SUMMER COOLING FOR SINGLE RESIDENCES,
A SYSTEM BASED ON NOCTURNAL RADIATION
AND STORED RAINWATER

BY

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ABSTRACT: SUMMER COOLING FOR SINGLE RESIDENCES, A SYSTEM BASED ON NOCTURNAL RADIATION AND STORED RAINWATER

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The popularity of all house air conditioning has posed a threat to urban energy networks. This study concerns itself with development of a residential cooling system which minimizes energy consumption by utilizing water storage, rooftop nocturnal radiation, and interior radiant cooling panels. Energy useage comparisons under identical conditions indicate the radiant panel-nocturnal cooling system uses but 1/6 the energy of an efficiently installed, conventional central air conditioner.

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I would like to gratefully acknowledge the creative help of Ed Allen in shaping the scope and direction of this design study. Special help from Tim Johnson and Sean Wellesly-Miller provided technical skills for calculating energy cost, heat gains, and equipment sizing.

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SUMMER COOLING FOR SINGLE RESIDENCES

INTRODUCTION:

The demands of the consumer are producing the current trend towards all-house air conditioning which contributes to a growing environmental energy crisis in and around metropolitan areas. The shortages of natural gas and cleanly generated electric power impose a limit on the additional burdens to urban energy networks. An effort should be made to reduce the energy consumption of these cooling systems to in turn reduce the future demand for clean energy.

A major component of the earth's surface heat budget is the exchange of long wave radiation between the ground and the upper layers of the atmosphere; a spaceward flow of infrared radiation continuous as long as the surface of the earth is warmer than outer space. The meteorologists call this radiational cooling. The effect is particularly pronounced on clear, dry nights, and is the major cause of the nocturnal cool down of the earth's surface. This natural heat dissipation process can be utilized to reject waste heat built up during daylight hours. The desert climate of the U.S. southwest has been known for the extreme temperatures of its diurnal cycle; and several building forms have evolved to utilize the noctural cooling of the buildings' mass as a hedge against the impact of the sun during the following day.

This paper will address itself, however, to developing an experimental cooling system for the more temperate, humid climate of the densely populated northeast. The summer season of the 40° N. Latitude is of moderate length with about a 90 day period when residences need to be cooled to achieve comfort in humid conditions. The particular context of the design will be a detached house on a rural site at the northern fringe of suburban Pittsburgh, Pennsylvania. The cooling system developed will be compared to equivalent systems typically used.

<u>PART 1</u>: The Cooling Method: Heat rejection to the atmosphere

The basic mechanism involved in the proposed cooling system is the use of a large reservoir of water as a 'rechargable' heat sink. The water temperature builds up during the day from the components of the building's heat gain (insolation, human metabolic heat, infiltration, humidity) and the accumulated heat is dissipated at night by pumping a continous layer of this reservoir water over the roof surface. The warm water then acts as a 'black body' radiator, as does the earth, and emits long wave radiation to the night sky, thereby becoming cooler.

The outflow of thermal radiation interacts with the layers of the atmosphere, which selectively absorb and reradiate portions of this energy back to earth. Much of the interception, absorption, and reradiation occurs in the layers of ozone, CO_2, and water vapor which occur naturally in the atmosphere. Roughly 75% of the reradiated energy comes from the first water vapor belt at 150 to 200 feet above the ground surface. The presence of moisture in the air or cloud cover increases the reradiation and hence reduces the net outflow of long wave radiation to space. Cloud cover reduces the nightime temperature drop and clear nights normally produce cooler mornings.

Warm water flowing slowly over a roof surface will increase the ambient radiant outflow and cool down to the effective temperature of the night sky. An expression to quantify this net radiation (outflow-reradiation) comes from the Stephan-Boltzman law of radiation exchange:

$$\frac{Q}{A} = \epsilon \sigma (T^4 - T_e^4)$$

which simply states that the heat flow is due only to the difference of the fourth power of the absolute temperatures. For this application: Q/A = heat flow from a roof surface in Btu.'s per hour per square foot of horizontal area covered. (Btuh/ft^2). T = absolute temperature of the water layer in Rankine degrees (°F. + 460). Te = effective temperature of the night sky in °R. when the effects of cloud cover and relative humidity are taken into account. For overcast conditions, the temperature of the lowest cloud layer is used. Typical Pennsylvania summer night temperatures of low clouds range from 40° to 55°F. ϵ = emissivity of water = 0.96 at 100° F.* σ = Stephan - Boltzman constant = 1.714×10^{-9} Btuh/ft.^{2} °R.^{4}

Solutions to this equation for a useful range of water and sky temperatures can be found in Table 1. For instance, typical equivalent temperatures for the summer night sky average 20°F. below the air temperature. (July nightly average air temp.=65°F.) So, if 80°F. water were exposed to the sky on a typical Pennsylvania summer night, the resulting heat flow would be about 30 Btuh. per square foot of horizontal roof area. For a roof covering an area of 2000 ft.^{2}, the heat loss could amount to 60,000 Btuh, the equivalent cooling capacity of a 5 ton air conditioner operating at peak capacity. The hitch (there must always be one) is the amount of water necessary - about 3,000 gallons for the nightly pumping cycle. The actual water consumption (loss due to evaporation) would range from 100 to 300 gallons depending upon temperature and relative humidity. Large water storage tanks make little economic sense unless one uses the context of a rural site, beyond the reach of a municipal water system. In many such wells are necessary but often unpredictable and limited. Residents duct rain water off their roofs into underground

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* Table 2-2 of Sparrow & Cess - reference 16

Effective heat loss of horizontal water covered roof surface

in Btuh per ft.²
by nocturnal radiation

WATER TEMP. in °F.

EQUIVALENT RADIANT TEMP. OF NIGHT SKY in °F.

	70°	75°	80°	85°	90°	95°	100°	105°	110°
70°	no exchange	4.9	9.9	14.8	20.1	26.0	31.8	38.0	44.4
65°	4.9	9.9	14.8	19.6	25.0	30.8	36.7	43.2	49.2
60°	9.9	14.8	19.6	24.6	29.9	36.0	41.6	47.0	54.2
55°	14.3	19.2	24.2	29.2	34.4	40.2	46.2	52.6	58.8
50°	18.7	23.6	28.6	33.5	38.8	44.6	50.8	56.9	63.2
40°	27.1	32.0	37.0	41.9	47.2	53.0	58.9	65.1	71.5
20°	42.8	47.8	52.8	57.6	63.0	69.0	74.5	80.8	87.1
0°	56.2	61.2	66.0	71.1	76.2	82.2	88.0	94.0	100.6
-40°	78.6	83.7	88.3	93.4	98.2	104.4	108.4	116.2	122.4

based upon Stephan-Boltzman equation:

$$\frac{Q}{A} = \varepsilon \sigma \left(T_w^4 - T_s^4 \right)$$

Temp.'s in °R.

