will be useful in this area. Two very simple ones are shown in Figures 1, 2, and 3 of this proposal. It should be possible to develop a complete set of apparently viable diagrams in a short time. Subsequent work will involve primarily picking appropriate hardware for these diagrams, and determining likely testing requirements for those components for which satisfactory operation does not seem certain. Satisfactory operation depends on the application. In the system shown in Figure 3, failure to seat properly of the one way valve on closing is acceptable so long as leakage is not excessive. Failure to open in the right direction (or at least failure to open fast enough to drain the collector before frost damage) might however be catastrophic. A number of program subtasks are presented below.

a Determination of Plumbing Diagrams

Work Statement Workable plumbing diagrams with draining provisions will be developed for all likely solar energy utilization systems.

Discussion Shown in Figures 1, 2, and 3 were simple plumbing diagrams which can be used if the circulation pump is below the water surface (and hence can not lose its "prime"), and if the system is not hooked up to the water main. Potable systems will generally have to operate at full line pressure, drained water will generally be dumped into the sewer, and makeup will come from the water main (with all attendant noise and water hammer problems). In many swimming pool applications, particularly those built on level ground involving sunken pools, the pump is above pool level. Both these systems require more complex diagrams. Generally one-way valves will not be sufficient; one will need a combination of one way valves and solenoid ("normally-open" valves and/or "normally-closed" valves) to produce a draining system plumbing diagram which seems to have a chance of success. Solenoid valves can be actuated with modern solar energy control systems such as the Rho Sigma (Reference 26) equipment.

b Determination of Acceptable Hardware

Work Statement: Available literature on valves and other components will be examined in order to determine what equipment, if any, can be seriously proposed for these systems.

Discussion: For draining systems to be viable, all valves should operate repeatedly in an acceptable manner during a long life. This is no trivial matter. The valves will be exposed repeatedly to water of a perhaps somewhat random chemistry, followed by air which was polluted. In the Pasadena system (Figure 1 and 2) a copper alloy valve with a teflon seat has shown the effect of such a cycling process, by dripping very slightly. It still opens perfectly, and the dripping is no problem. In other applications such behavior might however not be acceptable.

It is likely that if one is willing to pay enough one can obtain equipment with a long enough reliable lifetime. It should be determined whether such a choice is possible based on present knowledge without independent testing. If excessively expensive valves are necessary the draining system may not be a viable approach.

c Comparison of Complete Systems

Work Statement: Complete systems will be designed for a number of different applications, evaluated and compared with competing concepts.

Discussion: Complete systems will require corrosion-resistant collectors and all the necessary plumbing and valves. Systems of this type will be designed for a number of different applications (again aimed at establishing system capabilities and limitations), and these will be compared with competing systems.

d Specification of Required Testing Program

Work Statement: Components seeming to require further testing will be identified, and the required testing will be specified.

Discussion: It is likely that the most cost-effective testing work for these systems would not be tests in a full solar energy utilization system, but rather an accelerated cycling process with simulated water and air environment conditions. It is unlikely that these will be totally conclusive in checking out acceptable hardware, since corrosion and other chemical reaction problems can not be satisfactorily scaled up in time. It is however possible to get a good idea regarding the cyclic fatigue, and it will certainly be possible to use this technique to weed out many valves which are too cheaply built to be satisfactory. Complete system tests may be desirable on selected components.

B Study on Evaporating Collectors with Condensing Heat Exchangers

From an engineering point of view this is the most challenging part of the work, requiring the most careful design and analysis. Getting a workable design of an evaporating collector which is not excessively over-designed will be an interesting task. Coupling such a device to a condenser is also a challenging task. Fluids, pumps, and other components must be chosen. A number of the necessary areas of work are described below.

a Choice of Fluid

Work Statement: The fluid to be used in this application must have acceptable vapor pressure, cost, environmental effects, stability, heat transfer characteristics, vapor flow characteristics, surface tension and a number of other properties. Many fluids will be compared so as to choose the best fluid or fluids.

b Determination of Workable Collector Designs

Work Statement: Workable collector designs will be generated for the evaporating collector.

Discussion: It is assumed liquid is to be supplied to a lower manifold,

evaporated in collector tubes (of the type shown in Figures 1 and 2) and vapor withdrawn from the top. The lower manifold must be large enough to supply liquid equally to all tubes. The tubes must be large enough so as to impose relatively low vapor pressure drops, yet small enough so that the vapor drags along enough liquid to wet the whole tube (hopefully without the need for a capillary mesh of the heat-pipe type). The upper manifold should serve as a vapor separator, with the separated liquid returned to the lower manifold.

It is quite clear that this is a difficult process, and that the end product can not be expected to be identical to a collector which might result from a significant hardware R&D and testing program. Nevertheless, the work is not markedly different from previous work performed in the design of aircraft air conditioning evaporators. The collector problems themselves are relatively straightforward since at least in the evaporating region temperatures will be virtually uniform.

c Determination of Condenser Design and Performance Criteria

Work Statement: Optimum condenser designs will be generated for each specific solar energy system, and it will be attempted to produce simple guidelines for optima following the work described in the proposal Appendix.

Discussion: Most heat exchangers are designed and evaluated on the basis of constant heat transfer coefficients. In a condenser the condensation heat transfer coefficients are not constant. In 1916 Nusselt showed that the coefficients are related to the local temperature difference (heat transfer driving force). By making the differential equation describing heat exchanger performance non-linear, this makes it impossible to obtain strictly valid closed form solutions for either the design or the performance of a condenser. It is however possible to derive equations which allow condenser performance to be determined with a simple algebraic iteration process, rather than having to use a numerical integration process on a computer. These equations were derived by Mr. de Winter in the early 1960's in work on aircraft air conditioner condenser design, and will be used to obtain guidelines on the optimum condenser design requirements. Similar equations were derived for boiling heat exchangers, in which similar non-linear terms exist. The equations are as yet unpublished.

d Choice of Circulation Pumps

Work Statement: The best circulation pumps will be chosen for collector systems of varying sizes.

