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HEATING SYSTEMS FOR AIRPORT PAVEMENT SNOW, SLUSH, AND ICE CONTROL

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FINAL REPORT

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16. Abstract

The uniqueness of the investigations reported herein is in the application of pavement heating systems to airport runways, taxiways, and ramps. Electrical, oil-fired steam, and solar heated pavement systems were investigated. Pavement area sizes ranged from a full runway (1,500,000 ft^2) to a ramp (60,000 ft^2). Both new and existing construction installations were considered. Climates ranged from severe (Juneau, Alaska) to relatively mild (Baltimore, Maryland). Because slush is more disruptive to airport operations than dry snow, and because the pavement heating systems become very expensive to build and operate as the weather climate becomes very severe, Juneau was eliminated from the studies and Chicago, Illinois was substituted in its place.

Of the three systems investigated, the capital, total annual, and annual operating costs for an electrically heated runway are the highest. The capital and total annual costs for a steam heated runway are lower than for either the electrical or solar systems. The annual operating cost of the solar system is the lowest for the range of pavement areas represented by runways and ramps.

The electrical system is the least efficient and the steam system is the most efficient in the utilization of the Nation's energy resources. For the most part, the solar system does not use the Nation's energy resources.

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METRIC CONVERSION FACTORS

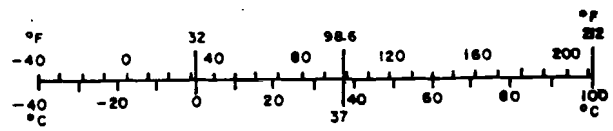
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

The heating of pavements in the winter to remove snow, slush, and ice is not new. Electrical heating elements for use in flexible and rigid pavements are commercially available. At the present time, a large electrically heated highway interchange is under construction in Louisville, Kentucky, and an earth heat pipe ramp is being installed in an interchange in Oak Hill, West Virginia.

The uniqueness of the investigations reported herein is in the application of pavement heating systems to airport runways, taxiways, and ramps. Whereas, in a highway situation, vehicular traffic can tolerate slush and occasional accumulation, aircraft cannot. The second material difference between these applications is in the size of the pavement area to be serviced. The Louisville, Kentucky, interchange represents a pavement area of 160,000 ft^2. A typical airport ILS runway has an area of 1,500,000 ft^2. Other differences exist between these applications but these have only second order effects on the heating system designs.

The requirement to eliminate slush on heated runway and taxiway surfaces, for all snow conditions except for occasional severe blizzards, imposes a minimum surface heat flux requirement on airport pavement heating systems. The minimum surface heat flux requirement is higher than that imposed on heated highway pavements. This eliminates from consideration earth heat pipe systems in all except mild winter environments.

In addition to the higher surface heat flux requirements, the airport pavement areas to be heated are an order of magnitude larger than the typical highway interchange areas. The combination of higher heat fluxes and larger pavement areas thus results in large energy source subsystems for airport applications. For example, a 60,000 horsepower steam generating plant will be required to service a 1,500,000 ft^2 runway in the Philadelphia to New York regions. These large energy requirements represent a severe drawback for electrically heated pavement systems because of the high cost of standby power for this convenient and high quality form of energy.

The desire of the Nation to conserve energy was taken into consideration when the heating systems to be studied were selected. The heating system uses heat which is obtained, most commonly, by burning oil, gas, or coal. The most efficient method of transporting heat from one location to another is by steam. Therefore, one of the systems investigated was an oil-fired steam system. This system conserves more of the Nation's fossile fuel than does the electrical heating system. This is because of the electrical system's losses associated with converting heat into electricity and then electricity back into heat.

Nevertheless, the electrical system was retained in the investigation for purposes of comparison because it represents a technology which is in commercial existence. On the opposite side of the energy conservation spectrum, the earth heat pipe system does not require the use of our natural fossile fuel resources. Unfortunately, in its present state of development, it was not considered able to meet the specified pavement heat flux requirements and, therefore, it was eliminated. A system utilizing the radiant energy of the sun was substituted for the earth heat pipe system in this investigation.

Consequently, the systems selected for investigation are the solar system which conserves most of our natural fossile fuel resources; the steam system which, for this application, uses the resources most efficiently; and the electrical system which represents the most inefficient use of our fuel resources. The state-of-art technology of these systems is the exact opposite of their fuel conservation rating. The hardware for the solar system is now under development in the United States, whereas the hardware for the electrical system is commercially available.

The investigation was required to determine the economic feasibility of using heated pavements for airports. This proved to be more difficult than anticipated. It was initially thought that the airport costs attributed to snow were only related to the annual snowfall. It is now known that this is not exactly true which, in a way, turned out to be fortunate insofar as economic feasibility is concerned.

The design feature which is perhaps the most unique is the use of heat pipes in the energy distribution subsystems of the steam and solar systems. Like a metal

conductor, the heat pipe is a passive heat transfer device. Unlike a metal conductor, the heat pipe can transfer heat over long distances without an appreciable temperature drop. The heat pipe (described in more detail in Section 5) is a proven device and, when designed and applied within its limitations, will provide years of trouble-free service. The ammonia/steel heat pipe combination specified for the energy distribution subsystems of this investigation has been qualified for use in permafrost stabilization on the 6-billion dollar oil pipeline now being constructed in Alaska.

As the history of technological development has demonstrated many times, new systems benefit the most by technology advances. Although the solar system, as presented herein, incorporates the best of today's proven technology, there are under investigation in the United States improvements which, if successful, will increase its attractiveness for this application (Reference 11).

A design of the recommended pavement heating system was prepared as part of this study. The pavement area selected was the intersection of ILS runways 15-33 and 10-28 located at the Baltimore-Washington International airport. Specification DTM-098-1001 (Installation/Acceptance Specification for Solar Heated Runway Intersection) for this design is reproduced in Appendix C. The DTM drawings (and the referenced subordinate drawings) listed on pages 3 and 4 of DTM-098-1001 may be obtained from the National Technical Information Service.

2. PAVEMENT HEATING REQUIREMENTS

There are two aspects of airport pavement heating for which the requirements must be determined with reasonable accuracy. The first deals with the amount of heat flux needed at the pavement surface to maintain a snow and ice free surface under the specified weather conditions. The second aspect deals with the amount of energy needed to be expended annually by the pavement heating system to perform its intended function.

The requirements for surface heat flux and annual energy affect the various pavement heating systems differently. In all cases, the required level of surface heat flux determines the capacity of the pavement heating system. For the electrical system, the capacity is determined by the rating and spacing of the electrical heaters and the rating of the electrical substation. The capacity of the steam system is determined by the capacity of the steam boilers, and the surface heat flux is adjusted by changing the steam pressure. The capacity of the solar system is determined by the temperature and flow rate of the heated storage water.

Each system must be capable of supplying the annual energy requirements. The electrical system receives its energy from a public utility; and, therefore, its energy supply is virtually inexhaustible. The energy source for the steam system is a fossile fuel (coal, oil, or natural gas). Except for spot shortages that may occur for a particular fuel type, the steam system is also assured of an inexhaustible energy supply. The solar system, on the other hand, is designed for a specified consumption of annual energy. If more consumption is required, the area of the solar collectors and the volume of the water storage reservoir must be increased.

It is evident, therefore, that the designs of electrical and steam heated pavement systems are determined by the specified surface heat flux and that the design of a solar heated pavement system is determined by both the specified surface heat flux and annual energy consumption. The capital cost of each system is determined by its design. Operating costs are partly determined by the cost of energy and, in the case of the electrical system, also by the system capacity (demand power).

This study concerns itself with not only the practicality of airport pavement heating systems but also with their economic justification. Therefore, a considerable part of the study effort was devoted to establishing the requirements for pavement surface heat flux and annual energy consumption. This was done for climate conditions represented by O'Hare International airport and for a Reference airport.

2.1 Surface Heat Flux for O'Hare and Reference Airports

The surface flux necessary to assure the melting of incident snowfall on a runway pavement can be determined as a function of the ambient conditions and the behavioral characteristics of the thermal distribution subsystem. For this reason, a thermal model has been developed which analyzes the transient behavior of actively heated concrete pavements subjected to a variety of initial and boundary conditions representative of typical ambient environments. The development of this model can be categorized according to the determination of the resistance from the concrete surface to the ambient sink, the resistance network within the concrete, and the transient behavior of actively heated pavements. The program efforts associated with the development of this model, and the results obtained through its application to ambient environments simulating O'Hare and the Reference airports, are discussed below.

The thermal resistance between the concrete surface and the ambient environment must account for heat transfer through convection, radiation, and for a wet surface evaporation. Empirical relationships for these ambient losses have been determined under a previous DOT program (Reference 5) and are summarized in the following paragraphs.

Convective heat transfer at the surface is defined by the following equation:

$$q_{c,v} = (1 + 0.3V)(T_s - T_a)/3.41$$

where:

$q_{c,v}$ = convection heat loss (watts/ft^2)

T_s = temperature of surface (^oF)

T_a = ambient temperature (^oF)

V = wind speed (mph)

The radiative heat transfer is expressed by the following relationship:

$$q_r = \left[0.22\,(T_s - T_a) + 3.50\right](1 - 0.75\,n)$$

where:

q_r = radiative heat loss (watts/ft^2)

T_s, T_a = (same as above)

n = cloud cover in tenths

The evaporative heat loss of a wet surface is expressed as:

$$q_e = (0.0201\,V + 0.055)\,(p_{v,w} - p_{v,a})\,h_{f,g}/3.41$$

where:

q_e = evaporative heat loss (watts/ft^2)

$p_{v,w}$ = vapor pressure associated with surface temperature (inches of Hg)

$p_{v,a}$ = atmospheric vapor pressure (inches of Hg)

$h_{f,g}$ = enthalpy of saturated vapor at surface temperature (Btu/lbm)

The experimental nature of the previous DOT program has enabled the validation of the above equations; hence they are judged to accurately describe the heat transfer mechanism between the concrete surface and the ambient sink.

Another important aspect in the modeling of an actively heated concrete pavement is the determination of the thermal resistance between the heat source and the concrete surface. This determination is made as a function of concrete properties and design parameters associated with the thermal distribution subsystem. For this purpose, a two-dimensional nodal network model was developed. This model used the computer program THERMO (originally developed at Goddard Space Flight Center in the early 1960's). This network model was used to simulate the behavior of line source and mat distribution subsystems. A schematic representation of the network for a line

source is shown in Figure 2.1. A general description of the nodal network and the assumptions it incorporates follows.

Basically, the analytical model is capable of predicting transient and steady-state behavior of the nodal network as a function of specified initial conditions, boundary conditions, and heat input from the element of the distribution subsystem. All nodes at the concrete surface are coupled to the ambient sink by conductances consistent with the ambient loss equations. Conductances between adjacent nodes within the concrete are evaluated for a concrete conductivity of 1.0 Btu/hr-ft-^{o}F. Based on experimental results of the previously referenced DOT program, the contact resistance between the concrete and the heat source element is neglected. Nodes at the lower concrete surface are connected to a ground source temperature by a conductance value derived during the previous program. A thermal capacitance is assigned to each node to allow solutions to transient problems.

In addition to satisfying the thermal balance between the concrete surface temperature and the ambient environment, the nodal network is also capable of simulating heat loads resulting from fusion requirements. This is accomplished by incorporating adjustable heat sinks at all the surface nodes. Adjustment to the heat load at any node is controlled by the absolute temperature of that node. This feature enables surface temperature stabilization at the fusion temperature and accumulation whenever the available flux into a surface node is exceeded by the ambient losses and the melting requirements.

This nodal network has been used extensively in the parametric evaluation of the thermal distribution subsystem. The bulk of the analysis was performed on line source distribution subsystems of 6-inch spacing. Mat subsystems were also evaluated. This subsystem evaluation was conducted to determine the effects on performance of line source depth and spacing, pavement conductivity, and transient boundary conditions.