$\varepsilon = .96$ for water

$\sigma = 1.714 \times 10^{-9}$ Btu/ hr. ft.² °R.⁴

TABLE 1

tanks called cisterns. These rain water collection tanks range in size from 3,000 to 10,000 gallons and serve as a source of unpotable water for washing, toilet flushing, and/or hot water. The cistern function of an underground tank could easily provide the reservoir capacity of cooling water to be pumped over the roof at night. There are certain basic techniques involved in using the roof as an emitter of thermal radiation. The radiation exchange or flow depends only on the temperature differential so it is rather important to have a pitched roof face the sky rather than the side of a hill or another 'hot' roof. Another key problem involves the flow rate of the reservoir water over the roof. The ideal configuration would be a slow-moving, continuous layer of water over the entire roof surface. The emissivity of water at moderate temperature is 0.96, nearly that of a perfect 'black body' radiator of thermal energy. Listed below are emissivities of material sometimes used on roofs. (from Table 2-2 of E.M. Sparrow and R.D. Cess, Reference 16)

METALS		Temp. °F.	ϵ
Aluminum,	commercial sheet	200	0.09
Copper,	polished	100	0.04
	dull	100	0.15
	black-oxidized	100	0.76
Sheet steel, strong rough oxide		100	0.80
Lead,	grey oxidized	100	0.76
Tin,	bright	100	0.06
Zinc,	galvanized grey	100	0.28

NON-METALS	Temp. °F.	ϵ
Slate asbestos	100	0.97
Clay, fired	200	0.93
Concrete, rough	100	0.94
Glass, smooth	100	0.94
Paints, black gloss	100	0.90
white	100	0.89-0.97
various oil paints	100	0.92-0.96
Roofing paper	100	0.91
Rubber, hard	100	0.94
soft, grey, rough	100	0.86
Water, 0.1mm or more thick	100	0.96
Various woods	100	0.80-0.90

Water has one of the best emittance values of any material commonly used on a roof. If the water is evenly distributed over the roof area, the emittance value of water can be used in the Stephan - Boltzman equation; allowing the actual roofing material to be a reflective metal, for instance, which would reduce solar heat gain. The construction of the roof and materials used can work together to produce the ideal values of surface heat loss from the water film. For instance, if a conventional, heavy tar-and-felt-covered concrete roof is under the sun all day, the heat retained in the materials is enough to keep it warm long after the sun has set. This is to be avoided as it would inhibit the complete cooling of the water. The ideal characteristics of the roof structure would be:

1. High reflectivity of exterior surface to reduce heat buildup during the day.

2. Low pitch or special baffle patterns to effect an even flow of water at night.

3. Low thermal mass of roof sandwich to avoid retention of solar heat.*

4. High insulative capacity to prevent heat penetration to the interior.

5. Unobstructed 'view' of the sky.

*If the thermal capacity of the proposed construction must, for some other reason, be high; then roof surfaces ought to be oriented away from S.W. and W. exposure to avoid heat buildup as the sun goes down and the pumping period begins.

PART 2: Radiant Cooling of the interior.

Thus far I have discussed a heat rejection system based upon water storage and nightime circulation over the roof surface. The question which remains is the method of collection and transfer by which heat is extracted from the interior during daylight hours. Convective air currents serve as the primary mode of heat transfer in most conventional cooling systems. The circulating air is needed to carry off heat and moisture from occupants and equipment. Another heat transfer mode, less commonly applied to buildings, is radiation, or heat flow from a warm body to a cooler one. A basement room with concrete walls can feel cool inspite of a high air temperature because the walls themselves are cool and absorb body heat by the exchange of radiant energy.

If cool water were to circulate within the house in the walls or ceilings, a major portion of the heat load could be absorbed, carried off, stored, and rejected at night.

There are several reasons why radiant cooling is worth considering in the interest of conserving energy. With cool interior surfaces, air circulation can be slower, wider swings in air temperature can be tolerated, and solar radiation can be absorbed before it can heat the air. By reducing the air flow rate, less energy need be expended for cooling and for pushing the additional air through ducts. (Part 3 will deal in further detail with energy cost comparisons.) Many radiant panel systems exist (the idea is ancient), ranging from electrical resistence coils embedded in plaster to parallel copper piping with snap-in metal panels. Applications of these systems have mostly been for heating, but the metal tube fluid systems are theoretically capable of both heating and cooling. However, several problems have to be overcome. The cost of lining one's ceiling with ½ inch copper tubing, six inches center to center, would be prohibitive at today's prices. Condensation is a problem common to all radiant panel cooling systems. Regional weather records for Pittsburgh show that the dew point of air during summer days can often exceed 70°F. The use of radiant panel cooling would require dehumidification of the fresh air necessary to remove moisture and odors.

This would necessitate the use of a mechanical heat pump to achieve the cold temperatures (45°-50°F.) required to remove water from the air in sufficient quantity.

Ideally, a radiant cooling system would use all room surfaces as cooling panels, but this would be impractical. Furniture, rugs, wall hangings, etc., would interfere with the cooling process because the body must 'see' the cool surface to be cooled by it. The ceiling is the logical choice for cooling panel placement, since it will be unobstructed, and will induce convection currents, bringing cool air to the floor. This convection will account for only a small portion of the cooling effect, but it will prevent stratification.