Discussion: It is likely that the best pumps will be hermetic units, and that they will be rather small because of the low flowrate requirements. Manufacturers literature will be examined to determine viable models. This will include not only flowrate, and pressure capability requirements, but also materials compatibility considerations.

e Comparison with Competing Systems

Work Statement: The cost effectiveness and reliability of the evaporating collector-condensing heat exchanger approach will be compared with that of other systems.

Discussion: As in other systems, different designs will be generated for various applications, and these will be evaluated and compared with other systems in terms of likely cost-effectiveness and reliability.

f Definition of Needed R&D

Work Statement: R&D necessary to develop the most cost-effective items will be defined during the program.

Discussion: There is little doubt that a workable evaporating collector can be designed. The work of Tellier in 1885 and of Molera and Cebrian in 1880 show that workable equipment could be made nearly 100 years ago. It does not seem likely, however, that the equipment which can be designed and produced from "first principles" will be very close to optimum. During the work the most serious uncertainties in present knowledge will be defined, and the necessary R&D to clear up these uncertainties will be recommended. It may be desirable to follow up on these even if evaporating collectors do not seem attractive in water heating applications. For Rankine cycle work evaporating collectors might still be worthwhile.

C Study on Double-Loop Heat Exchanger Systems

The study on double-loop heat exchanger systems is expected to yield the most definitive results. There are several reasons for this:

- a) A double loop heat exchanger system is a straightforward system which can be made to work with no need for a significant development effort. It might not be the most cost-effective system, but there are no serious research questions or unknown areas, no really difficult design problems.
- b) The basic work of system analysis, integration and optimization has already been completed, and has been described in a technical paper about to be published in December 1975 in Solar Energy, and included in this proposal as an Appendix.

Because of the level of confidence and of understanding which exists in double-loop heat exchanger systems at this time, it is felt to be possible to proceed directly towards the preparation of a definitive design routine which can be incorporated into the HVAC literature (for example the ASHRAE Handbooks) to allow the HVAC practitioner to specify - with a high degree of confidence - an exchanger which is very close to optimum for the system he is considering.

This part of the study will be aimed at preparing simple design routines involving a short text with figures or tables, which could, for example, be used verbatim in such publication as the ASHRAE guides. The work will involve:

- a) Determination of simple and complete procedures for specifying optimum heat exchangers. This will require the performance of a number of other tasks shown below.
- b) A study of the effect of other than optimum heat exchanger design. If the specified heat exchanger is somewhat too large or too small, for any one of a number of reasons, then a cost penalty will be incurred. It is desirable to study this penalty in detail for different heat exchanger lines and collector types.
- c) A study of the criticality of the "matched flowrate-specific heat product" concept discussed in the Appendix. It is clear that it is desirable to have such matched products, but it is not clear at this point how much of a penalty is paid if one does not have a matched system. This part of the study will determine what design process, if any, is necessary for flowrate control.

- d) A study of the effects of other than optimum heat exchanger type. In solar air heating systems, for example, one must transfer (at least some) heat from air to (potable) water. A gas-to-liquid heat exchanger is difficult to build in a counter flow geometry. Most end up looking like a car radiator, which is a cross-flow exchanger. Cross flow exchangers are inherently less effective than counter flow exchangers.
- e) A determination of the heat transfer fluids, or types of fluids, most likely to find widespread use. This will involve a significant amount of discussion with other investigators working on double loop systems, with building code and fire prevention officials and with several fluid manufacturers. Preliminary work in this area has already been done at Altas. Since the choice involves considerations of toxicity and combustibility, the choice is not a straightforward technical question.
- f) A study of likely design requirements for toxic heat transfer fluids, and of the resulting viability of such toxic fluids as ethylene glycol.
- g) A study to determine what are likely heat transfer coefficients for the most likely heat transfer fluids.
- h) A determination of the most likely collector characteristics and heat exchanger characteristics for the purposes of the design procedures.
- i) A determination of the switchover point from a heat exchanger-circulation pump approach to a jacketed tank approach for water heating.
- j) A determination of desirable presentation techniques for the material, through a perusal of such volumes as the ASHRAE guides, and discussion with people who have been preparing such material.
- k) Preparation of the final design procedure material, with the assistance of several editing cycles using people with construction industry and/or ASHRAE experience.
- l) A determination of the cost effectiveness of the heat exchanger scheme compared to the other approaches for a number of typical applications.
- m) Preparation of a final report documenting the full study in depth, and including the final design process description. The design process description will also be issued separately.

This is simply a list of necessary things to do if one is to develop a dependable design tool of dependable usefulness to those who need it. A more complete discussion of these items is given below. For each item there is a short work statement followed by a discussion.

a Determination of Simple and Complete Procedures for Establishing the Specifications of Optimum Heat Exchanger

Work Statement A procedure will be established which will allow the average person who is at present specifying heating and cooling equipment for buildings to establish the specifications of the optimum heat exchanger to be used in a double loop solar heat collection system. The procedure will be made as simple and self-contained as possible without serious compromise of reliability.

Discussion This is the most important objective of the work proposed on heat exchangers, and all the other sub tasks are designed to further the objective. A series of criteria will be tested in order to determine which one is the simplest one which can be expected to be sufficiently reliable. It might be possible, for example, to say: "Make the heat exchanger a counterflow shell-and-tube type, with a heat transfer area equal to 4% of the collector area (see example in Appendix)." One would however have to be certain that the cost and performance characteristics of foreseeable heat exchangers and of collectors would be constant enough so that such a guideline indeed leads to an optimum design. For the case shown in the Appendix this guideline would work. For other equipment it might be quite misleading, and it might in fact be much better to force the equipment specifier through a 10 minute selection process if the end result will be a saving of perhaps \$100 per unit in what might be a housing tract development. It will be necessary to make a careful choice in this area, balancing accuracy and simplicity. The pros and cons of different approaches will be documented in full in the regular progress reports. Outside opinions will be sought regarding the suitability of the proposed procedures from people closely associated with the construction and heating and cooling industries.

b Effect of Other - Than - Optimum Heat Exchanger Design

Work Statement The optimum heat exchanger design is a counterflow heat exchanger with a heat transfer area (exchanger size) picked so as to minimize total investment cost per unit heat collected. The penalty incurred through over-design and through under-design will be studied in depth.