Due to the finite conductance paths within the concrete runway, line source distribution subsystems result in flux variations at the concrete surface which are dependent on the depth and spacing of the line sources. Based on economic and performance

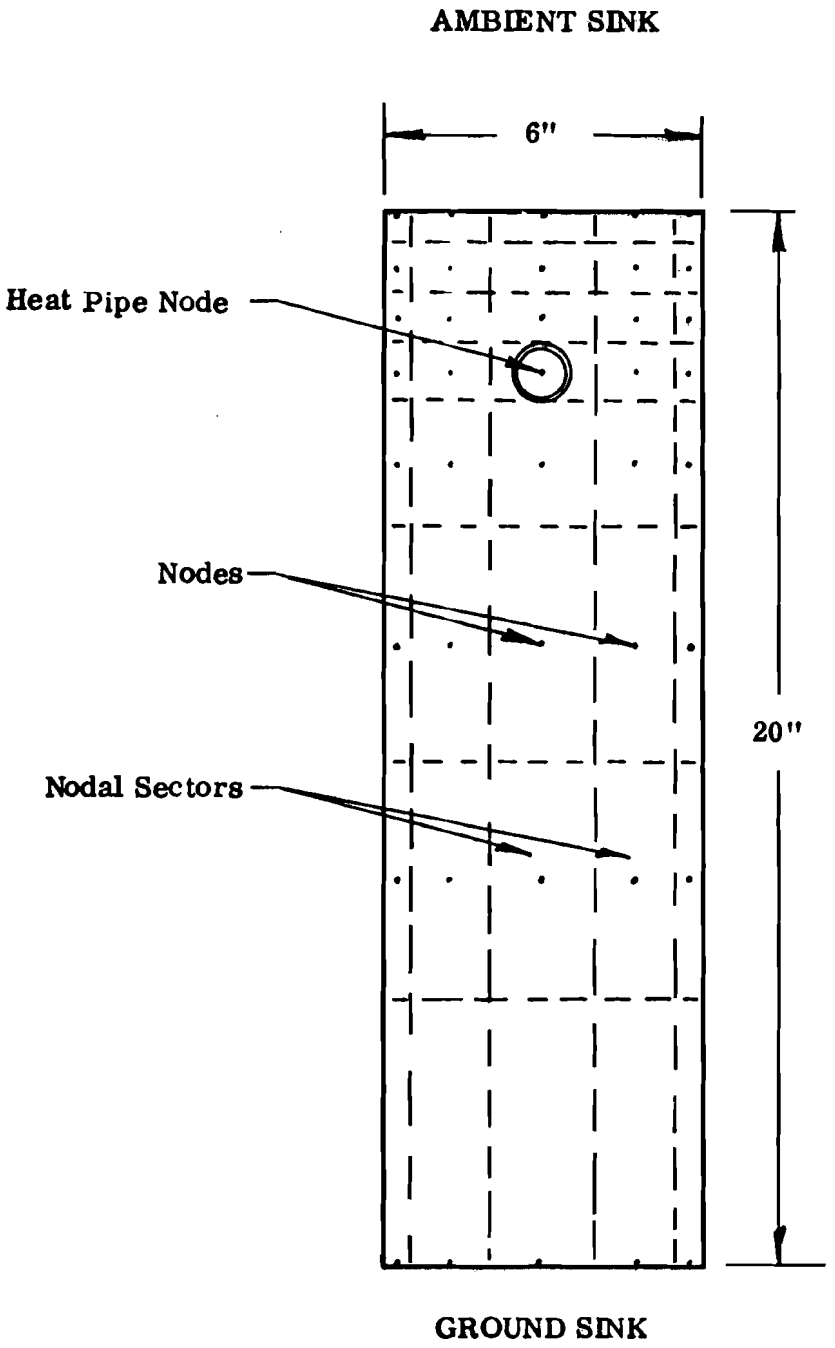


FIGURE 2.1

NODAL NETWORK MODEL FOR A LINE SOURCE

considerations, 6 inches was selected as the line source spacing. The variation in surface flux for a line source spacing of 6 inches and depths of 2 inches and 3 inches is shown in Figure 2.2. At each depth, the surface flux variation is given for dry and melting surfaces. For a fixed line source flux, the curves show the surface flux profiles when the ambient temperature is 19°F and the wind speed is 11.5 mph. The dashed curves are for a dry surface, and the solid curves are for snow melting at the rate of 0.04 inch per hour. At a line source depth of 2 inches, the surface flux variation is much greater than the variation at a depth of 3 inches. Also, the flux difference between the wet and dry surfaces is more apparent at the smaller depth. These two observations are indicative of the magnitude of the resistance paths within the concrete. At depths near 3 inches, the value of the conductance from the concrete surface to the sink has little effect on the flux distribution. It is also evident from Figure 2.2 that the average surface flux during melting (for a constant heat input) is slightly above that for a dry surface. This can be explained by the fact that the dry surface flux variation is a steady-state prediction, while the melting surface predictions are taken after a large (24 hours) but finite time period and include a small contribution due to sensible heat loss.

The depth and spacing of line source distribution subsystems also affect the relationship between the source's flux and temperature. At a constant line source flux, line source temperature increases as spacing increases. The effect of line source depth on the temperature-flux relationship for a spacing of 6 inches is shown in Figure 2.3. Generally, as line source depth increases, its equilibrium temperature at constant flux increases. This figure assumes that the surface temperature is isothermal at 32°F. The temperature-flux relationship for the heat distribution subsystem is a determining factor in the overall design of systems incorporating low temperature energy sources.

The nodal network has also been used to determine the effect of the thermal inertia of the pavement thermal distribution system on melting capabilities of line source and mat systems. This evaluation predicts the surface accumulation on a concrete surface as a function of input heat flux and preheat period. The ambient conditions used