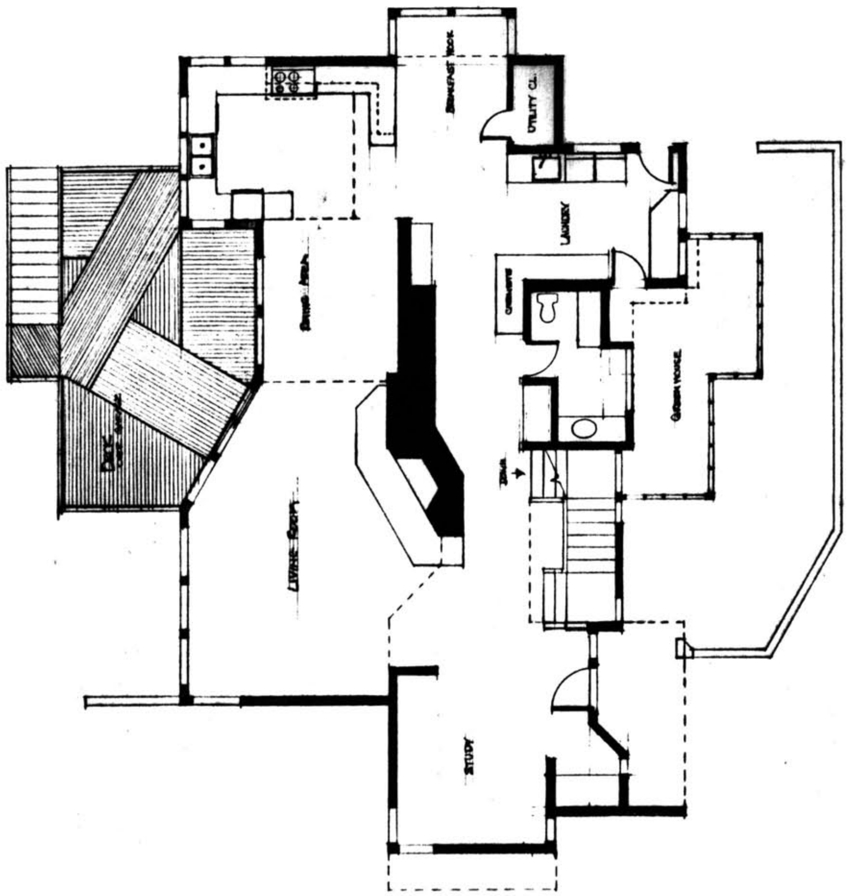
At this point, it may be helpful to include a few design suggestions for the person planning to use radiant cooling in the design of a new home. In general, rooms with high ceilings are more comfortable in hot weather because the hottest air rises above the occupants and can be extracted by exhaust ducts. The use of radiant panels in the entire ceiling should suggest open planning so that a person radiates to a larger ceiling area than that immediately overhead.

All normal precautions to reduce heat gain should be utilized in siting and planning. Fixed and shaded glass, proper and abundant insulation, reflective coloring of outside exposed surfaces, and roof overhangs to shade east, south, and west walls are reasonable control measures. With these considerations in mind, a house has been designed to use as a vehicle for the development of an efficient radiant panel system integrated with the roof emitter system discussed earlier in Part 1. The house design and head gains are summarized in Figures 1 through 3. The problem most difficult to resolve was the physical configuration of the radiant panels in an attempt to find an alternative to high cost copper tube and pan systems. (Ref. For a thorough discussion of conventional radiant panels, see ASHRAE Ref. 2) A continuous layer of moving water must be passed through the ceilings to keep them at a constant low temperature of 60° to 65°F. The final configuration, see Fig. 4, makes extensive use of plastics in the form of header pipes, connecting tubes, and thin vinyl bags resembling a cross between a water bed and an air mattress. The vinyl must be of the type which prevents bacterial growth. In the event of possible minor leakage (all components must be pretested), access must be provided to all fittings to allow necessary joint tightening or bag replacement. The bags are therefore placed flat on top of a ceiling of suspended metal decking which is arranged in tiers to allow access to the bags and headers from the side. The metal decking serves to conduct heat to the water bags, as well as to provide some necessary noise absorption for the

Main Level Plan

$1/16'' = 1'\text{-}0''$

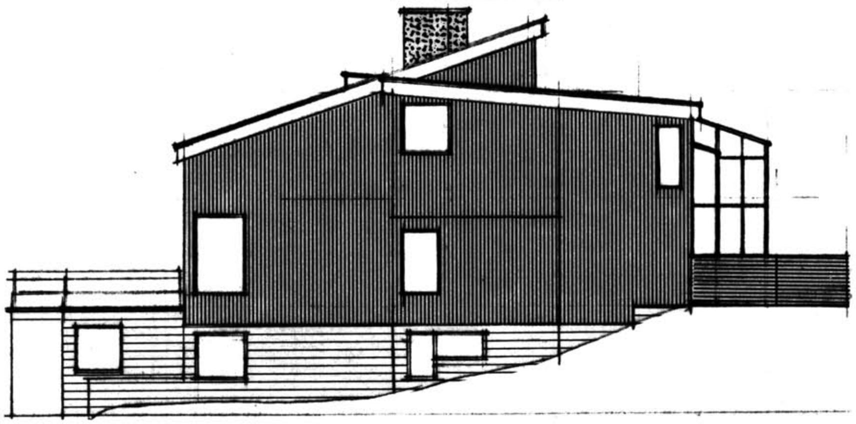
area = 2000 ft.^{2}



HEAT GAIN, Btuh

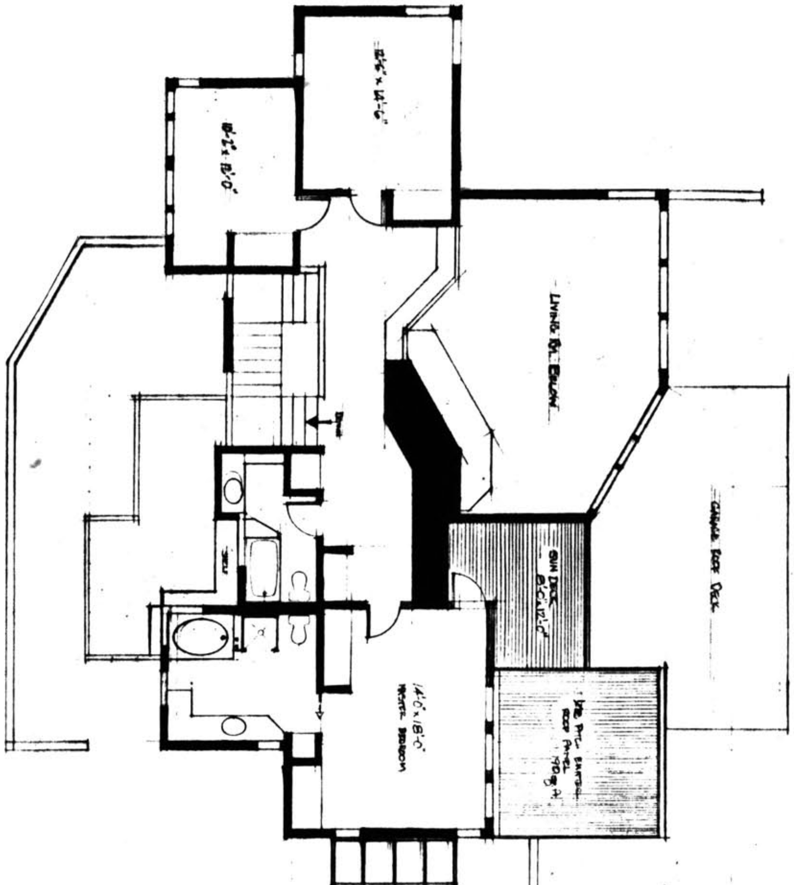
<u>Sensible heat</u>	
walls, shaded	1500
exposed	3500
roof	5000
all glazing	20000
<u>Latent heat</u>	
people, plants, appliances, cooking	5000

Tight windows and positive air pressure on the interior eliminate heat gain due to infiltration of outside air.