Discussion There are many possible ways in which an other-than-optimum heat exchanger may end up in a solar system, even if the criteria for choosing the right exchanger have been set forth clearly to the specifier*. Over the years, scale

*The production of simple procedures for determining specifications of the heat exchanger may in itself lead to slight off-optimum designs. This also has to be examined.

depositions on the water side may make the exchanger characteristics change, so that the exchanger becomes poorer than originally expected. The heat exchanger series being considered by the specifier might not have a model of precisely the right size, so that one either has to choose one which is too small, or one which is too large. There might be uncertainties in the determination of the input parameters to the optimization scheme, which might lead to a heat exchanger of other-than-optimum size. In each of these cases it is desirable to have a clear idea of the potential cost incurred. Before one can be satisfied with the final design routines such effects must be thoroughly investigated.

c Criticality of the "Matched Mass Flowrate - Specific Heat Product" Concept

Work Statement The criticality of the "matched flowrate-specific heat product" concept will be studied in detail. Allowable mis-match tolerances will be established. The requirements for and specifications of control equipment necessary to keep the mis-match at acceptable levels will be determined.

Discussion In the technical paper it is mentioned that a counterflow heat exchanger yields the lowest temperature approach between the two streams when the two fluids have an equal WC_p (mass flowrate-specific heat) product. Such a matched product does not just happen, but must be a matter of system design or flowrate control. It is necessary to consider typical plumbing layouts and pumps which might be used, to determine whether the WC_p products can be matched closely enough. If this is not possible, throttling valve adjustment routines must be established, or active pumping control requirements must be determined. The penalty incurred through WC_p product mismatch must be calculated in order to establish the tolerances required. It may be possible that a mismatch in one direction can be tolerated better than one in the opposite direction.

d Criticality of Heat Exchanger Type

Work Statement Different types of heat exchangers (other than the optimum counterflow type) will be examined and collection penalties will be determined for heat exchanger types other than the optimum counterflow type in order to determine the importance of choosing the right model.

Discussion A counterflow heat exchanger is inherently the most effective one for transferring heat between two streams of equal WC_p (mass flowrate-specific heat) products.

Such counterflow heat exchangers are closely approximated by a shell and tube exchanger in which the tube side has a single pass, and the shell side has a single pass also and flows in the opposite direction.

In most cases involving liquid-to-liquid heat transfer it should be possible to specify a counterflow heat exchanger of a suitable size. In some cases, particularly if one uses air heaters, it may however not be possible. In most gas heat exchangers the pressure drop becomes exceedingly critical, since with the large volumetric flowrates the pumping power levels become excessively high unless pressure drops are minimized. There are hence incentives to go to a design which has a large cross section for gas flow, and a short flow length for the gas flow. One ends up with a flat, thin exchanger which looks like a car radiator. It is quite difficult to channel the two streams in a counterflow fashion. The result is nearly always a crossflow exchanger, which is inherently less efficient than a counterflow heat exchanger.

There are also heat exchangers of a plate and fin geometry, rather than a shell and tube type. These can also be made in cross or counterflow arrangements of different types, and are available in many varieties and sizes. They may be preferable in the case of toxic fluids, since it may be possible to have vented leakage layers between the water and heat transfer fluid streams. Availability and characteristics of these exchangers should be documented.

e Determination of Heat Transfer Fluids Most Likely to Find Widespread Use

<p><u>Work Statement</u> The best heat transfer fluid (or fluids) will be determined by considering cost, toxicity, stability, corrosion characteristics, availability, flammability, ecological effects, and heat transfer and fluid flow properties. Other groups working with heat transfer fluids in solar energy systems will be approached for opinions on this matter.</p>

Discussion Water corrodes many metals, and because of its expansion on freezing can break tubing. In virtually all other aspects it is however an ideal fluid for solar collection. It is cheap, widely available, nonflammable, nontoxic, has no environmental dangers, and has excellent heat transfer properties. Many people are considering other collection fluids, such as Dowtherm J, ethylene or propylene glycol-water mixtures with corrosion inhibitors, and others. As of yet there seems to be no general consensus regarding the best fluid to use. In 2 or perhaps 5 years

there certainly will be a consensus, although there may at that time be more than one fluid which has found general acceptance. For the purpose of this study it is desirable to eliminate as many unlikely candidates as possible, and to develop the final exchanger criteria only for fluids which seem to have a good chance of widespread useage.

f Study of the Characteristics and Viability of Toxic Fluids

Work Statement Toxic fluids will be studied in detail, and system design requirements imposed by the "Interim Performance Criteria" document recently released for solar systems (reference 6) will be determined. System cost and performance will be determined, and fluids which are clearly impractical will be eliminated.

Discussion The interim performance criteria document recently issued for solar systems (reference 6) makes it necessary to have toxic fluids channeled in such a fashion that leakage can not possibly get into drinking water. This may make it impossible to use a direct heat exchanger, and hence impose higher temperature differences and higher equipment costs on the system. It is perhaps possible to use heat exchangers of the "plate and fin" type, with vented (empty) layers between the water and toxic heat transfer fluid. It is not at all clear that fluids of serious toxicity have enough advantages of other types (e.g.cost) to outweigh these problems. This area must be examined carefully.

g Determination of Heat Transfer Coefficients

Work Statement Heat transfer coefficients likely to exist in the solar collector and the heat exchanger will be determined, for use as inputs to the optimization procedure.