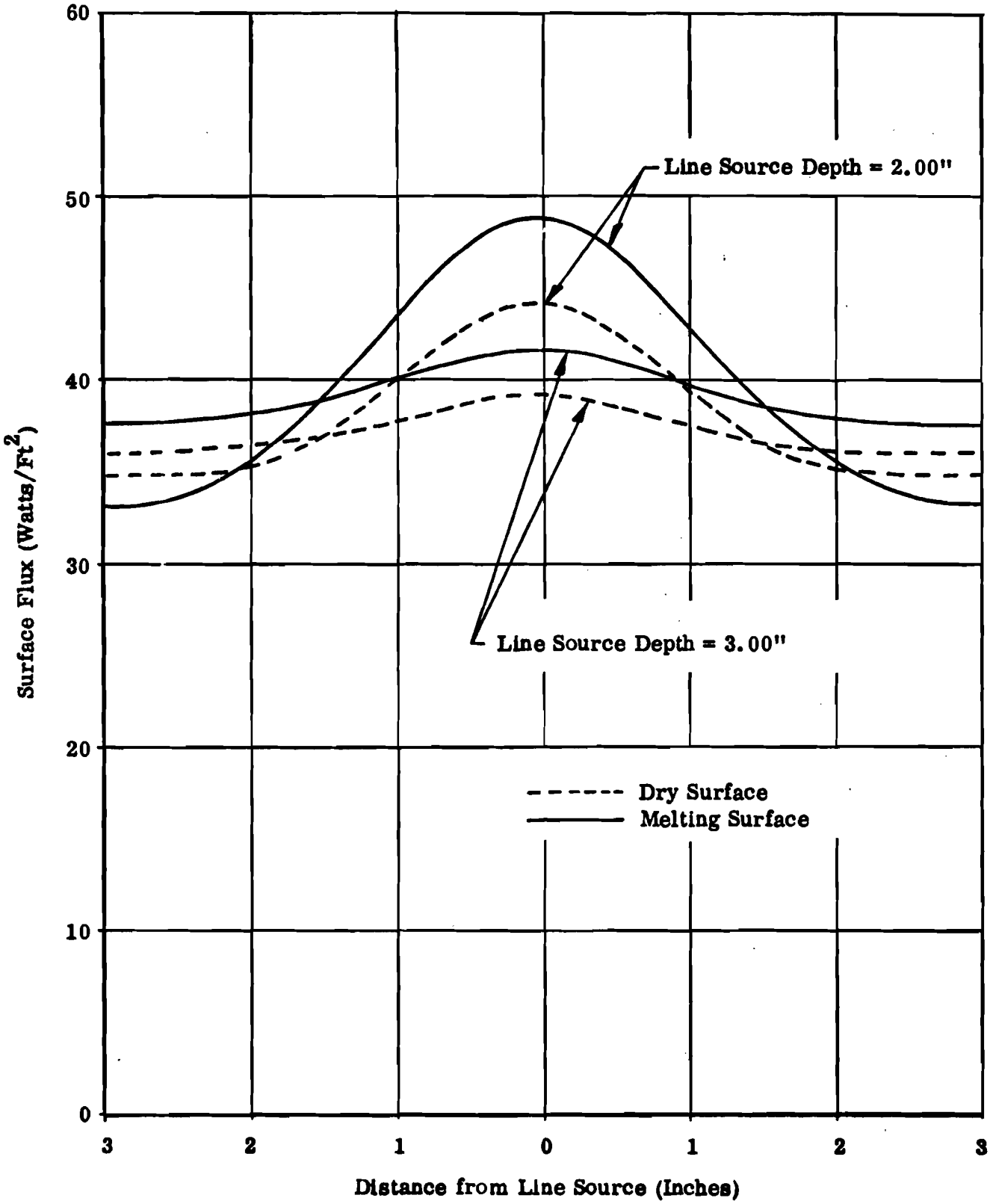


FIGURE 2.2

SURFACE FLUX VARIATION FOR CONSTANT HEAT INPUT
FOR A LINE SOURCE DISTRIBUTION SUBSYSTEM

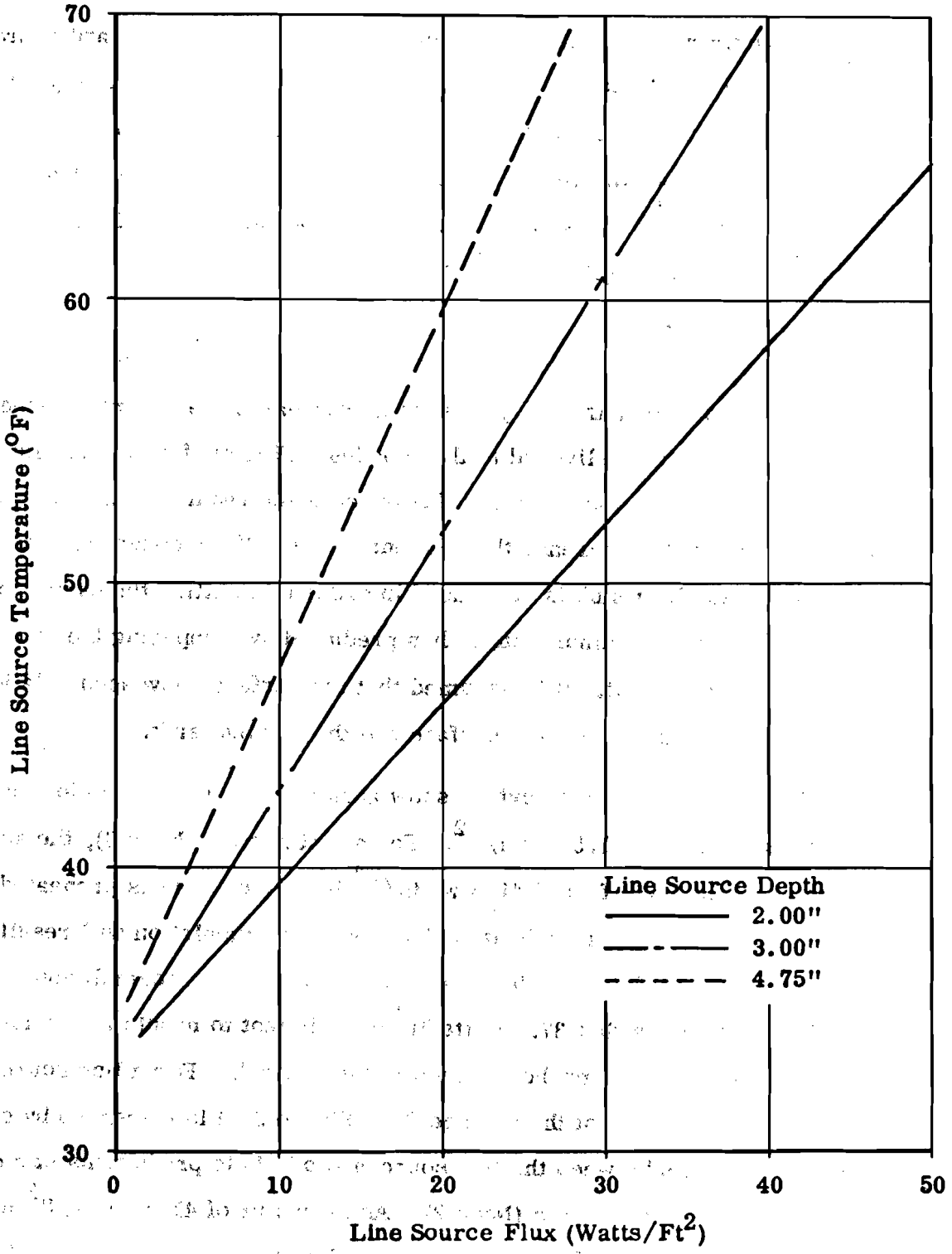


FIGURE 2.3

LINE SOURCE TEMPERATURE VERSUS
LINE SOURCE FLUX FOR A MELTING SURFACE

simulated the most severe winter month environments at O'Hare and the Reference airports. Initially, the concrete pavement is assumed to be in thermal equilibrium with an average ambient environment (defined by an average daily temperature and an average wind speed according to the published weather data for each airport). The pavement is then subjected to more severe ambient conditions (defined by the minimum daily temperature and average wind speed). At the same time, it is assumed that the heat distribution system is activated. This condition is allowed to persist for a definite period (preheat), after which snowfall begins. The snowfall rate is defined at each location as one-third of the recorded maximum monthly snowfall falling within a 24-hour period. The relative humidity is assumed to be 85 percent during the snowfall. During the snowfall period, which lasts 18 hours, the analytical model compares the flux requirements at the surface nodes to the flux delivered to these nodes. (The surface temperature is assumed to be 32°F). When the delivered flux exceeds the required flux, the surface temperature is increased to increase the ambient losses. If the converse is true, the magnitude of the fusion heat sink is decreased in order to stabilize the surface temperature at 32°F. The snow accumulation is then predicted by comparing the fusion heat sink to the fusion requirement. It is assumed that the surface snow accumulation does not affect the conductance between the surface and the ambient sink.

Table 2.1 summarizes the surface snow accumulation in Chicago for heat input fluxes of 37.5 watts/ft^2 and 41.5 watts/ft^2. For a mat system (Node 3), the surface will remain clear at an input flux of 41.5 watts/ft^2 if the pavement is preheated for a period of 6 hours. For shorter preheat periods, snow accumulation will result but will eventually disappear. At the lower input flux, the fact that the accumulation is decreasing after 18 hours indicates that 37.5 watts/ft^2 is sufficient to handle the incident snowfall (mat system) provided the preheat period is long enough. For a line source distribution system, centralization of the surface flux (Figure 2.2) is evidenced by comparing predictions between the line sources (Node 1) to predictions at a distance from the line source (Node 2). An input flux of 41.5 watts/ft^2 is sufficient to overcome the effects of surface flux centralization, as evidenced by the slight accumulation (0.1 inch) over Node 1 for a preheat period of 6 hours. At an input flux of 37.5 watts/ft^2, the analytical predicts a constant increase in snow accumulation

Weather Information	Ambient Temperature : 19°F Wind Speed : 11.5 mph						Snowfall : 0.4"/Hr Relative Humidity : 85%					
Heat Flux (Watts/Ft^2)	37.5						41.5					
Pavement Preheat Period (Hrs)	3			6			3			6		
Node Number	1	2	3	1	2	3	1	2	3	1	2	3
Max. Accumulation (Inches)	4.4	3.0	2.5	3.4	1.5	1.3	2.6	1.1	0.9	0.1	0.0	0.0
Duration of Accumulation* (Interval Hours)	1-18	1-18	1-18	1-18	1-18	1-18	1-18	1-13	1-12	2-6	---	---
Accumulation Trend After 18 Hours	I	D	D	I	D	D	D	M	M	M	M	M

*The system behavior is summarized for the first 18 hours of snowfall.

Node Location

(1) Surface Node Between Heat Pipes
(2) Surface Node 1.75" Away From Heat Pipes
(3) Surface Node Above Heat Pipe Mat

Accumulation Trends

I = Increasing
D = Decreasing
M = Melting

TABLE 2.1

HEAT DISTRIBUTION SUBSYSTEM BEHAVIOR FOR O'HARE AIRPORT

over Node 1. Actually, this is not entirely accurate because of the insulating effect of the snow covering which would increase melting capability and eventually stabilize the snow accumulation thickness. However, the inclusion of this effect would require detailed analytical modeling which is not needed for the analysis of acceptable system performance.

Table 2.2 summarizes the behavior of a mat and a line source subsystem for the Reference airport at input heat fluxes of 23 watts/ft^2 and 25 watts/ft^2. At the lower flux, a mat system is the only acceptable distribution system provided that the preheat period is 6 hours. At the higher heat flux, the line source distribution system will result in no snow accumulation for a preheat period of 6 hours.

The surface heat flux values used in the economic analyses were 26.8 watts/ft^2 for the Reference airport and 37.5 watts/ft^2 for O'Hare International airport. Recognizing that the weather conditions used in the transient analyses are more severe than the average weather conditions, the value of 37.5 watts/ft^2 for the surface heat flux for O'Hare is considered acceptable.

2.2 Annual Energy Requirements for O'Hare and Reference Airports

The pavement heating systems consume energy throughout the winter in performing their snow melting function. The amount of energy consumed depends on the severity of the winter climate (temperature, humidity, wind speed, and amount of snowfall) and on the number of times the heating system must be activated. During the winter, energy consumption varies from month to month. In the United States, the energy consumption is the highest in January because this is the month during which the most severe winter weather occurs.

The weather data used to calculate the annual energy requirements for O'Hare and the Reference airports is given in Table 2.3. This table presents the typical average monthly weather conditions which exist at these two airports. Note that the total number of snow days for O'Hare is 12 and for the Reference airport the total is 10.

In order to proceed with the energy consumption calculations, certain assumptions had to be made:

Weather Information	Ambient Temperature : 26.3°F Wind Speed : 11.0 mph						Snowfall : 0.5"/Hr Relative Humidity : 85%					
Heat Flux (Watts/Ft^2)	23.0						25.0					
Pavement Preheat Period (Hrs)	3			6			3			6		
Node Number	1	2	3	1	2	3	1	2	3	1	2	3
Max. Accumulation (Inches)	3.1	2.2	1.3	3.3	0.8	0.2	2.3	0.5	0.0	0.0	0.0	0.0
Duration of Accumulation* (Interval Hours)	1-18	1-18	1-18	2-18	3-18	4-18	1-18	1-15	---	---	---	---
Accumulation Trend After 18 Hours	I	I	I	I	I	D	D	M	M	M	M	M

*The system behavior is summarized for the first 18 hours of snowfall.

Node Location

(1) Surface Node Between Heat Pipes
(2) Surface Node 1.75" Away From Heat Pipes
(3) Surface Node Above Heat Pipe Mat

Accumulation Trends

I = Increasing
D = Decreasing
M = Melting

TABLE 2.2

HEAT DISTRIBUTION SUBSYSTEM BEHAVIOR FOR REFERENCE AIRPORT

FAA WJH Technical Center
00090612

Month	O'HARE AIRPORT					REFERENCE AIRPORT				
	Ambient Temp. (°F)	Relative Humidity (%)	Wind Speed (mph)	Amount Snowfall (inches)	Snow Days Per Month	Ambient Temp. (°F)	Relative Humidity (%)	Wind Speed (mph)	Amount Snowfall (inches)	Snow Days Per Month
Oct	55.1	64.3	9.8	0.3	0.5	--	--	--	--	--
Nov	39.9	70.3	11.4	2.5	1.0	47.0	70	10	0.9	0.5
Dec	29.1	73.8	11.2	9.7	3.0	35.9	70	11	6.0	2.0
Jan	26.0	67.3	11.5	9.7	3.0	33.2	70	11	7.5	2.0
Feb	27.7	65.5	11.7	7.9	2.0	33.4	68	11	9.0	3.0
Mar	36.3	64.8	11.9	7.7	2.0	40.5	69	11	5.5	2.0
Apr	49.0	62.5	11.8	1.1	0.5	51.4	69	11	1.0	0.5

TABLE 2.3

TYPICAL MONTHLY AVERAGE WEATHER DATA
FOR O'HARE AND REFERENCE AIRPORTS

- Ten inches of snow are equivalent to one inch of water. Under this assumption, the thermal energy required to melt one inch of snow is 22 watt-hrs/ft^2.

- The duration of the average snowfall is 18 hours. This is a conservative assumption because the duration of a snowfall is a function of the storm size (Reference 1). For storms dropping between 0.5 and 3.5 inches of snow, the median duration is 10 hours. The median duration for storm sizes in excess of 6.5 inches of snow is 16 hours.

- The preheat duration is 6 hours (see Section 2.1).

- The pavement surface during melting is at 32°F.

- The pavement surface is wet during preheat and melting. This is a conservative assumption since the thermal losses for a wet surface are higher than those for a dry surface.

- The air temperature during December, January, February, and March is 32°F for the Reference airport thermal loss calculations. This assumption was required because the average monthly temperatures for the Reference airport are above 32°F throughout the winter (Table 2.3). If these higher temperatures were to be used, the thermal loss calculations would produce negative numbers which would indicate a heat input to the pavement surface.

Using these assumptions, the monthly thermal loss and snow melt energy requirements listed in Table 2.4 were obtained for O'Hare and the Reference airports. The total annual energy requirement for O'Hare is 3,073 watt-hrs/ft^2 and for the Reference airport it is 1,487 watt-hrs/ft^2. These values were obtained by summing up only the positive monthly requirements for each airport.

The control subsystem for each pavement heating system must be capable of maintaining the pavement surface at 32°F during snow melting. Pavement surface temperatures higher than 32°F will result in higher energy consumptions than those reported.

MONTH	O'HARE AIRPORT			REFERENCE AIRPORT		
	Thermal Losses (Watt-Hrs/Ft^2)	Snow Melting Requirement (Watt-Hrs/Ft^2)	Total Energy Requirement (Watt-Hrs/Ft^2)	Thermal Losses (Watt-Hrs/Ft^2)	Snow Melting Requirement (Watt-Hrs/Ft^2)	Total Energy Requirement (Watt-Hrs/Ft^2)
Oct.	-384	7	Negative	---	---	---
Nov.	-215	55	Negative	-33	20	Negative
Dec.	686	213	899	180	132	312
Jan.	1040	213	1253	242	165	407
Feb.	637	174	811	382	198	580
Mar.	-59	169	110	67	121	188
Apr.	-287	24	Negative	-75	22	Negative
			3073			1487

TABLE 2.4

ENERGY REQUIREMENTS FOR SNOW REMOVAL
AT O'HARE AND REFERENCE AIRPORTS

3. DESCRIPTION OF HEATING SYSTEMS

Pavement heating systems may be subdivided into three subsystems:

- Energy source subsystem is that part of the system which supplies the energy. This energy can be in various forms such as heated fluids, vaporized fluids (steam), radiation (infrared), and electricity.

- Energy distribution subsystem is that part of the system which distributes the energy in the pavement. The energy may be distributed by various methods such as electrical heating cables, fluid or steam pipes, and heat pipes.

- Energy transport subsystem is that part of the system which carries the energy from the energy source subsystem to the energy distribution subsystem. The energy may be transported by such means as electrical cables and pipes.