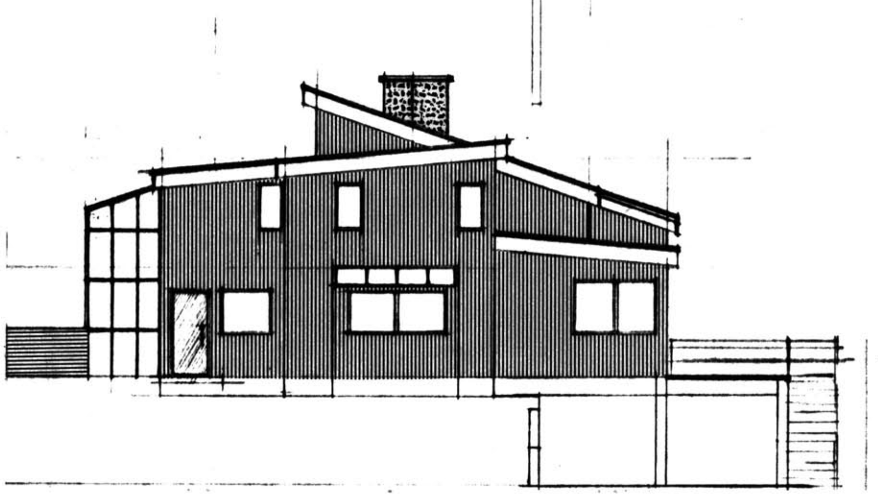


West elevation

FIGURE 1

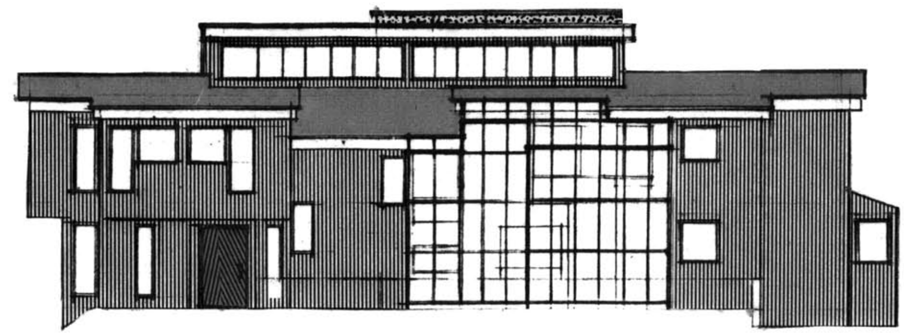


Upper Level Plan
1/16"=1'-0"