Discussion One of the requirements for a simple and effective optimization scheme aimed at the equipment specifier is the elimination of the need for calculation of intricate input numbers. One can not expect the equipment specifier to determine average fluid properties, to perform intricate calculations on the shell side flow patterns in a heat exchanger, to calculate Prandtl numbers, to determine transition Reynolds numbers, and to choose the best heat transfer coefficient correlation to use for the particular problem. It should be a part of the proposed work to determine the heat transfer coefficients (and overall heat transfer coefficients) which can be expected with the fluids and heat exchanger types likely to be used.

h Determination of the Most Likely Collector Characteristics and Heat Exchanger Characteristics

Work Statement The different collectors being marketed or developed will be examined, and the cost and heat collection characteristics will be determined for the most likely models to gain widespread acceptance. Commercially available heat exchangers which might be used will be studied to make sure that the design procedures will be applicable.

Discussion The most important characteristics of the collector -as shown in the Appendix- are cost and the rate of change of collection with increasing temperature (the $F_R UA$ product). If these two characteristics are known, and if it is assumed that the collector and heat exchanger have the same lifetime, then we can choose the optimum heat exchanger for a particular application. A study will be made of these characteristics for the collectors likely to be of importance.

It is likewise necessary to characterize the available heat exchangers. To date the work in the technical paper has been done with Whitlock exchangers. For the purpose of the paper this was acceptable. It would however be quite improper to produce a design procedure which would tend to give business preferentially to one company, particularly if there are other competitors fully capable of supplying good equipment. The heat exchanger manufacturers offering suitable equipment will have to be identified, their literature and product lines will have to be studied, and the final design procedures will have to be prepared in such a way as to be applicable to all of them without giving unfair advantages to any manufacturer.

i Determination of Minimum System for Which a Heat Exchanger, rather than a Jacketed Storage Tank, Should be Used

Work Statement For large systems such as used for heating or cooling buildings the use of a heat exchanger seems to be a viable approach. For small single family potable water systems a jacketed tank seems to be more likely to be cost effective. The collector size will be determined at which a switch in design approach should be made from one approach to the other.

Discussion It was mentioned in the technical discussion that in small systems one can not afford the extra cost of an extra circulation pump and heat exchanger, whereas in a large system one can not afford the heat exchanger penalty produced by a jacketed-tank heat exchanger. The cost and performance of optimized designs

(using both approaches) must be determined carefully to determine the switchover point in terms of collector size.

j Determination of Desirable Presentation Techniques for the Final Design Procedure Material

Work Statement Different graphical techniques and other forms of presenting the design procedure information will be considered so as to determine the simplest and most convenient way to present the material to the HVAC practitioner.

Discussion The final design procedure material can only be valuable if it is accurate and convenient to those who will be using it. It will need to be made as simple as possible. It should be assumed that the user will have no previous experience with heat exchangers, yet will need to be able to specify in a short time a heat exchanger which will be dependably economical. Previous handbook material will be studied in order to determine the most suitable formats to use for the information, and drafts will be sent to and discussed with ASHRAE officers and HVAC practitioners.

k Preparation of the Final Design Procedure Material

Work Statement A complete package will be prepared of the final design procedure material, suitable for inclusion in any handbook on the design of solar systems.

Discussion The final design procedures developed in the study will be documented in full in a complete and self contained package, made as simple and concise as possible. Independent people will be asked to comment on the material, and tests will be made to see if people unfamiliar with the background of the material can indeed use it correctly and rapidly. It should be noted that many potential solar HVAC practitioners may have no experience with heat exchangers, and may have no other occasion to use heat exchangers. Graphs and tables will be provided in camera-ready copy to those interested in including the material in publications such as handbooks.

l Determination of Cost-Effectiveness of the Heat Exchanger Scheme

Work Statement A number of complete designs will be generated for specific applications for a one-to-one comparison with the other system concepts.

Discussion One of the most important objectives of the proposed work is the comparison of cost-effectiveness of the various schemes of transferring heat from

collector to storage. To do this a number of typical applications must be chosen, and a reliable design must be generated for all the possible alternate schemes. These "typical" applications must be chosen carefully so as to illustrate the advantages and disadvantages of each system, and to show clearly (if this is possible within present knowledge) when each system should be used and when it should not. Thus it is already felt a switchover from heat exchanger to traced tank system is likely at some system size; it is merely necessary to design different sized systems to pin this down. Pressure isolation characteristics of the heat exchanger might make it better than other systems if the collector is very far above the storage tank. Again this height can be varied.

m Preparation of Final Report

Work Statement A final report will be prepared documenting the work and the design procedure material in full.

Discussion The design procedure is to be aimed at people who want to pick the right design without getting excessively involved in the reasoning behind the process. The final report should document all the reasoning that went into the development of the design process, and should be made useful to those who want to understand the reasoning in depth.

n Other Considerations

There are other minor effects which will have to be considered in the study. There is, for example, a question of start-up and turn-off transients. It is desirable to minimize the thermal inertia of collectors as much as possible, so as to minimize the solar heating which is lost each day simply to get the system up to operating temperature. The heat exchanger adds to this thermal inertia, as does the rest of the heat transfer loop system. It is desirable to minimize the thermal inertia of the heat exchanger and the heat loop system, and to insulate these components in an optimum way. It may be possible to arrange the heat exchanger in such a way (e.g. under the storage tank) that the heat stored daily in the heat exchanger is more or less automatically transferred to storage. This area will have to be considered if the study is to be complete. There will undoubtedly be other questions which will come up during the course of the work.

It should be noted that no testing work is contemplated during the present program. It is felt that the performance of both the flat plate collector and of heat exchangers is understood well enough so that testing will not be necessary. It is expected that both the heat exchangers and the collectors available commercially will be characterized accurately through independent tests. In the coupling of two well characterized devices, there seem to be no mysteries requiring an independent testing program, particularly since in the near future there should also be many other groups who will -as part of other programs- have results available which will allow for any desirable degree of confirmation of the predicted equations. Several jacketed tanks will be built and tested during the proposed program, but with inhouse ALTAS CORPORATION funds.