The variants of the above subsystems can be combined to generate many pavement heating system designs. Of the various possible combinations, three have been selected for detailed study:

- Electrical Pavement Heating System
- Oil-Fired Steam Pavement Heating System
- Solar Pavement Heating System

The electrical system utilizes electric heating cables in the pavement (energy distribution subsystem), whereas the steam and solar systems utilize heat pipes to distribute the heat in the pavement. Obviously, the energy source subsystem for the electric system could be diesel-electric and for the steam system it could be steam-electric. Similarly, the energy distribution subsystem for the electrical system could consist of electrically-heated heat pipes (Reference 5). The systems selected for study appear to be the best practical compromises of the many available alternate systems.

The electrical, steam, and solar systems described in the following subsections are based on the requirements for the Reference airport. In each case, the system de-

sign is for an entire ILS runway (10,000 feet long and 150 feet wide). The systems are designed to provide a minimum surface heat flux of 26.8 Watts/ft^2, and they each consume 1.49 Kilowatt-hours/ft^2 annually.

3.1 Electrical Pavement Heating System

The electrical system consists of a high voltage substation, control room, high voltage underground cables (running from the substation to runway area), electrical heating cables (embedded in the pavement), and a drain water system. The overall layout of the electrical system is shown in Figure 3.1.

As in all system designs, the aboveground structures are located 750 feet from the centerline of the runway. The high voltage cables run from the 50,000 Kva substation to and along both sides of the runway. The cables are located inboard of the drain water trenches. At 200-foot intervals, the high voltage cable is tapped into the high voltage sides of the runway transformers. These transformers reduce the voltage from 12,000 volts to 480 volts which is the working voltage for the heating cables. A flow diagram of the electrical system is shown in Figure 3.2.

Unlike the Louisville, Kentucky, electrically heated interchange, the design shown in Figures 3.1 and 3.2 does not use redundant heating cables in the pavement. Rather, the design approach has been to rely on the reliability of high quality heating cables and to fuse each cable individually so that chain reaction failures cannot occur (Figure 3.2). A single heating cable failure will affect 750 ft^2 of runway surface. The effect of this failure can be mitigated by continuously operating the particular 200-foot runway section in which the failure occurred. This can be done by turning on the magnetically operated breaker associated with the involved transformer.

The electrical system is sized to meet the specified heating requirement of 26.8 Watts/ft^2. The heating cable has a rating of 10 watts per linear foot; and, with a spacing of 4 inches, this provides a heating capability of 30 Watts/ft^2.

In all probability, the system will be turned on in anticipation of snow or ice conditions and turned off when these conditions pass. Although this is wasteful of energy, this is the traditional method of operating electrical heating systems. As explained in

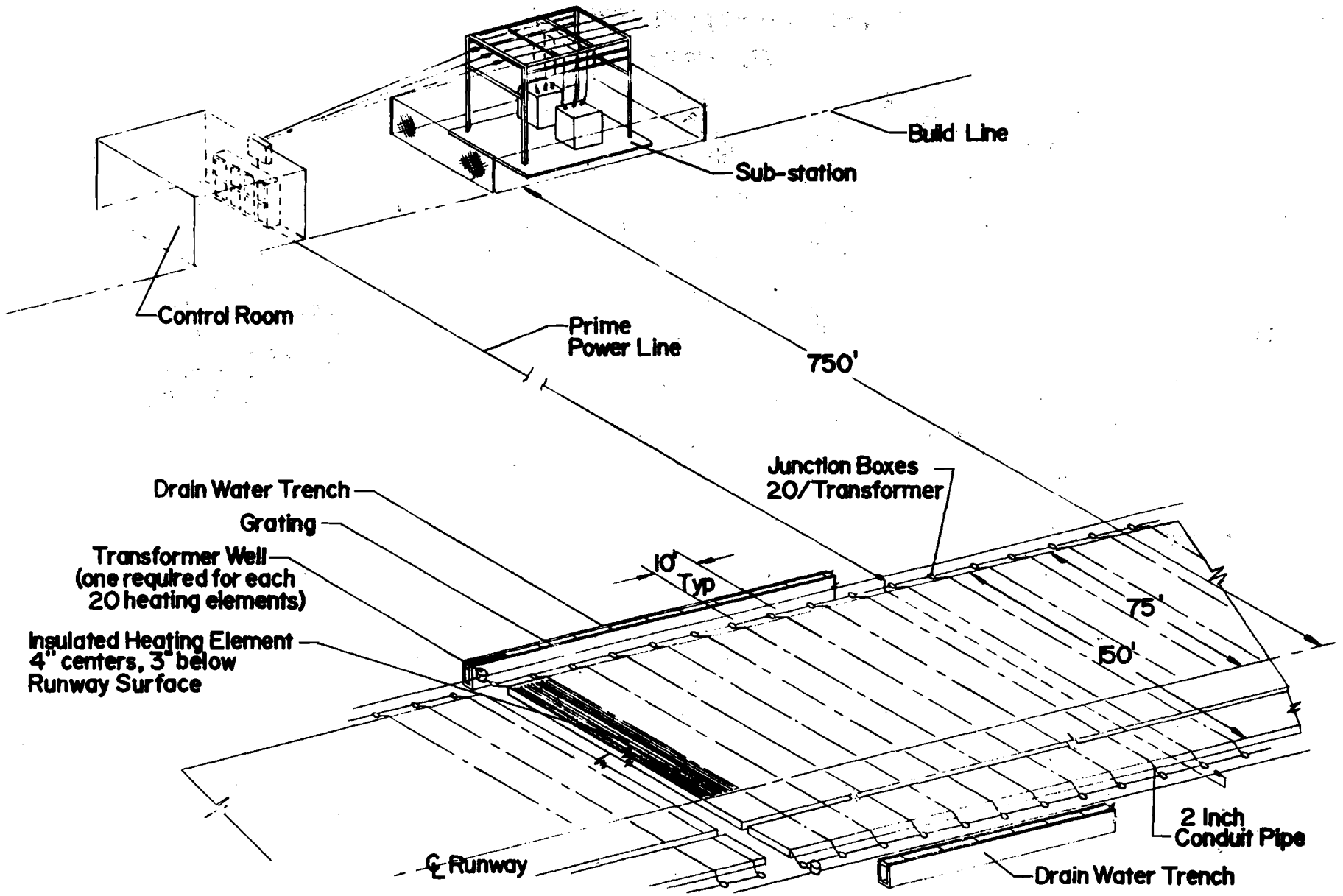


Figure 3.1

Overall Layout of Electrical System

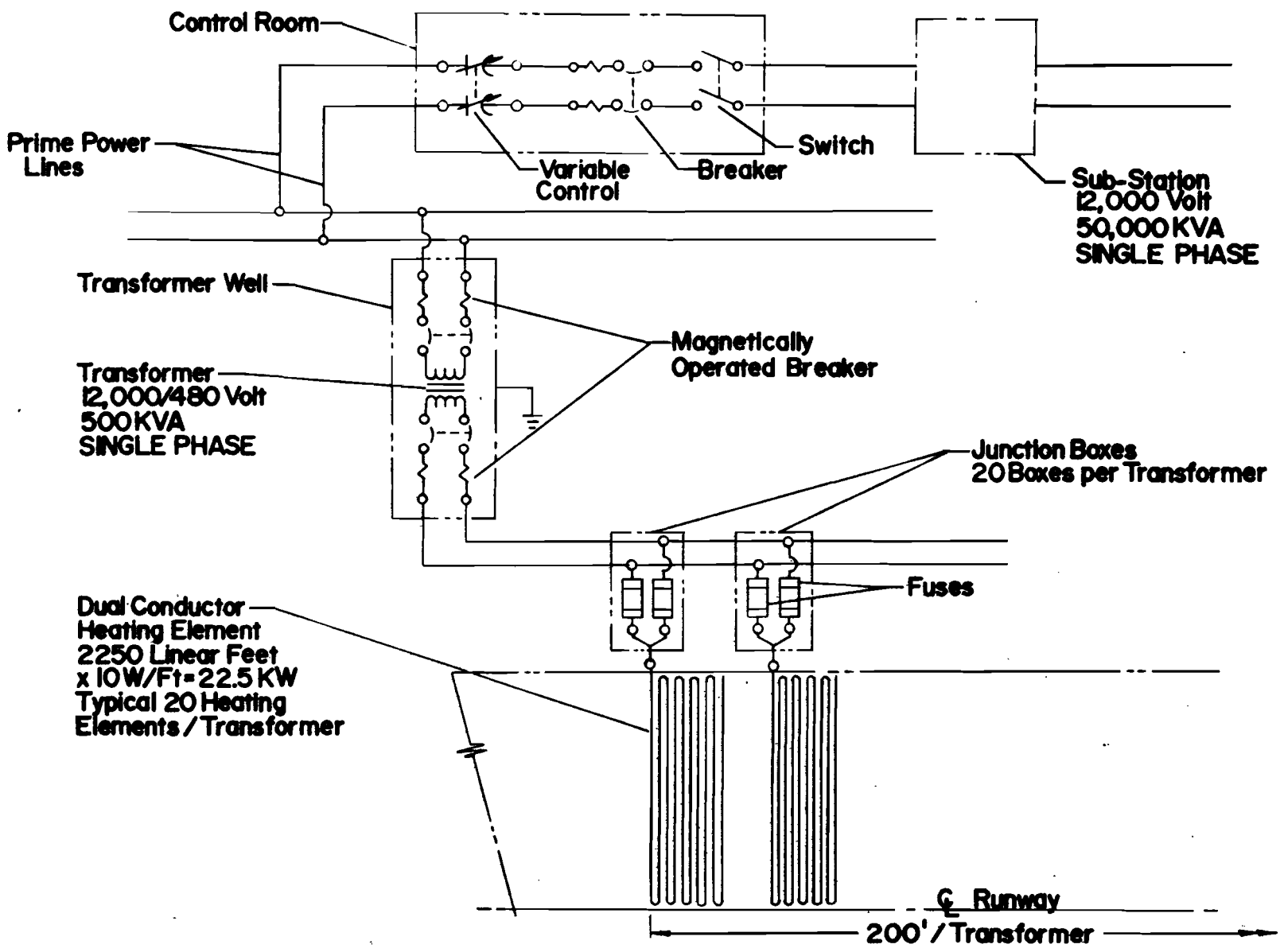


Figure 3.2

Flow Diagram of Electrical System

Section 2, it is only necessary to maintain the surface of the pavement temperature slightly above 32°F during conditions of snow or ice. This can be done rather easily by monitoring pavement surface temperature at several locations and feeding this information to an on/off controller connected to the main substation circuit breaker.

Further details of the electrical heating cable installation which forms the energy distribution subsystem are shown in Figures 3.3 and 3.4. The subsystem is susceptible to failure at places where the heating elements enter the pavement and at places where pavement cracking occurs. Figures 3.3 and 3.4 illustrate the use of 2-inch rigid conduit anchored in the pavement. This construction eliminated stress concentrations on the heating cable. The entire pavement slab (10 feet wide by 75 feet long) shown in Figure 3.3 must be continuously reinforced. Joints are not allowed in this pavement.

3.2 Oil-Fired Steam Pavement Heating System

The overall layout of the steam system is shown in Figure 3.5. The system consists of an oil-fired steam generating plant, pipes carrying steam to the steam trenches located on either side and along the length of the runway, heat pipes which run from the steam trenches into the pavement, and drain water trenches.

The boiler building and control room (Figure 3.5) contains three packaged oil-fired boilers; two of which are required for operation and the third one is for standby. The nominal plant output required for snow melting is 147,700 pounds of steam per hour at a pressure of 15 psia. Because this pressure is only slightly above atmospheric pressure, relatively thin gauge piping is required for steam transport.

The boiler building also contains facilities for treating boiler feed water. Although condensate return is provided, a certain amount of system leakage will occur; therefore, the makeup water must be treated to eliminate harmful salts. In addition, provision is made for deaeration of the feed water. For the most part, the valves controlling the flow of steam to the runway are hand operated. The expense of a fully automated steam plant cannot be justified because a plant operator will be required in any event.