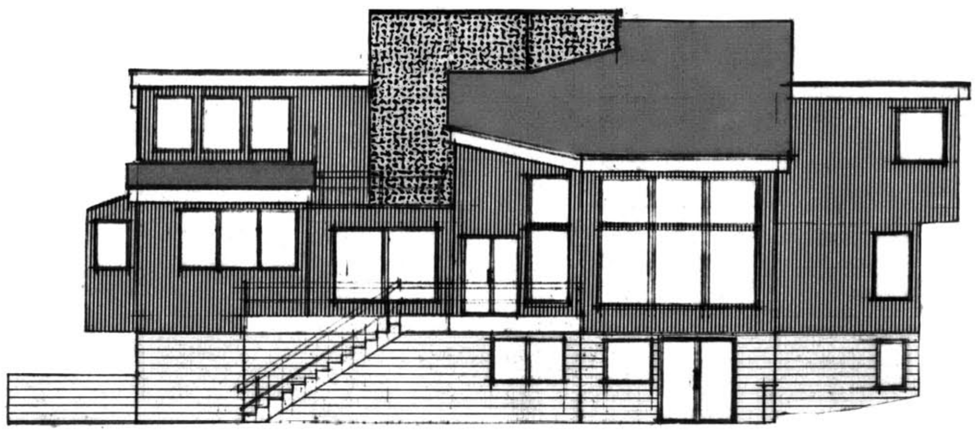


East elevation

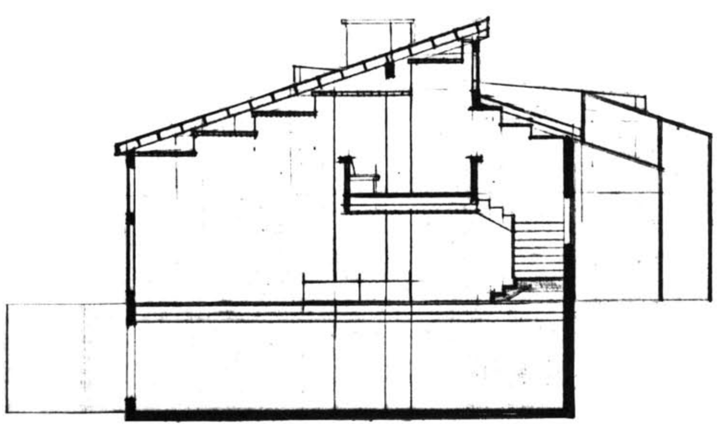
FIGURE 2



South elevation



North elevation



Section
1/16″ = 1′-0″

shows tiers of radiant panels under pitched roof

FIGURE 3

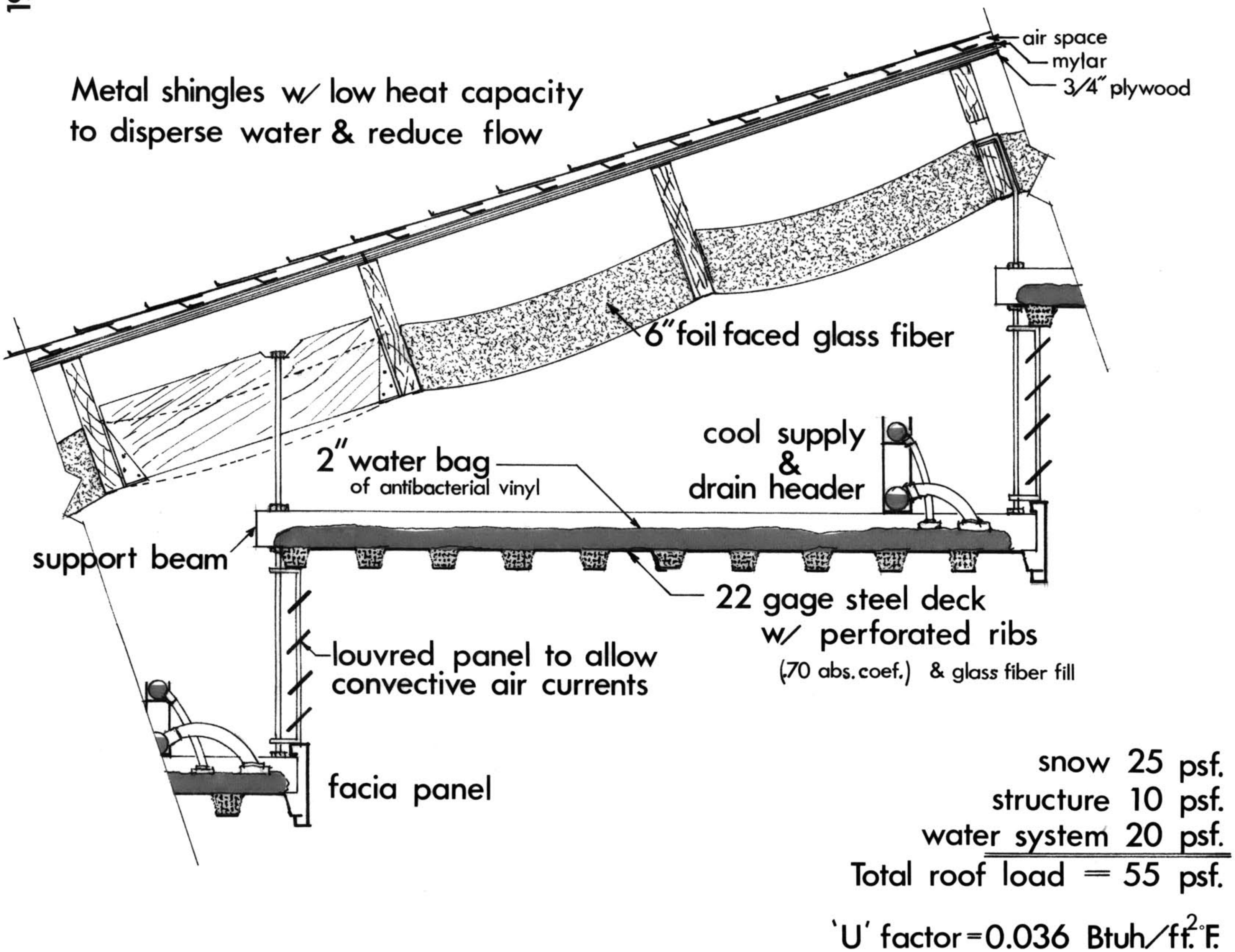


FIGURE 4

Radiant panel configuration under pitched roof

1 inch = 1 foot

space below. The high ceiling and metal surfaces could produce an acoustical disaster, especially if air became trapped in the bags and they began to gurgle. (In this scheme, water does not circulate during the night.) The circulating water is supplied by gravity feed at a very low pressure, which is maintained by special chambers, located at the end of every supply header, which overflow into drains should the pressure surge briefly. This is to insure the long life and reliability of the system. The vinyl, heat-welded bags are channeled to circulate water evenly over the metal deck. Each individual bag covers an area of about 30 sq. ft. and is kept in darkness to avoid ultraviolet decay or eventual brittleness caused by direct exposure to sunlight. Once working, the system should be durable and maintainance-free.

PART 3: Comparison to other systems.

This section is a summary of calculations comparing the above radiant panel--small heat pump system to two other space conditioning systems using air convectionand no radiant panels. One has an air-to-water heat pump, a water storage tank, and nocturnal heat rejection on the roof. The other has a conventional central air conditioning plant, or air-to-air heat pump. The energy consumption of the three systems is calculated and compared and an attempt is made to compare first costs of materials and equipment.

Air entering the prototype house from the outside must be dehumidified and cooled from the 90°F., 50% relative humidity air, to air which leaves the house at conditions lower than 75°F., 60% relative humidity. Industry recommendations (ASHRAE) for ventilation rates approve a minimum of ½ room air change per hour for areas kept cool by radiant panels. If the heat gain is removed by air only, as in two of the systems, air change rates in excess of 1½ room air changes per hour are recommended. This is partially due to the inefficiency of air as a heat transport medium,and to the need for 'faster' air to counteract the radiation of warm walls and ceilings to one's body reversing the normal radiation component of body heat from a loss to a gain. In a sense, a radiant panel cooling system is the system preferred by the body because heat is rejected through radiation as well as conduction. It may well be healthier and more invigorating than systems relying entirely on chilled air. For purposes of comparison, the energy consumption of the three systems will be calculated assuming identical conditions for the skin of the house. The same insulation, tightly gasketed windows, and glass area will be assumed. For simplicity, the same heat loads will be used for all systems, 30,000 Btuh sensible and 5,000 Btuh latent. In the radiant panel-- small heat pump system, the sensible heat is absorbed through the panels by the circulating water, and the latent heat is removed in the dehumidification of the ventilation air. The other systems remove both sensible and latent heat with a mixture of dehumidified fresh and recirculated air. The ventilation rate for the last two systems is 1,250 cfm, based on a minimum allowable temperature of introduced air of 67°F. This lower limit is somewhat arbitrary. There is no reason why air entering the rooms could not be colder, except for the discomfort to persons near the air diffusers. The 1,250 cfm amounts to about 1 3/4 room air changes per hour. All systems employ energy conservation devices such as heat recovery wheels which utilize the 75°F. exhaust air to begin to cool incoming air. The two air streams do not mix, but exchange heat by means of a rotating wheel of wire mesh. The assumed efficiency is 25%, contributing about 1,500 Btuh sensible cooling. (See system diagrams Figs. 5,6,& 7). The work input in watts for mechanical components, i.e. pumps, fans, heat pumps, is listed for each system, and the total energy cost in dollars is based on the equivalent of 90 days of peak operation per cooling season. (See Fig. 8).

Predicting and estimating the first cost of an untried and complex system of radiant panels, water tanks, and special roof surfaces is beyond even the usual ball-park guessing techniques. Figure 9 lists differences between these three systems in terms of the physical equipment used in each.