D Study on Liquid-Liquid Spray Tower Systems

The study on the liquid-liquid spray tower systems is at this point the least defined one of all. There is a lot of material developed on desalination programs as is made clear by the references in the CSU proposal (reference 24) and in the other desalination literature found by ALTAS (references 14, 15, 17-25, 27, 31). Nevertheless at this time the likelihood of success in designing a cost-effective and reliable system from "first principles" is much lower for this system than it is for the other systems. It is unlikely that the literature on fluid-water-metal interactions is reliable and thorough enough to be able to choose fluids with confidence. Likely as not it will be found that some fluids which appear promising will react with water, or will be catalyzed by some metals. Nozzle configurations, jet sizes, spacings and pressure drops, tank height to diameter ratio, fluid choice and a number of other factors will have to be decided not on the basis of calculations and literature study alone but will require a significant amount of testing.

In contrast, in the double loop heat exchanger system it proved possible to perform a straightforward and simple analysis of the system. In the draining systems the plumbing diagrams are a straightforward exercise in logics, and failures should be due exclusively to hardware failure rather than incorrect design perse. In the evaporating collector-condensing heat exchanger combination there is no question but that one can design a workable (though perhaps not close to optimum in cost-effectiveness) system by simply making an intelligent use of current engineering

understanding in collectors, heat pipes, boiling and condensing heat transfer, single phase and two phase fluid flow, and heat transfer and heat exchanger analysis.

Much of the detailed system development and testing necessary in the liquid-liquid spray tower system will be done at CSU, and there is no reason to plan for any significant duplication of effort. The planned work is described below.

a Literature Search and Study

Work Statement A complete collection will be made of all the literature available to date which seems to have a significant bearing on liquid-liquid spray tower design and operation.

Discussion - The CSU proposal (ref.24) contains a number of references to previous work in spray towers. ALTAS has independently uncovered a number of references. Copies of the significant references will be obtained, literature abstracts will be searched to see if there are other recent publications, and then the references quoted in the first references will be examined for further significant work. A consensus of usefulness on the individual papers will be obtained in conjunction with CSU personnel, and the collection will be documented with a short topical report (such as the F.de Winter annotated bibliography on the flat plate collector, reference 2, but much shorter).

b Determination of System Performance Description

Work Statement A set of equations, correlations, guidelines, and other criteria will be assembled to describe as fully as possible the equipment performance to be expected.

Discussion A preliminary understanding of the likely performance of liquid-liquid spray towers to be used in solar energy systems will be obtained in the proposed CSU work in the first 6-7 months. It will be attempted to have a clear understanding of all previous work in the literature by then, to follow the CSU work and try to fit it into the existing understanding, and to assemble as complete and reliable a set of design and performance guidelines as possible at the time. Since it is planned to avoid duplication as much as possible, this work of necessity has to be scheduled based on CSU outputs.

c Determination of the Specification of Mature Systems

Work Statement Plausible designs will be generated of actual hardware which

might be produced industrially, and cost and performance estimates will be made on a basis compatible with the evaluations used on the competing systems.

Discussion The CSU unit to be tested for one year on a solar house will no doubt be heavily influenced, in design, construction, choice of materials, etc. by the fact that it is an experimental unit. It is quite unlikely that the design will provide a reliable guideline on the ultimate equipment costs, since the design will rather be aimed at exploring details of equipment operation. It will be necessary to produce plausible designs (based on understanding available at the time) of the type of equipment likely to be marketed should the development work prove successful. This will include only such control and measurement provisions which appear essential to correct operation, but no special observation ports, disassembly flanges, or similar provisions.

Equipment designs will be generated aimed specifically at exploring equipment advantages and disadvantages. As an example, in large systems the liquid-liquid spray tower system may be more cost effective than a heat exchanger system except if the collector is more than say 30ft above the storage tank. In this case the spray tower would force the tank to operate at 1 atmosphere gage, while a heat exchanger system could have an unpressurized tank. Small systems will be explored to see at what point a jacketed tank makes more sense. It will be attempted to come up with plausible approaches to heat potable water with a large system designed for house heating and cooling, without violating code requirements on water-toxic fluid proximity.

d Comparison With Competing Systems

Work Statement The final system designs will be compared with competing systems in order to determine advantages and disadvantages.

Discussion System size, height difference between collector and storage, geographical location, and many other factors may favor one system over another. System comparisons will be made and these will be used to influence the design specification until the limits of usefulness of the systems are established. Unknown areas will be identified.

E Study on Traced Tank Systems

The study on traced tank systems will be fairly simple. Optimized designs will be generated to compare with other systems, and cost and performance figures will be generated. It should be noted that the work will be supported by the design, construction and test of several traced tank systems on inhouse ALTAS funds. The following subtasks will be involved.

a Design of Pressurized Tanks

Work Statement The wall thickness and shape of tanks will be determined for typical pressurized and unpressurized warm water tanks of various sizes.

Discussion - The wall thickness of a tank (probably of steel) is very important in the determination of the heat transfer characteristics when coils are bonded to the wall. The cost also depends on wall thickness. Dependable wall thickness values will be determined using appropriate codes.

b Heat Transfer Analysis of Jacketed Tanks

Work Statement The heat transfer characteristics of the jacketed tank will be determined to find the effective resistance to heat transfer between heat transfer fluid and water.

Discussion The heat transfer in a jacketed tank such as shown in Figure 5 involves (mostly) natural convection in the jacket, coupled to natural convection in the tank. If the heat transfer pictures on both side of the wall are analyzed and coupled then one can obtain the effective heat transfer resistance, needed to determine performance and hence cost-effectiveness.

c Heat Transfer Analysis and Optimization of Traced Tanks

Work Statement The heat transfer coupling between fluid and water will be determined for traced tanks, and optimum tube spacing, bonding techniques, and diameters will be found.

Discussion The heat transfer picture of a traced tank must also be solved. The heat transfer through the fluid convection coefficient, tube wall, tube-to-wall bond, and then through the tank wall to the internal water heat loss coefficient is quite analogous to the heat loss path in some of the Hottel-Whillier-Bliss configurations of the liquid-heating collector, and the same equations can be used to determine the requirements for bond conductance, tube spacing, wall thickness, etc. It will be

necessary to determine an optimum configuration, with an optimized tube diameter and tube spacing, and an adequate bond conductance and wall thickness. It will be interesting to see whether in steel tanks the wall thickness required by codes is thick enough to satisfy the requirements of the thermal design optimum.

d. Comparison of Different Systems

Work Statement Jacketed and traced systems will be compared against competing systems for cost-effectiveness.