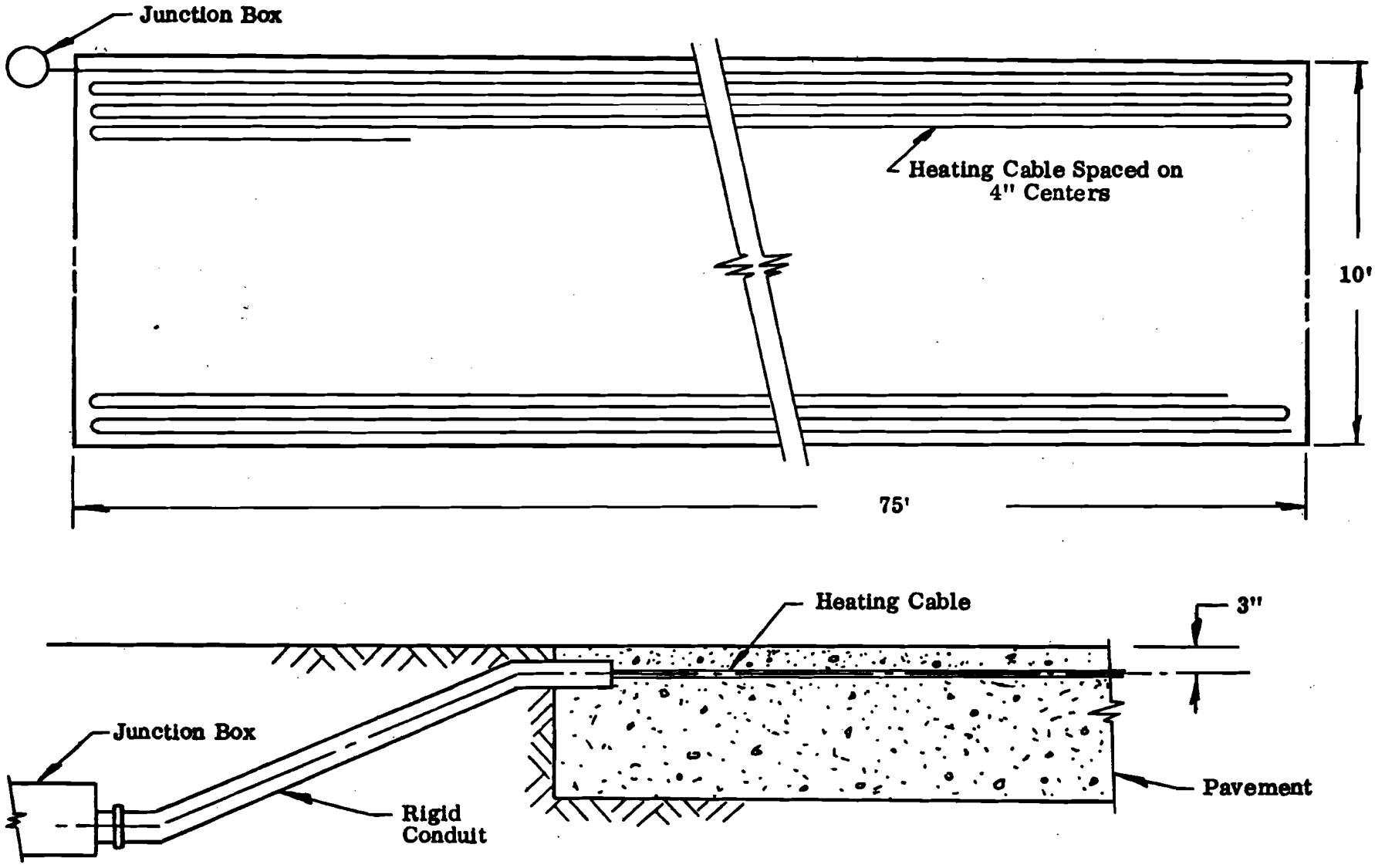


FIGURE 3.3

DETAILS OF ELECTRICAL HEATING CABLE INSTALLATION

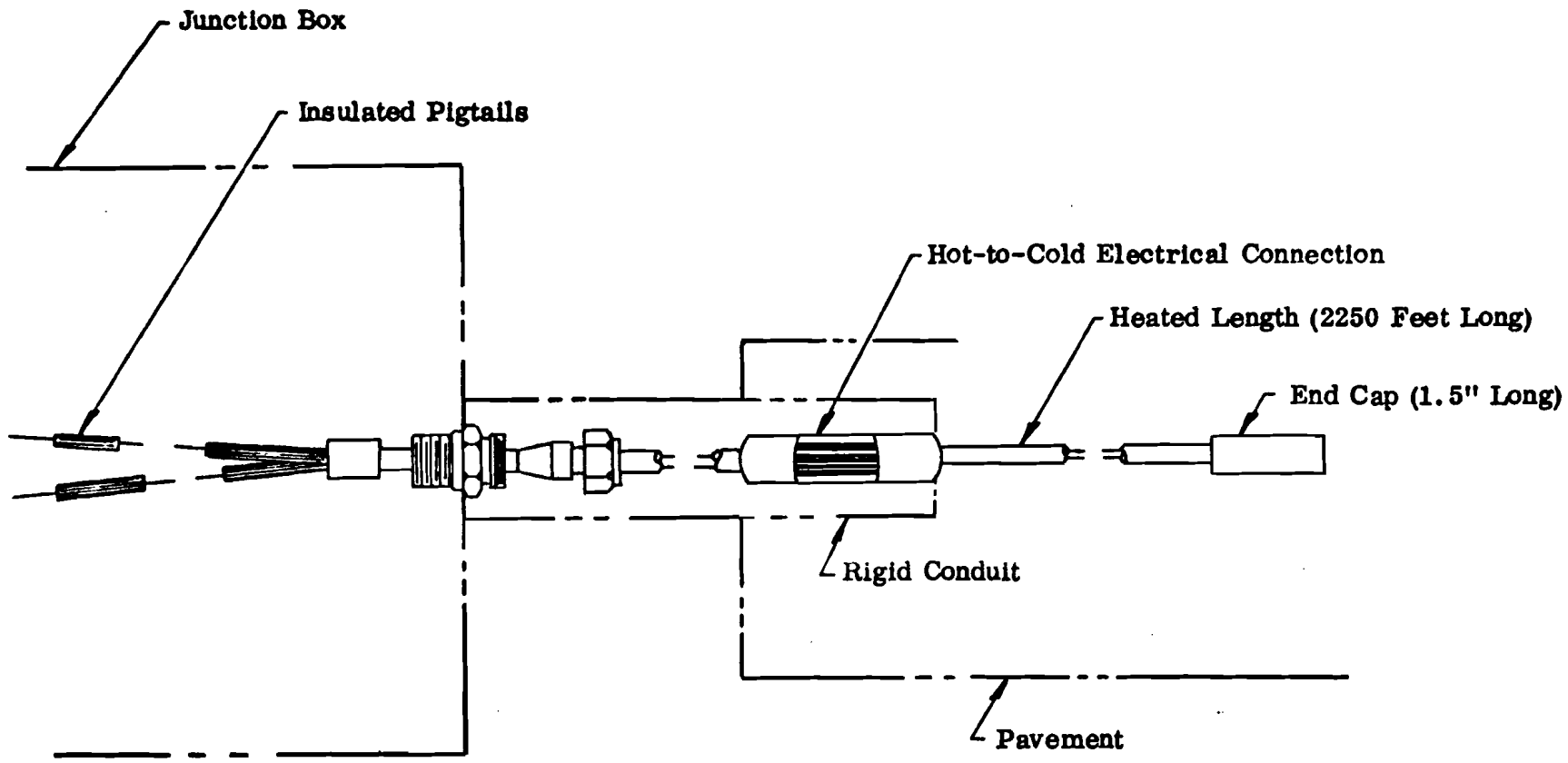


FIGURE 3.4

ELECTRICAL CONNECTION BETWEEN JUNCTION BOX AND ELECTRICAL HEATING CABLE

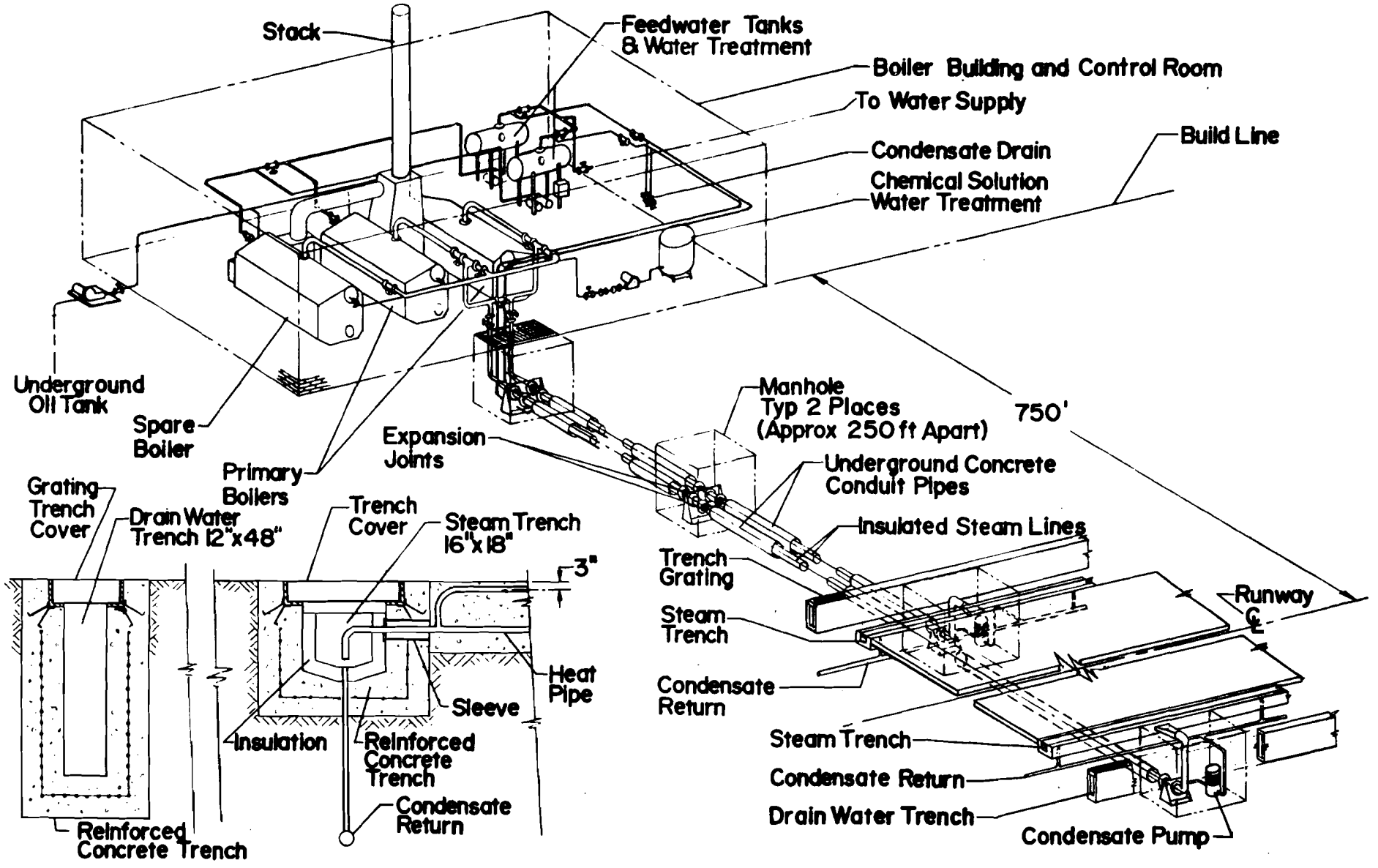


Figure 3.5
Overall Layout of Steam System

Two 20-inch steam pipes connect the steam plant to the runway steam trenches. These pipes are insulated and are contained within concrete conduit pipes. When the steam passes through these pipes, they elongate 9.5 inches because of thermal expansion. Manholes are provided in two places along the 700-foot length. These manholes contain bellows-type expansion joints which keep the pipes from overstressing themselves and buckling.