RADIANT PANEL SYSTEM with Air-to-water Heat Pump

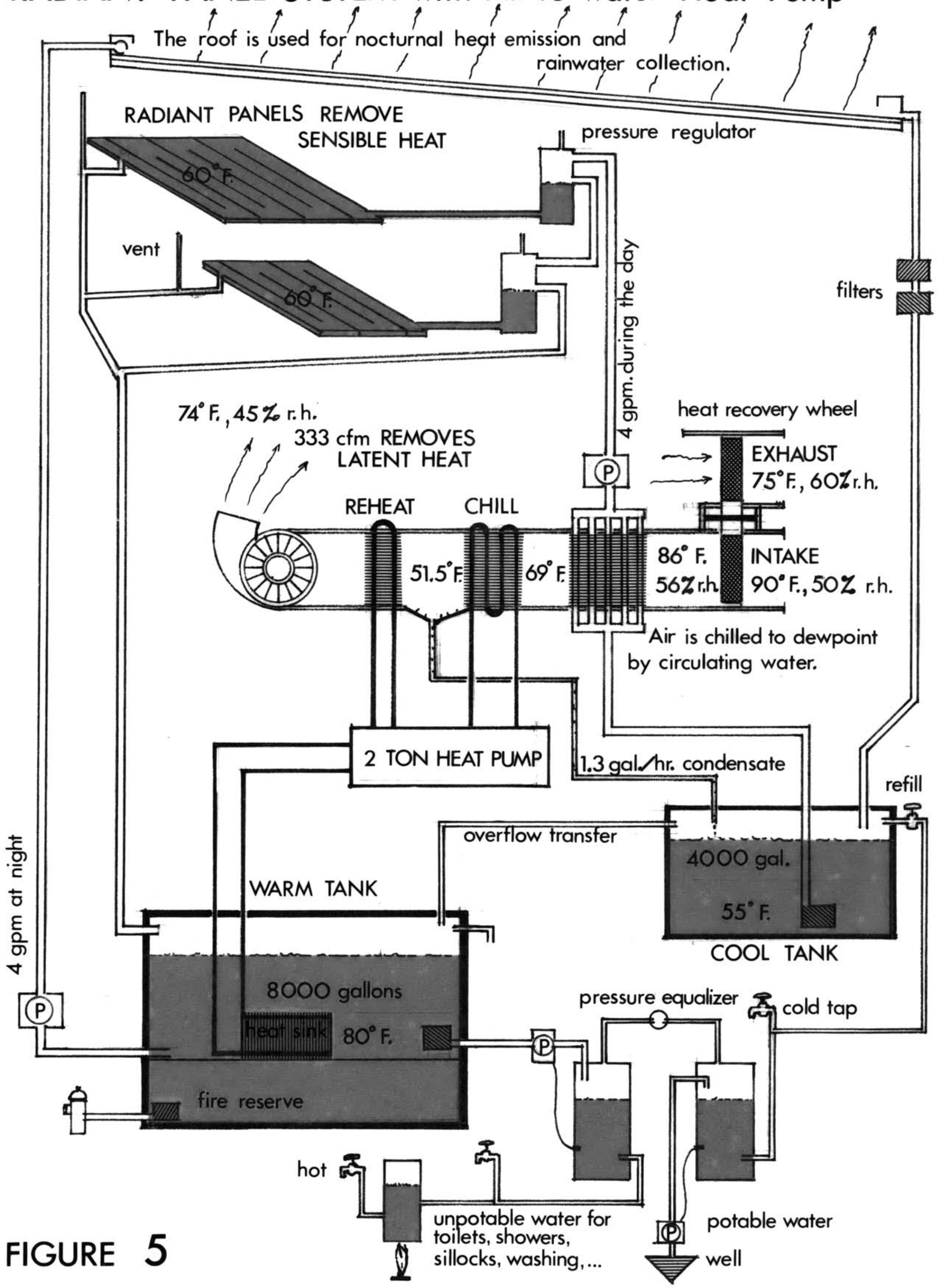


FIGURE 5

CONVECTION: Air-to-water Heat Pump

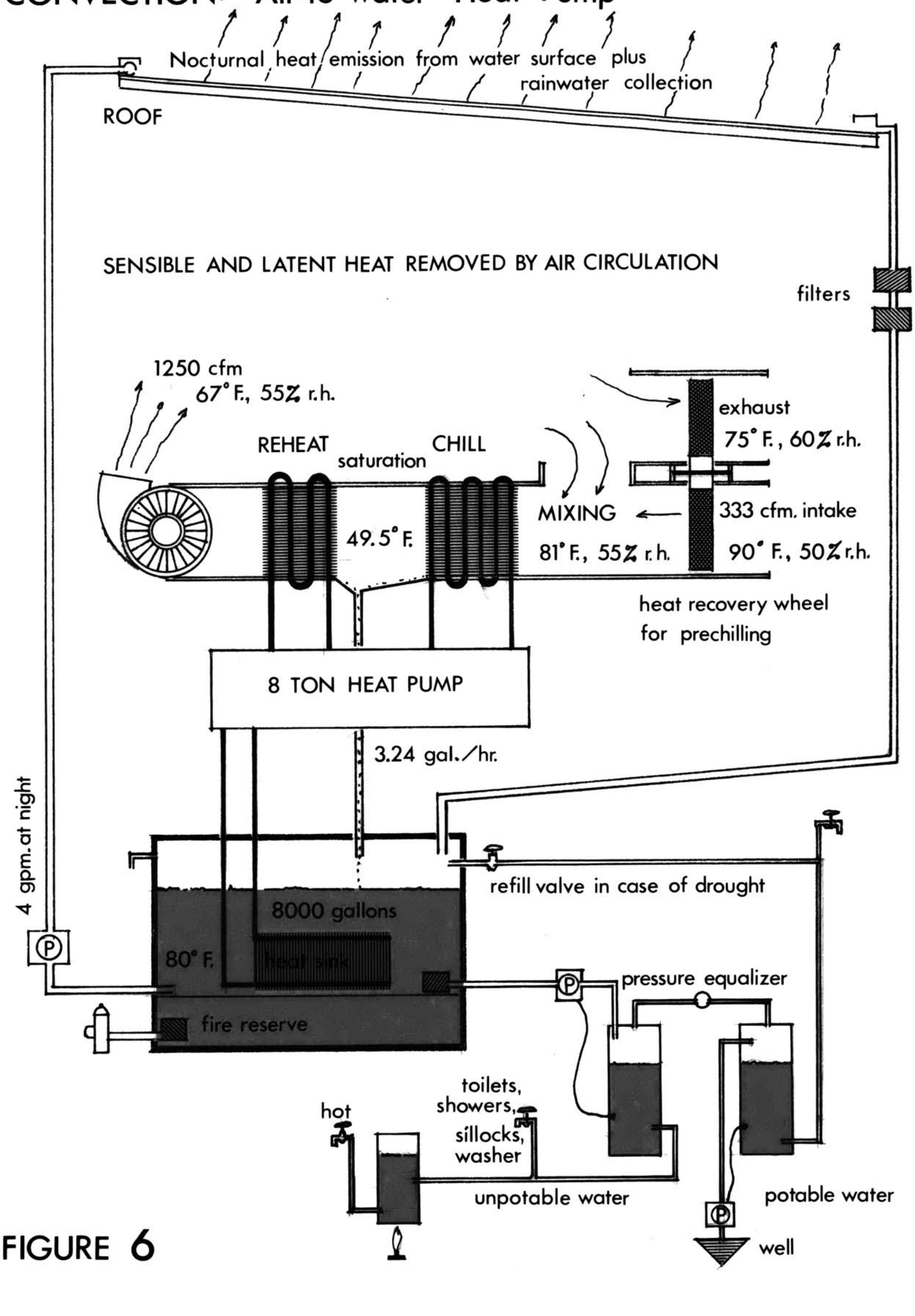


FIGURE 6

CONVECTION: Air-to-air Heat Pump

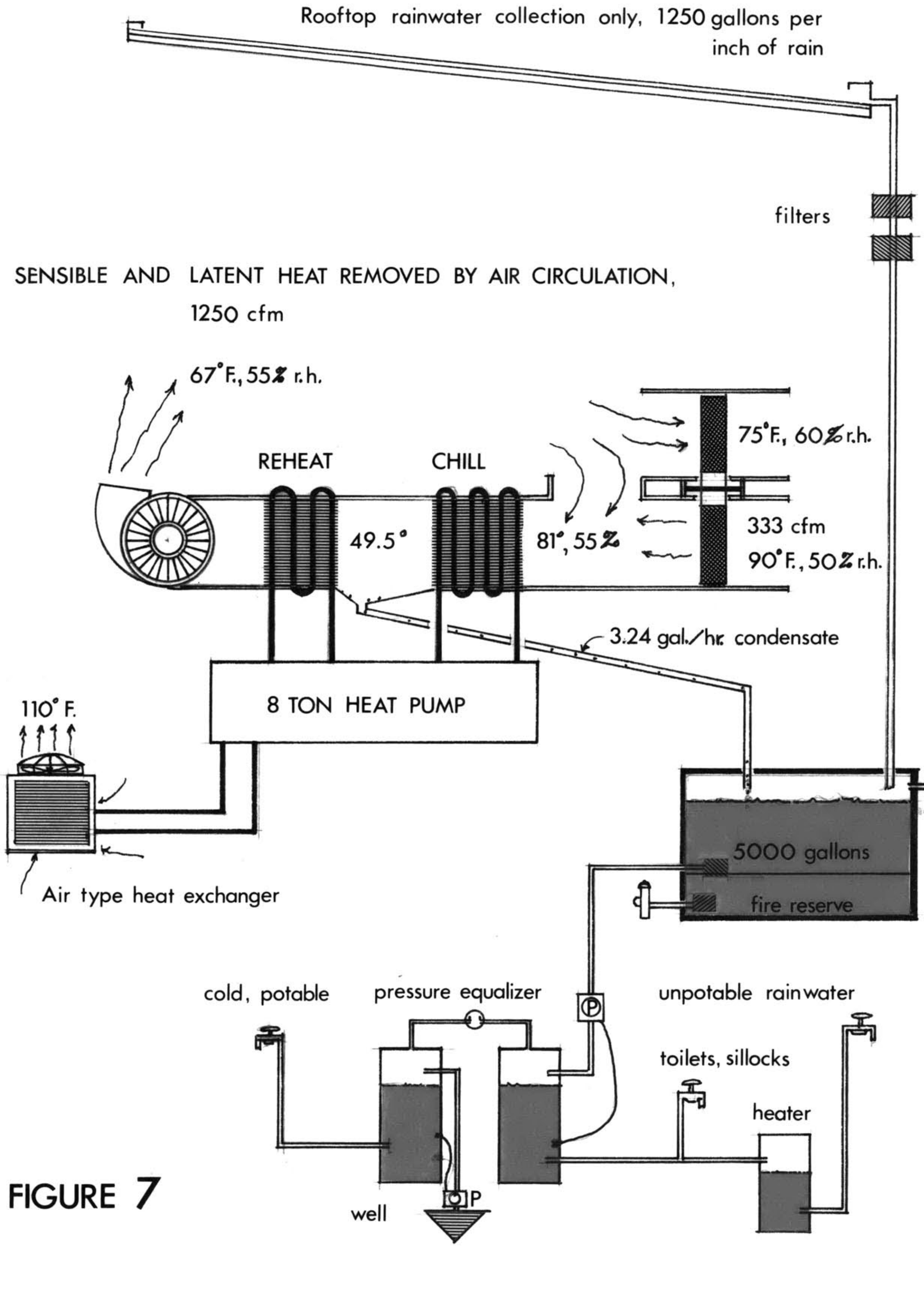


FIGURE 7

FIGURE 8

SYSTEMS COMPARISON: Energy Costs

RADIANT PANEL SYSTEM with an AIR-TO-WATER HEAT PUMP	CONVECTION with AIR-TO-WATER HEAT PUMP	CONVECTION with AIR-TO-AIR HEAT PUMP
] peak day	] peak day	] peak day
PUMPING OPERATIONS		
3000 gallons over roof (night) 3000 gallons thru house (day)	3000 gallons over roof at night	none
],200 watts	600 watts	
FANS		
333 cfm 6,400 watts	],250 cfm 24,000 watts	],250 cfm 24,000 watts
]2 HOUR USE OF HEAT PUMP		
PERFORMANCE COEFFICIENT = 9.0	PERF. COEFF. = 8.4	PERF. COEFF. = 3.6
power consumption 7,200 watts	30,500 watts	70,000 watts
TOTAL DAILY ENERGY USE FOR COOLING THE HOUSE		
]4,800 watts	55,]00 watts	94,000 watts
90 DAY COST @ $0.03 per kwh		
$40.00	$]50.00	$255.00

FIGURE 9

SYSTEMS COMPARISON: Equipment

RADIANT PANEL SYSTEM with AIR-TO-WATER HEAT PUMP	CONVECTION with AIR-TO-WATER HEAT PUMP	CONVECTION with AIR-TO-AIR HEAT PUMP
4000 gallon tank		
8000 gallon tank	8000 gallon tank	5000 gallon tank for rainwater retension
2 ton (24,000 Btuh) heat pump	8 ton (96,000 Btuh) h.p.	8 ton (96,000 Btuh) h.p.
0.5 horsepower ventilating fan	1.5 hp. fan	1.5 hp. fan
Roof piping to spray water at night	Roof piping	none
Dispersion shingles	Dispersion shingles	ordinary roofing
Radiant panels (water bags, metal decking, piping, etc.)	none	none
Air ducts to handle 333cfm.	Ducts to handle 1,250 cfm	Ducts for 1,250 cfm.
ROOF structured for 55 psf.	ROOF structural load of 35 psf.	Roof load 35 psf.
2 1/10 hp. pumps to circulate cooling water and lift water to the roof	1 1/10 hp. water pump	no pumps other than those for normal plumbing

When comparing the three systems, one should note the energy savings of the air-to-water heat pump over the conventional air-to-air type. The additional first cost to provide only the rooftop and tank arrangement is minimal when balanced against 41.2% running cost savings over the air-to-air system. Although running costs are very low for the radiant panel system, unless one were to fabricate and install these radiant panels on a do-it-yourself basis, the first cost might be prohibitive -- due mostly to labor. The radiant panel system could be largely homemade from common industrial stock, but would be very laborious to install.