Discussion As in the other approaches, a series of different system designs will be made, aimed at exploring the advantages and limitations of the jacketed or traced tank approach, and these will be compared with other systems.

e. Definition of Required Research and Development

Work Statement Additional work needed in the development of cost-effective jacketed or traced tanks will be identified, and work required on stratification will be recommended.

Discussion In addition to the work described in this proposal there will be an inhouse-funded ALTAS program which will also result in the construction and testing of hardware. Between these two programs, required R&D will be identified and described.

F. Study of Other Relevant Questions

There are a number of questions which cut across system boundaries. Some of these have already been discussed in some detail in the technical discussion, and further discussion here does not seem needed. Some others are discussed below.

a. Description of Collector Performance

Work Statement A realistic description of viable collector designs will be prepared and used for system evaluation and comparison.

Discussion The ALTAS CORPORATION recently finished two studies in which computer programs were prepared and results were obtained which are highly relevant to the proposed work. In one study, copper and aluminum absorption plates were cost optimized for specific applications. Cost-optimized collector designs are hence already available, and these cost optima can be updated as desirable. In another study, daily integrated net heat outputs were generated for these collector designs in different

latitudes (32°N, 40°N, and 48°N) for operation at specific liquid input temperatures (see reference 34). These results are also directly applicable, and can be updated as necessary. The computer programs are quite sophisticated, following the general Hottel-Whillier-Bliss approach, but using the exact Stokes equations for normal and parallel components of polarization of incoming solar energy with up to 6 lights (sheets of glass), with easy expansion capability to 9. There is a provision for making the outermost glazing of a different thickness, refractive index, and extinction coefficient. All inner lights are equal.

It should be noted that in system evaluation and comparison some assumption must be made regarding annual heat consumption profile. It seems most realistic to assume consumption is pretty flat, and to use a corresponding collector inclination.

b Determination of the Effect of Storage Tank Pressure on Storage Tank Cost

Work Statement The effect of storage tank pressure on storage tank cost will be determined for tanks of capacities between 100 gallons and 10,000 gallons operating between 150°F and 250°F.

Discussion Except in those systems in which a heat exchanger produces a pressure isolation between the collection and storage loop, the storage tank may have to operate at a pressure dictated by the hydrostatic head imposed by the collector level. Using basement or buried tanks and rooftop collection systems, this hydrostatic head can easily be 1 or 2 atmospheres, a sizable design pressure for a large storage tank. Such a design pressure could be required independently if water storage is wanted above 212°F. The cost effect of the pressure must be known if one is to make a rational choice of heat transfer methods. It is conceivable that in some applications a spray column might be a cheaper and more effective way to transfer heat, but the requirement for a "high pressure" tank might make a heat exchanger approach better anyway. It is unlikely to be practical, in most cases, to put a large storage tank up on the roof at the same level as the collectors. The various pressure vessel and boiler codes will be used to determine tank design variations and cost variations. It should be noted that many of the costs involved with heat storage, such as excavation, installation, plumbing, etc., are likely to be affected little by storage tank design pressure.

c Determination of Optimum Insulation Thicknesses

Work Statement Optimum insulation thicknesses will be calculated, and will be assumed to apply to all plumbing, tanks, and collector parts.

Discussion A realistic evaluation and comparison of the different systems will require the calculation of heat losses from the plumbing, the collector, the heat exchangers, and the tank. In order to do this it is necessary to determine the amount of insulation on these parts. Simple optimization procedures will be used to determine these values.

d Determination of Optimum System Designs

Work Statements The most cost-effective systems for each design concept will be determined using existing computer programs.

Discussion Beyond the heat exchanger paper shown in the Appendix, much experience has been accumulated on the cost-optimization of systems. A computer program for optimization and sensitivity studies was written a long time ago (reference 33), and has already been used on solar energy systems (reference 35). Other cost effectiveness work in solar energy systems has also been done (reference 34).

III SCHEDULE, BUDGET PROGRESS PAYMENT ESTIMATE, AND REPORTING INFORMATION

A Expected Schedule

The overall program does not involve a major engineering effort. Judging purely from the man hours involved, it might seem possible to do it in perhaps 5 or 6 months. It is however undesirable to do so. The work will require interactions with many people across the country such as heat exchanger and collector manufacturers, solar energy specialists using or considering double loop systems, heat transfer fluid manufactureres, etc. In interactions of this type, there are always delays, and on a project of this type it is wasteful if one does not make plans to switch to other work at such times. An additional compelling reason for extending the length of the work somewhat is the fact that the work on the direct contact liquid-liquid spray tower will be based largely on CSU research work, for which the results should be available only some 6-7 months after the start of the work. The work on the definition and intercomparison of the different heat transfer concepts has hence been planned on the basis of a 15 month program, with the corresponding milestone chart shown on page 43.

In the milestone chart on page 43 very little detail is shown on the heat exchanger work. This is because much of the preliminary work has already been accomplished. The main work on the heat exchanger systems will consist in the development of a definitive specification procedure aimed at the HVAC industry. A milestone chart for this work is shown on page 44.

PROGRAM MILESTONE CHART

Months A.R.O.

Milestone Chart for Preparation of Heat Exchanger Selection Material

B Expected Budget

The detailed budget is shown on the standard DD-633 form shown below. The work on the preparation of final guidelines for the specification of optimum heat exchangers involves a significant amount of parametric calculations to determine the required accuracy of the specification procedure, the effect of mis-matched flowrates, to simulate start-up transients and investigate associated thermal inertia problems, to prepare the final design graphics, etc. It is planned to do this work on a digital computer. The project includes consulting involvement by people with previous experience in preparing written material aimed at HVAC practitioners. It also includes one trip to New York for discussions with ASHRAE personnel and others in the New York Engineering Center. The preparation of the final graphics, and some of the interpretation of computer results and collection of manufacturers information will be done by an engineering aide.