The 20-inch steam lines penetrate the approximate midpoints of the 10,000-foot long steam trenches on either side of the runway (Figure 3.5). Into these trenches protrude the ends of the heat pipes (energy distribution subsystem) which extend out of the edges of the runway pavement. The thermal link between the heat pipes and the steam occurs as the result of warm steam ($\sim 212^{\circ}F$) condensing on the colder surface ($\sim 80^{\circ}F$) of the heat pipe. For every pound of steam that condenses, approximately 1000 Btu of heat is released to the pipe in the form of heat of condensation. The steam condensate (water) collects in the bottom of the steam trench and is pumped back to the boiler building (Figure 3.6). In order to prevent noncondensible gas blockage in the steam trenches, thermally sensitive air relief valves will be required at each end of the two trenches.

The steam trenches are constructed of reinforced concrete. In order to minimize thermal expansion differences between the steam trenches and the runway pavement, each steam trench is lined on its inside with a 4-inch thick layer of urethane foam insulation. A sleave (Figure 3.5) is used between the heat pipe and the steam trench to protect the heat pipe from shear stresses resulting from any residual expansion differences. Each steam trench will be sectioned along its length and the sections will be connected by standard flexible joints. This will avoid generating destructive thermal stresses.

As in the electrical system, two drain water trenches are located about 15 feet away from both sides of the runway. During the snow melting process, considerable quantities of water are produced. Unless adequately drained away, this water will freeze along the runway edges when the air temperature is below freezing. The drain water in the trenches will be discharged either into sanitary drains or into a suitable holding area where natural drainage and evaporation will dissipate the water.

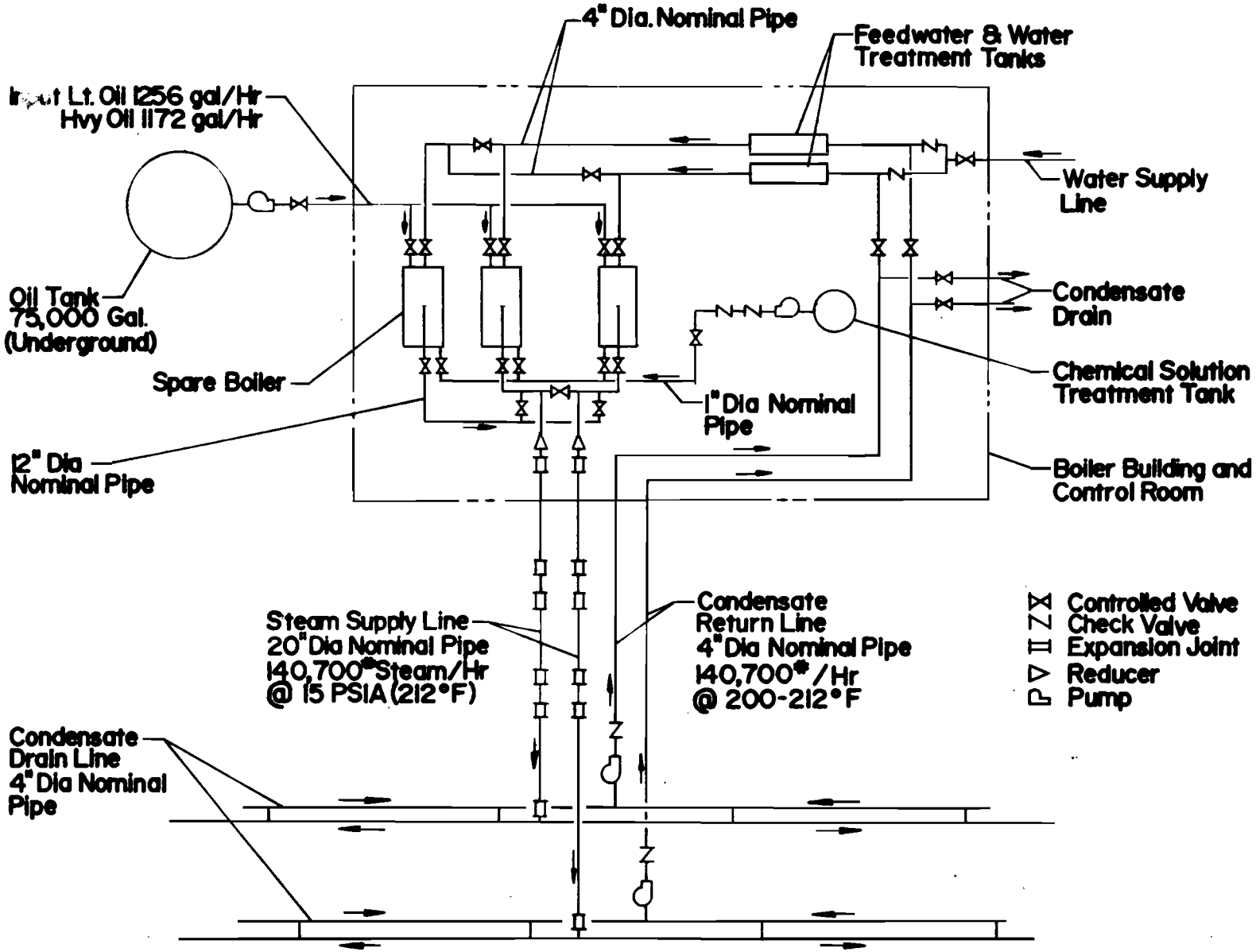


Figure 3.6

Flow Diagram For Steam System

All trenches must be covered with structural lids which are designed to withstand the wheel loading of a Boeing 747. The lids on the steam trenches will be solid and insulated on the underside. The lids on the drain water trenches will be a grating.

The heat pipes comprising the energy distribution subsystem (Figure 3.5) are of the closed loop design. This heat pipe design is only suitable for new construction. It has the advantage that it is very tolerant of nonuniform pavement settling, which is a common occurrence in new constructions. The heat pipes are placed on 6-inch centers, and their centerline is located 3 inches below the surface of the pavement. Each heat pipe must be able to carry the equivalent of 1 Kilowatt of heat. The details of the heat pipe construction are discussed in Section 5.1.

Thermal control of the steam system can be accomplished rather simply. To a first approximation, the amount of heat delivered to each heat pipe by the saturated steam in the steam trench is proportional to the exposed surface area of the heat pipe. Therefore, by permitting the condensate level in the steam trench to vary, the exposed surface area of the heat pipe can also be made to vary. Steam cannot condense on that portion of the heat pipe which is below the surface of the condensate water. Several temperature sensors in the pavement surface are connected to a controller which, in turn, regulates the condensate return pump speed.

3.3 Solar Pavement Heating System

The overall layout of the solar system is shown in Figure 3.7. The energy distribution subsystem of the solar system is similar to that of the steam system with the exception that hot water replaces steam. The major difference between the two systems is in the energy source subsystem.

The energy source for the solar system is the sun. The radiant energy from the sun is, to varying degrees, available everywhere throughout the world. The radiant energy is converted into heat by means of solar collectors (Figure 3.7). Water, which is used as the process heat transfer fluid, is heated. The heated water is stored in underground storage tanks. This need to store the collected energy (in the form of hot water) arises because the radiant energy, which can be collected through-

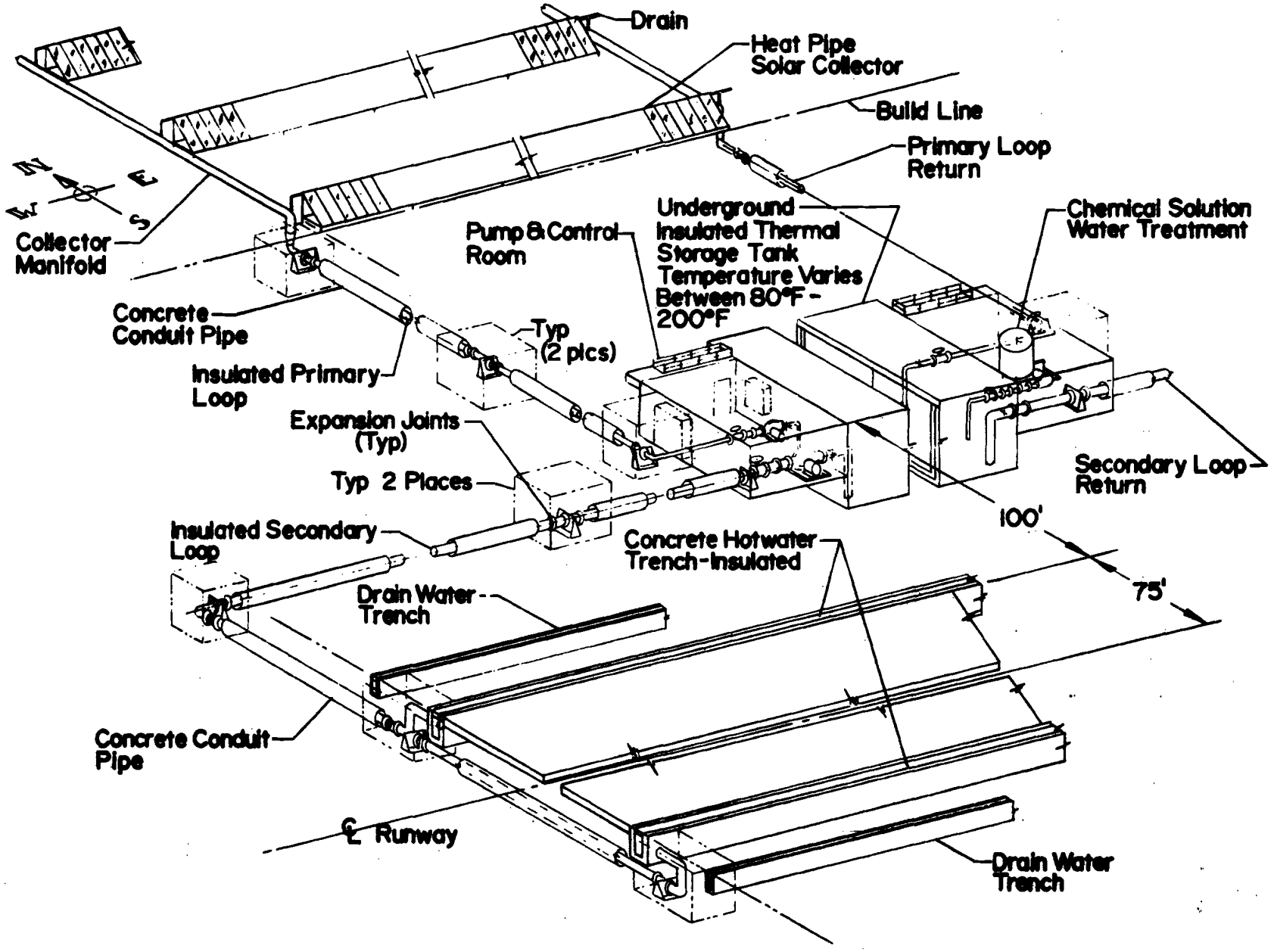


Figure 3.7
Overall Layout of Solar System

out the entire year, is used in the system for snow and ice removal for only a few winter months. System and economic considerations dictate the choice of collector area and hot water storage volume.

Energy is transported to the runway hot water trenches through 24-inch pipes. The same provisions as used in the steam transport system to prevent overstressing of this pipe are shown Figure 3.7. Because of energy transport subsystem considerations (Section 6), the solar system design shown in Figure 3.7 is duplicated for every 2000 feet of runway (300,000 ft^2 of runway pavement surface area). Therefore, a total of five such systems are required for a full 10,000-foot runway. This number may be adjusted downward through a more detailed optimization than was possible to do within the scope of this study.