SUMMARY

Night radiant cooling, using the roof to radiate waste heat, is an apparent success in terms of providing a more efficient method of heat rejection than mechanical heat exchangers operating in the heat of the day. The idea is worth further development in the form of small scale experiments to determine the reliability and cooling capacity of a full scale installation.

The three systems compared earlier offer a range of choice from a system which is obviously experimental but potentially economical to a compromise system with intermediate energy savings to an off-the-shelf system of proven reliability, predictable cost, and high energy consumption. The conventional cooling system (air-to-air heat pump), typical of many going into houses and small buildings everywhere, consumes six times the energy of the proposed radiant panel cooling system. For today's conditions, the intermediate system using an air-to-water heat pump, conventional convective cooling, and the night radiant cooling to the atmosphere offers a viable alternative at relatively little risk and maintainance. However, radiant panels could be cheap, efficient, and easy to install with the proper industrial support enabling the consumer to take advantage of a significant energy savings.

APPENDIX: Sample Calculations

Useful Conversion Factors

volume of 1 lb. dry air = 13.6 cu. ft. at 75°F., 50% r.h.
weight of 1 gal. water = 8.33 lbs.
weight of 1 cu. ft. water = 62.4 lbs.

1 ft.-lb./min. = 0.02260 watts
1 Btu./hr. = 1 Btuh. = 0.2930 watts
1 hp. = 745.7 watts

EQUIPMENT SIZING CALCULATIONS for the Radiant Panel System with an air-to-water heat pump (see Figure 5)

Given conditions:
Outside air at 90° F., 50% relative humidity, enthalpy of 33.4 Btu./lb.dry air
Minimum ventilation rate = 1/2 room air change per hr. = 333 cfm.
Air is exhausted at 75°F., 60% r.h.
30,000 Btuh. sensible heat is absorbed by water circulation in the radiant panels
5,000 Btuh. latent heat must be removed by air circulation

The Heat Recovery Wheel (25% efficiency) will cool 90° F. air to 86° F. if the outgoing air stream is at 75° F. The moisture content of the incoming airstream remains the same so the relative humidity increases from 50% to 56%.

The Circulating Water originates in a 4000 gallon underground tank at 55° F. The water is used to chill the incoming airstream down to its dewpoint (69° F.) by being pumped through fin-tubes before it reaches the vinyl bags of the radiant panels.
The change from 86° F., 56% r.h. to 69° F., 100% r.h. requires 4.2 Btu./lb.dry air (taken from a psychrometric chart found in any air conditioning manual).

Heat transfered to the water = 333cfm. x 60min./hr. x 1 lb.dry air/13.6 cu. ft. x 4.2 Btu./lb.dry air

= 6,180 Btuh.

The water temperature change is of course based on the volume of water passed through the fin-tubes. A 3000 gallon circulation volume in a 12 hour period is the flow necessary for adequate nocturnal radiant cooling on the roof.
The water flow rate through the fin-tubes is 4 gal./min.

Temp. increase of water = 6180 Btuh./(4 gpm. x 60 min./hr.) x 1 gal./8.33 lb. = 3.1F°

Due to inefficiencies and unavoidable heat gains, the temperature of water entering the radiant panels would be about 60° F.

If the 30,000 Btuh. of sensible heat is absorbed into the radiant panels, the increase in water temperature is:

Δ T = 30,000 Btuh./ (4 gpm. x 60 min./hr. x 8.33 lb./gal.)
 = 15° F.

The water enters the large storage tank at 75° F.

DEHUMIDIFICATION

The 5000 Btuh. of latent heat is to be removed by the ventilation air, exhausted at 75° F., 60% r.h. at 333 cfm. The difference in enthalpy between room entry air and exhaust air is:

5000 Btuh. x 13.6 cu.ft./(333 cfm. x 60 min./hr. x 1 lb.dry air)

= 3.4 Btu./lb.dry air

74° F., 45% r.h. air has the necessary enthalpy difference, and has the same moisture content as saturated air at 51.5° F. 51.5° F. is the low point temperature of the heat pump in the dehumidification process, cooling the air down from 69° F., 100% r.h. This cooldown involves an enthalpy change of 12.6 Btu./lb.dry air.

Required cooling capacity of the air-to-water heat pump =

12.6 Btu./lb.dry air x 20,000 cu, ft./hr. x 1 lb, d.air/13.6 cu.ft.

= 18,400 Btuh.

Conservative practice would use a 2 Ton (24,000 Btuh) capacity heat pump in case of long hot periods when the tank temperature might climb higher than normal.

Not all of the heat extracted from the air stream is rejected to the storage tank because of the reheat phase. The 12,000 to 14,000 Btuh. rejected raises the 8000 gallon tank temperature 3° to 5° F. to a maximum of 80° F.

The energy required to do that 18,400 Btuh. of cooling is calculated once the performance coefficient of the heat pump has been determined:

Perf, Coeff. = heat extracted/work done x 50% efficiency
 = Temp. low in °Rankine/ΔT
 = (460 + 51.5)/(80-51.5)
 = 18.0

therefore,

Work done = (18,400 Btuh. x 0.2930 WATTS/Btuh.)/ (18 x .50)
 = 600 WATTS (power used in one hour)

Power consumption for 12 hours (1 days operation) would amount to 7.2 Kwh.

PUMPING

2 pumps, each for 12 hours, 3000 gallons over a 30 ft. head

Power used per day (50% efficiency)

= 2 x 12hrs. x 30 ft. x 3000 gal./12hrs. x 8.33 lbs./gal. x 1 hr./60 min. x 0.2260 watts/ft.-lb./min.

= 1.2 Kwh per day

FANS

Assume a performance factor of 7 (~15% efficiency) and a duct pressure of 1 inch water or 5 lbs./ft.^{2}

Power used for 24 hour operation = 24 hrs. x 5 lbs./ft^2 x 333 cfm. x 7 x 0.02260 watts/ft.-lb./min.

= 6,400 watts

= 6.4 Kwh

TOTAL POWER USE

HEAT PUMP	7.2 Kwh
Pumps	1.2 Kwh
Fans	6.4 Kwh
	14.8 Kwh for one day of cooling

at $0.03 per Kwh, a 90 peak day cooling season would cost $40.00

Simular calculations for other systems produced the results listed in Figure 8.

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