Several other areas also require computer work. The work on the combination of an evaporating collector and a condensing heat exchanger will be with the assistance of a computer. The optimization work on traced or jacketed tanks for small systems will also be done on a computer. Other computer calculations may be made on the liquid-liquid spray tower system, and on plumbing diagram (pumping power-heat collection-tube diameter) optimizations.

Many of the tasks require a significant amount of careful engineering. A thorough search of scientific and manufacturer's literature is required to determine the correct choice of fluids. Careful heat transfer equipment design is required in the area of traced tanks. Circulation pumps, heat exchangers, valves, and other plumbing items must be selected in order to determine the cost and performance characteristics of workable, cost-effective systems. In the evaporating condensing systems it is likely a hermetic circulation pump will be almost essential. The evaporating collector must be understood. Code restrictions on the use of toxic fluids to heat potable water must be considered so that the systems examined will be acceptable.

CONTRACT PRICING PROPOSAL (RESEARCH AND DEVELOPMENT)					PAGE NO. 1		NO. OF PAGES 1	
NAME OF OFFEROR ALTAS CORPORATION				SUPPLIES AND/OR SERVICES TO BE FURNISHED Investigation of Viable Methods to Transfer Heat from Solar Liquid-Heating Collectors to Heat Storage Tanks.				
HOME OFFICE ADDRESS 2060 Walsh Avenue, Santa Clara, Calif.								
DIVISION(S) AND LOCATION(S) WHERE WORK IS TO BE PERFORMED Home Office, as above				TOTAL AMOUNT OF PROPOSAL \$ 64,314.00		GOVT SOLICITATION NO.		
DETAIL DESCRIPTION OF COST ELEMENTS								
1. DIRECT MATERIAL (Itemize on Exhibit A)				EST COST (\$)	TOTAL EST COST ¹	REFERENCE ¹		
a. PURCHASED PARTS								
b. SUBCONTRACTED ITEMS								
c. OTHER—(1) RAW MATERIAL								
(2) YOUR STANDARD COMMERCIAL ITEMS								
(3) INTERDIVISIONAL TRANSFERS (At other than cost)								
TOTAL DIRECT MATERIAL								
2. MATERIAL OVERHEAD ² (Rate % X \$ base =)								
3. DIRECT LABOR (Specify)				ESTIMATED HOURS	RATE/HOUR	EST COST (\$)		
Principal Engineer				820	\$13.40	\$10,988		
Senior Engineer				840	\$ 8.50	\$ 7,140		
Engineering Aide				360	\$ 6.50	\$ 2,340		
TOTAL DIRECT LABOR						\$20,468	\$20,468	
4. LABOR OVERHEAD (Specify Department or Cost Center) ³				O.H. RATE	X BASE =	EST COST (\$)		
Labor Overhead				97%	\$20,468	\$19,854		
TOTAL LABOR OVERHEAD						\$19,854	\$19,854	
5. SPECIAL TESTING (Including field work at Government installations)						EST COST (\$)		
TOTAL SPECIAL TESTING								
6. SPECIAL EQUIPMENT (If direct charge) (Itemize on Exhibit A)						EST COST (\$)		
7. TRAVEL (If direct charge) (Give details on attached Schedule)								
a. TRANSPORTATION						\$469.00		
b. PER DIEM OR SUBSISTENCE						\$180.00		
TOTAL TRAVEL						\$649.00	\$ 649	
8. CONSULTANTS (Identify—purpose—rate)						EST COST (\$)		
Officers of ASHRAE, and HVAC Practitioners, \$1800 estimated consulting fees, \$200 estimated expenses.						\$2000.00		
TOTAL CONSULTANTS						\$2000	\$ 2000	
9. OTHER DIRECT COSTS (Itemize on Exhibit A) Computer rental						\$5000	\$ 5000	
TOTAL DIRECT COST AND OVERHEAD							\$47,971	
11. GENERAL AND ADMINISTRATIVE EXPENSE (Rate 23 % of cost element Nos. 3, 4, 7, 8, and 9.							\$11,033	
12. ROYALTIES ⁴								
TOTAL ESTIMATED COST							\$59,004	
14. FEE OR PROFIT 9 % of item 13							\$ 5,310	
TOTAL ESTIMATED COST AND FEE OR PROFIT							\$64,314	
This proposal is submitted for use in connection with and in response to (Describe RFP, etc.)								
and reflects our best estimates as of this date, in accordance with the Instructions to Offerors and the Footnotes which follow.								
TYPED NAME AND TITLE Francis de Winter, President					SIGNATURE			
NAME OF FIRM ALTAS CORPORATION					DATE OF SUBMISSION December 16, 1975			

C EXPECTED PROGRESS PAYMENT INFORMATION

In the first few months it is planned to have a concerted effort to establish contacts with all groups with which interactions will be required, and to collect all data needed in the work. Then there will be a period of a lower level of activity, to develop the understanding needed to complete the final report. The last two months will be taken up primarily by documentation work. The projected level of expenditure throughout the program is shown in Figure 6.

FIGURE 6 Projected Level of Expenditure During the Performance of ERDA Contract No. E (04-3)-1238....Start of Work Was March 15, 1976.

B PLANNED REPORTS

It is planned to submit monthly informal progress reports, containing such information as necessary to gauge the progress made to date, and the conclusions reached. When particular parts of the study are fully documented (such as might be the case if a technical paper is prepared for presentation) it will be included in the progress reports.

Two final reports are planned: one covering the whole study, and one covering only the standard double-loop heat exchanger system.