A total collector surface area of 16,000 ft^2 is required for each 2000-foot length of runway for the Reference airport. These collectors are arranged in eight banks (Figure 3.7), and each bank consists of 2000 ft^2 of collector surface. The banks are connected in parallel. The details of the collector installation are shown in Figure 3.8. Each heat pipe panel is 42 inches wide and 113.5 inches high. The panels are mounted at an angle on a frame which is oriented in the east-west direction. The primary-loop water pipes are clamped to the panels at the top of the frame. Individual panel replacement can be accomplished without violating the primary-loop water pipes. During the winter when the sun is not shinning, the primary-loop water pipes are gravity drained. The fluid in the heat pipes is not water and will not freeze.

The hot water trench design for the solar system is shown in Figure 3.9. The trench is unique in that it is divided down its center by a perforated steel plate. Incoming water from the storage reservoir is fed into one side of the trench. Water is bled into the other side of the trench (heat pipe side) through a series of 1/2-inch diameter tubes located longitudinally at the bottom of the steel dividing plate. The level of water in the incoming side is purposely higher than the water level in the heat pipe side. This difference in elevation provides the driving head to force the water through the 1/2-inch tubes. The trench design shown in Figure 3.9 is dictated by thermal considerations (Section 6).

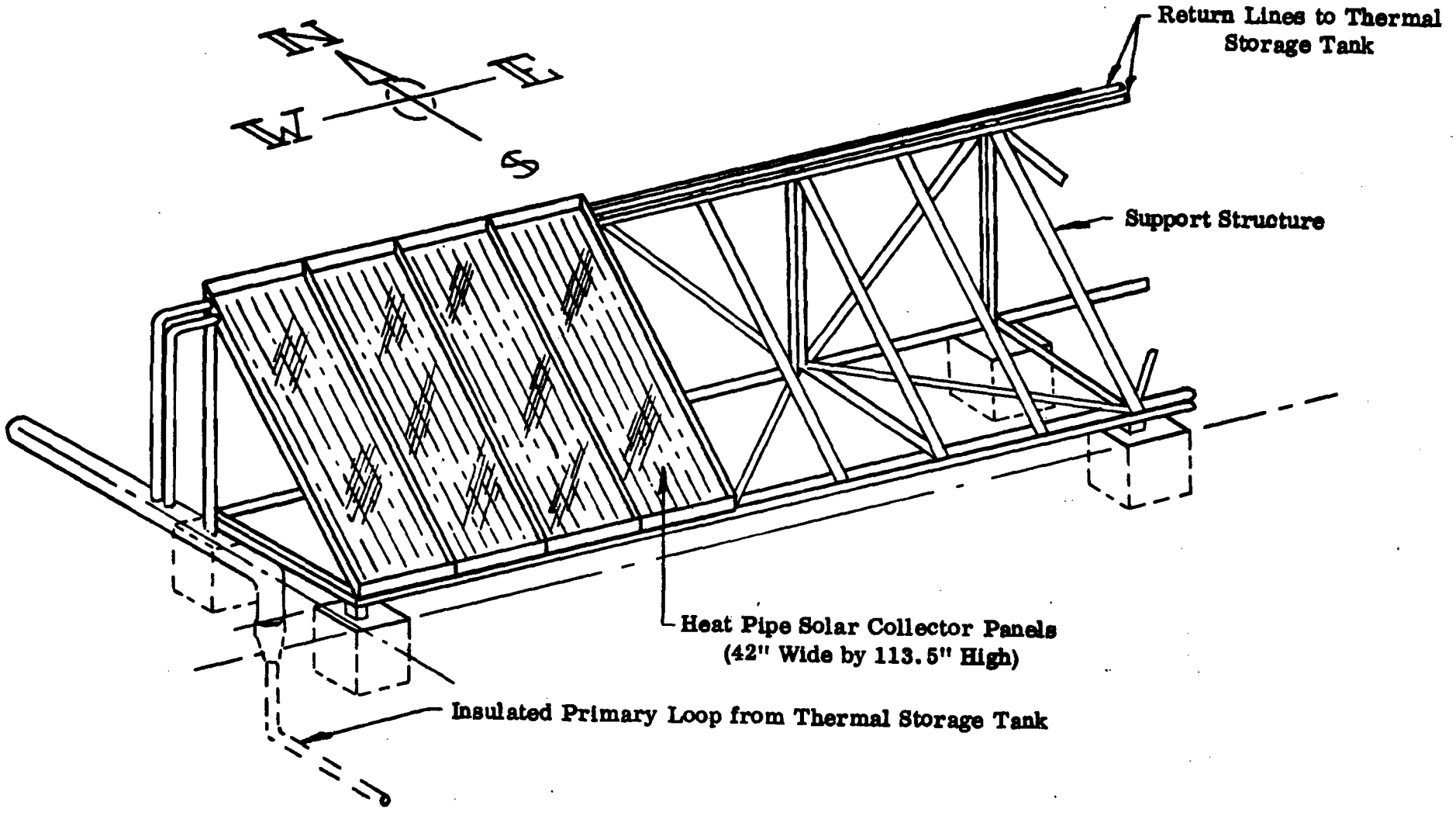


FIGURE 3.8

SOLAR COLLECTOR INSTALLATION

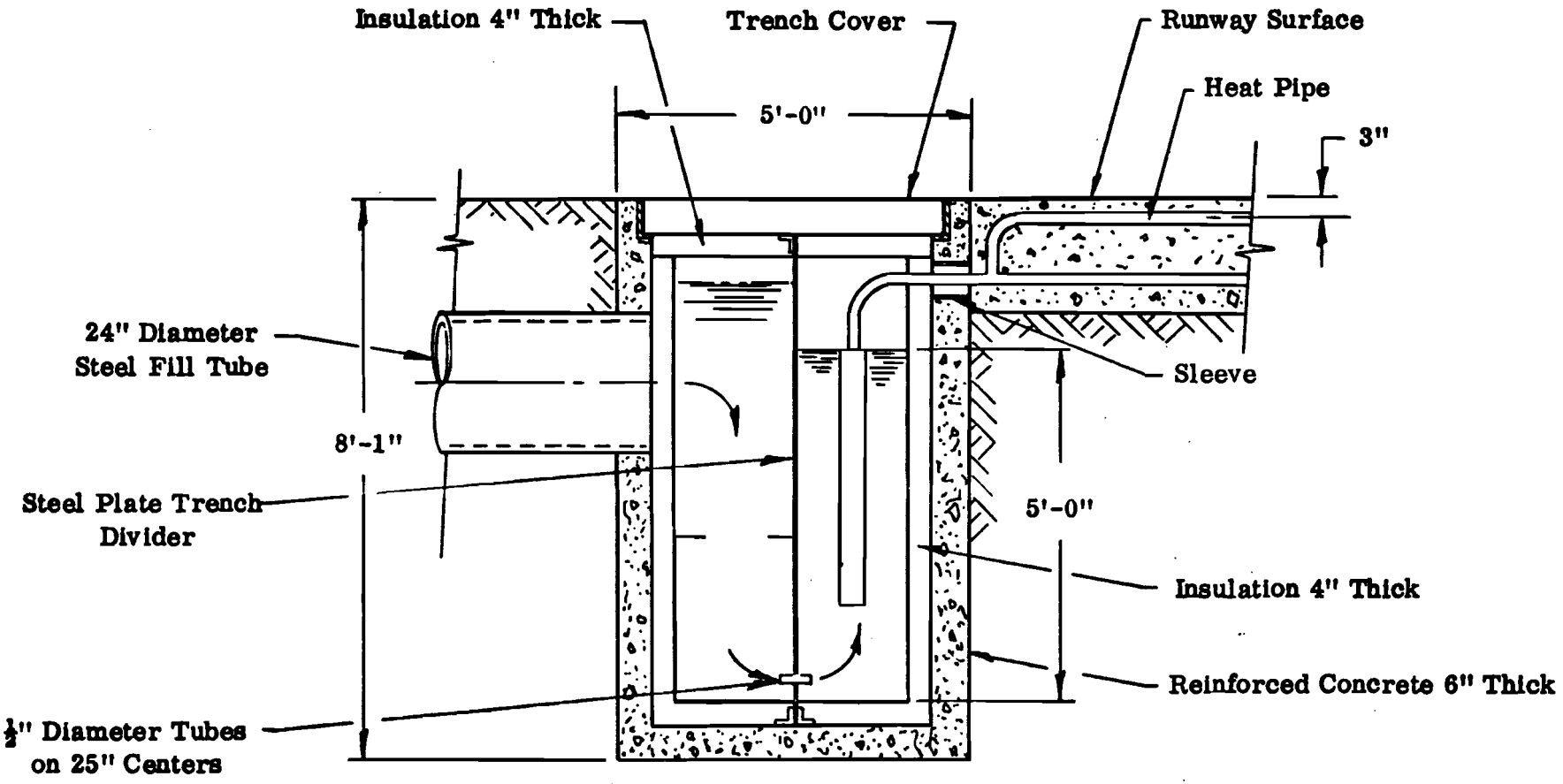


FIGURE 3.9

TRENCH DESIGN FOR SOLAR SYSTEM

The solar system flow diagram is shown in Figure 3.10. There are two flow loops for each system. The primary flow loop is used to recover the collected solar energy. The primary pump must supply water maximum flow rate of 4×10^5 lbs/hr at a head of 40 feet. The primary pump is operated only during sun hours. During a typical year, the primary pump will consume 842 Kilowatt-hours of electrical energy. Most of this energy will appear as heat in the primary loop water. The primary pump is sized to maintain the water temperature rise in the collector region to less than 10°F. The storage reservoir temperature varies between a minimum of 80°F at the end of the winter season to 200°F at the end of the summer season. The primary loop temperature, therefore, will not exceed 210°F.

The secondary flow loop pump (Figure 3.10) is turned on only when the energy distribution subsystem is to be activated. Water is pumped from the thermal storage tank to both hot water trenches at a maximum flow rate of 5.4×10^6 lbs/hr. The annual electrical energy consumption for each pump is 31,000 Kilowatt-hours. As in the case of the primary pump, a large portion of this energy will appear as heat in the secondary water.

Control of the solar system pavement surface heat flux can be accomplished by controlling the level of water in the heat pipe portion of the trench and by controlling the temperature of this water. The level of water determines the area of the heat pipe surface available for heat transfer. The temperature of the water determines the rate of heat transfer for a given heat pipe surface area exposed to the water. Because the variations of reservoir water temperature occur during the winter season, control is simplified by selecting a level of water and adjusting the water temperature in the heat pipe side of the trench. The water level in the trench can be adjusted to any value and held constant by controlling the relative speed of the secondary loop input and output pumps. The absolute speed of the pumps determines the mass flow rate of water in the trench. High mass flow rates will result in high trench water temperature because the heat pipes have less time to extract the heat from a given amount of water.