IV

REFERENCES

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- 2) F. de Winter: "Solar Energy and the Flat Plate Collector, An Annotated Bibliography published in an abridged form in November 1975 ASHRAE Journal, pp56-59, and in full as ASHRAE Bulletin S-101, November 1975.
- 3) F. de Winter: "How to Design and Build a Solar Swimming Pool Heater," Copper Development Association, Inc. Technical Report, (distributed free of charge), 405 Lexington Avenue, N.Y. 10017, August 1975.
- 4) F. de Winter(ed.): "Proceedings of the Solar Cooling for Buildings Workshop," Los Angeles, California February 1974, NSF report NSF-RA-N-74-063.
- 5) M. McFarland: "The Design of Long-Loop Convective Heat Transfer Systems for Solar Heaters," ASME Paper 72-WA/SOL-9.
- 6) "Interim Performance Criteria for Solar Heating and Combined Heating/Cooling Systems and Dwellings," U.S. N.B.S., Washington D.C. January 1, 1975.
- 7) "The Public Health Service Drinking Water Standards," U.S. Department of H.E.W., Washington, D.C. 1962.
- 8) "A Directory of Information Resources in the United States: Water" U.S. National Referral Center for Science and Technology, Washington, D.C. September 1966.
- 9) "American National Standard for Gas Water Heater," Volumes I and III, American Gas Association, Arlington, Virginia 1971.

Several standard references in the area of heat exchangers are included in the technical paper bound as an appendix into this proposal.

- 10) F.A. Brooks: "Solar Energy and its Use for Heating Water in California," Univ. of Calif. Agric. Exp. Sta. Bull. 602, November 1936.
- 11) E.J. Molera and J.C. Cebrian: "Boilers and Condensers for Vapor Engines," U.S. Patent No. 230,323, July 20, 1880.
- 12) C.L.A. Tellier: "The Utilization of Solar Heat for the Elevation of Water," Scientific American, October 3, 1885, page 214.
- 13) Day and Night Manuf. Co., Montevia, California: "Solar Water Heater Customer Literature and Installation Instructions," May 1930.
- 14) D.Q. Kern: "Evaluation of Liquid-Liquid Heat Transfer for Large Desalination," O.S.W. R&D Progress Report No. 261, July 1967.
- 15) P.L.T. Brian: "Engineering for Pure Water, Part 2, Freezing," Mech. Eng. Feb. 1968, pp 42-50.

- 16) F. de Winter and W.S. Lyman: "Home-Built Solar Water Heaters for Swimming Pools," Paper EH-70 presented at the International Congress The Sun in the Service of Mankind, Unesco House, Paris, 2-6 July, 1973.
- 17) S.P. Sukhatme: "Heat Transfer in the Liquid-Liquid Spray Tower," O.S.W. R&D Progress Report No. 120, October 1964. (See also Reference 31).
- 18) T.K. Sherwood and P.L.T. Brian: "Heat and Mass Transfer to Particles Suspended in Agitated Liquids," O.S.W. R&D Progress Report No. 334, April 1968.
- 19) Research Triangle Inst: "The Secondary Refrigerant Freezing Process-A Mathematical Study," O.S.W. R&D Progress Report No. 365, July 1968.
- 20) Struthers Sci. and Internat Corp: "Secondary Refrigerant Freezing Desalting Process: Operation of a 15,000 GPD Pilot Plant," O.S.W. R&D Progress Report No. 416, March 1969.
- 21) M. Ziering: "Spray Freezing, Decanting, and Hydrolysis as Related to Secondary Refrigerant Freezing," O.S.W. R&D Progress Report No. 786, June 1972.
- 22) M. Ziering: "Spray Freezing, Decanting, Melting and Hydrolysis as Related to Secondary Refrigerant Desalting," O.S.W. R&D Progress Report No. 816, July 1972.
- 23) Clarkson Coll. of Techn.: "Dispersion and Miscible Displacement," O.S.W. R&D Progress Rept. No. 822, Dec. 1972.
- 24) J.C. Ward: "Direct Contact Liquid-Liquid Heat Exchangers of Solar Heated and Cooled Buildings," Research Proposal Submitted to ERDA, Colorado State Univ., May 22, 1975.
- 25) A.F. Sarofim: Private Communication, December 1975
- 26) R.J. Schlesinger: Technical Information on Rho Sigma Differential Thermostats for Solar Water Heating or Hot Water System Control, Rho Sigma, 5108 Melvin Ave., Tarzana, CA 91356, Fall 1975
- 27) The literature in the desalination field applicable to liquid-liquid spray towers and freezing is not limited to the reports mentioned earlier. Also included among the O.S.W. R&D progress reports in this field are numbers 7, 10, 40, 41, 63, 94, 95, 96, 98, 113, 120, 141, 146, 157, 179, 180, 230, 239, 242, 256, 261, 282, 292, 294, 312, 334, 365, 368, 376, 408, 416, 436, 474, 494, 501, 517, 658, 738, 750, 770, 786, 797, 802, 816, 822, 823, 838, and 916. Many of these reports are not very useful. It has however become clear that between these reports and the references quoted therein a rich body of experience can be tapped.
- 28) D. Taff, "Discussion of Toxicity of Ethylene and Propylene Glycol" in letters to the editor, Solar Energy Digest (San Diego) Volume 5, No. 6, Dec. 1975.
- 29) J.A. Duffie: Personal Communication, February 28, 1975.
- 30) S.A. Klein, W.A. Beckman and J.A. Duffie: "A Design Procedure For Solar Water Systems" Paper presented at the July-August 1975 ISES meeting at UCLA and to be published in Solar Energy.
- 31) S.P. Sukhatme, M. Hurwitz and S.E. Sadek: "Heat Transfer in the Liquid-Liquid Spray Tower." AIChE Preprint 21 E, Atlantic City, September, 1968.
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- 33) F. de Winter, S.E. Sadek, and J.M. Reynolds: "Parametric Cost Studies of the Multi-Stage Flash Process," O.S.W. R&D Progress Report No.251, March 1967.
- 34) F. de Winter: "Sensitivity Studies on Selective Surfaces," to be published in the near future in the Proceedings of the First TRNSYS Users Meeting, Univ. of Wisconsin, November 13, 1975.
- 35) F. de Winter: "Cost-Effectiveness of a Possible Copper Product: Tapered Fins of Copper for the Flat Plate Solar Energy Collector," Altas Report CDA-9, September 30, 1975.