The temperature of the thermal storage tank will be measured and this will determine the proper level of water in the trench. Pavement surface temperatures at

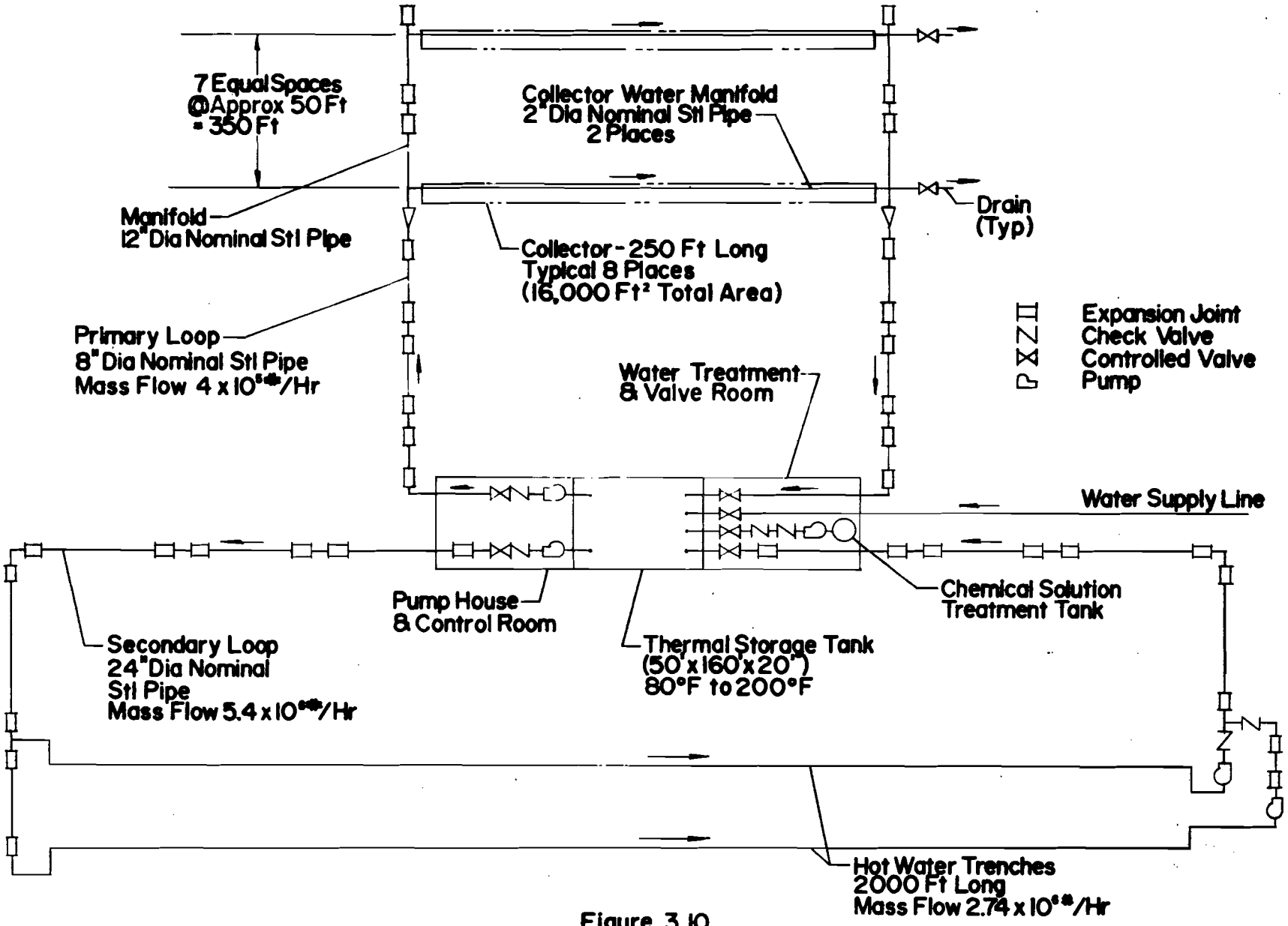


Figure 3.10

Flow Diagram for Solar System

several locations will be measured. This information will be fed into controllers which establish the proper speeds for the inlet and outlet secondary loop pumps. In this way, the pavement surface heat flux is controlled to assure continuous snow melting and ice removal.

4. HEATING SYSTEM/AIRPORT INTERFACE

Airports are characterized by large pavement areas. A typical ILS runway has a pavement area of 1,500,000 ft^2 which is equivalent to over 23 miles of 12-foot wide highway. However, unlike the highway, airport pavements are concentrated in a relatively small area.

Airport runway heating systems represent substantial facility additions which require updating of the Airport Layout Plan. This may also require the updating of the Environmental Impact Statement. On balance, airport pavement heating systems should have beneficial effects on the environment in areas of noise and pollution. By reducing or eliminating snow and ice caused delays, fuel consumption and the associated noise are reduced.

Aside from these overall considerations, the pavement heating system also interfaces with the airport in the areas of operation, maintenance, and construction.

4.1 Operation

When applied to an ILS runway, the pavement heating system brings airport operation a step closer to the realization of an "all weather" airport. Airport operation, however, is expanded to include the operation of the pavement heating system. This operation involves the following activities:

- Snow/Ice Forecasting: Accurate forecasting is more critical for pavement heating systems than it is for the present airport operations. Some preheat time is required for all pavement heating system designs. False initiations of the heating system are wasteful of energy; and, in the case of the solar system, they could prematurely deplete the thermal storage reservoir.

- Judging Runway Surface Conditions: The judgment references previously used are no longer valid. Visual observation of the runway may not be possible under certain snow conditions. Correlation of the runway surface conditions with nearby unheated pavement conditions is no longer valid. Pilot feedback and local observation by electronic means are probably the most reliable sources of information regarding runway conditions.

- **Heating System Operation:** The heating systems described in this study require the services of a trained operator. The heating system designs, if they are operated in accordance with instructions, will accommodate all icing conditions and all snow conditions except blizzards. Of course, the system must be maintained properly so that it will perform within specifications.

4.2 Maintenance

In the context used here, maintenance refers to keeping the airport operational during snow and ice conditions. It is not envisioned, for economic reasons, that pavement heating systems will completely replace all existing mechanical snow removal and ice control equipment. In order to obtain the maximum advantage of pavement heating systems, the existing mechanical equipment must be programmed in such a way as to either eliminate or minimize delays. The economic advantages of proper equipment deployment, when associated with pavement heating, are explored in Section 9.

At issue here is the runway itself. By heating the runway, mechanical equipment can be kept off the runway during snow and ice conditions. With the runway clear of equipment and snow or ice, aircraft are free to arrive and depart. The pavement heating system can be designed to extend into certain taxiways and high speed turnoffs. The decision to increase the heated area in this manner is an economic and operational one. It appears, from results of this study, that some but not much area extension may be justified. The amount of area extension is probably determined by the skill and programming of the mechanical equipment operators at a particular airport.

4.3 Construction

Construction interfaces include the physical involvement of the pavement heating system with airport runways, taxiways, turnoffs, ramps, drainage, lighting, marking, land use, and paving. Understandably, the integration of a heating system into a new pavement installation will result in a better overall construction. Incorporating heating elements in either new or existing pavements represents the greatest deviation from existing construction practices.

The loop heat pipe (Figure 5.1) is designed for installation into newly laid rigid pavements. The pipe is installed transverse to the length of the runway (Figures 3.5 and 3.9). For a 150-foot wide runway, the transverse length of a continuous slab will be 75 feet. Expansion and construction joints are not permitted in this length. This requires that the entire 75-foot slab must be poured at the same time. The width of the slab (in the longitudinal direction of the runway) cannot be less than 10 feet and, preferably, should exceed 20 feet. To accommodate the wheel loadings of modern multi-jet aircraft, a slab thickness of 20 inches has been selected.

The design of the rigid pavement system with the loop heat pipes installed is shown in Figure 4.1. The system consists of heat pipes spaced longitudinally on 6-inch centers. The location of the centerline of the 1-inch IPS pipe is 3 inches below the surface of the pavement. A welded wire fabric is placed directly over the heat pipes. The depth of the loop (centerline of the 1-inch pipe to centerline of the 1/2-inch pipe) is 10.62 inches. The bottom 1/2-inch pipe rests on and is attached to a welded wire fabric. In the 75-foot direction, the slab can be considered to be continuously reinforced.

The slab must withstand mechanical and temperature-induced stresses. Mechanical stresses result from dynamic and static wheel loading from aircraft, and the distribution of load concentrations is a function of slab thickness. Temperature-induced stresses result from seasonal temperature changes of the slab and from temperature gradients developed in the slab due to weather conditions and due to the pavement heating system.

Concrete is used in compression for structural members. The compression strength of Portlant concrete AASHO M 134, Class A, is more than 3500 psi after curing 28 days. Its true tensile strength is about 8% of its compressive strength. Tensile strength is seldom relied upon in the design of concrete structural members. In critical structural members, such as long concrete beams which develop tensile stresses under loading, the concrete is prestressed so that only the compressive strength of the concrete is utilized. Other concrete structures contain reinforcing steel such as deformed steel bars, welded wire fabric, and clipped or welded bar mats to take up tension loads.

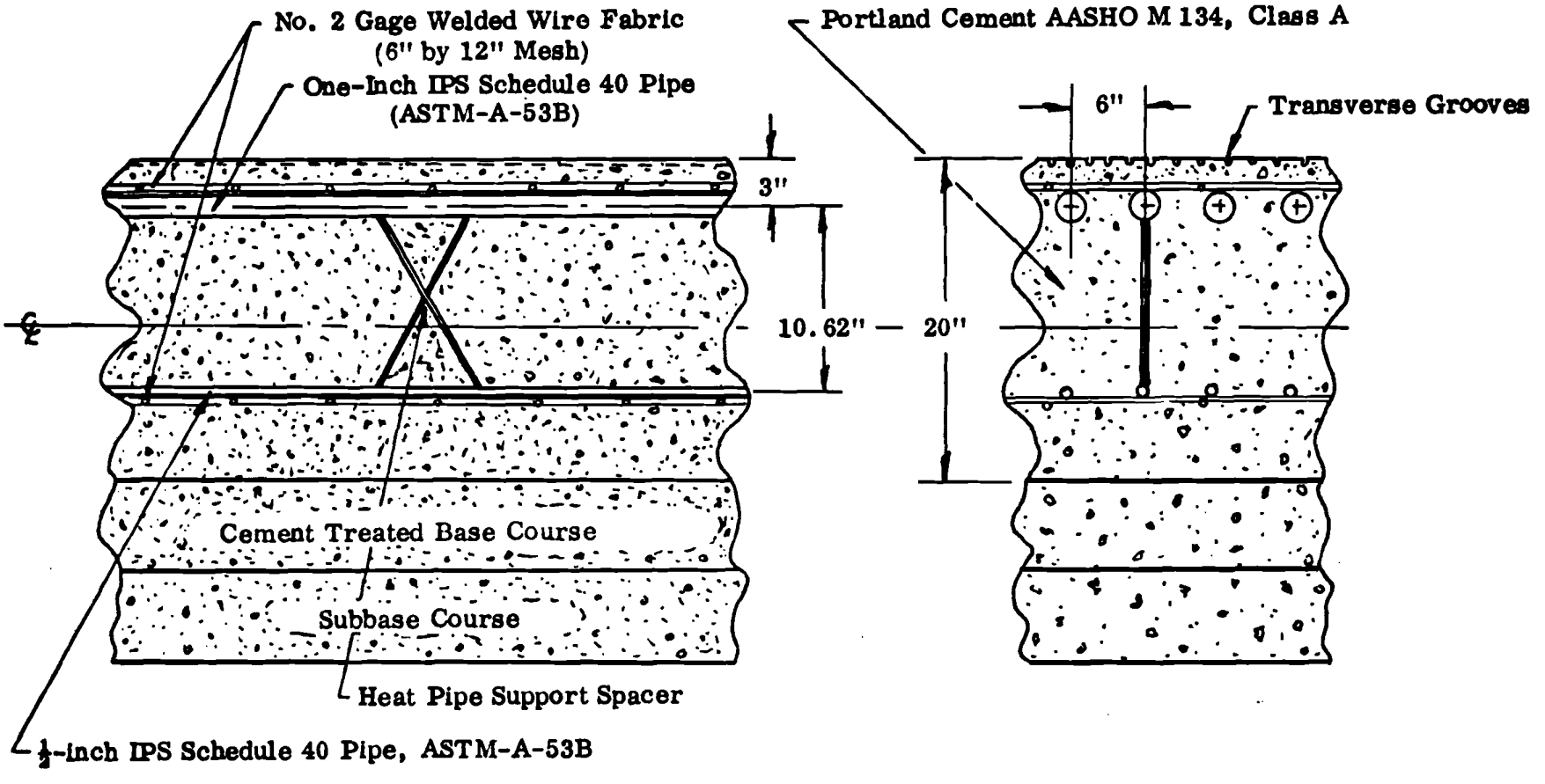


FIGURE 4.1

LOOP HEAT PIPE INSTALLATION IN RUNWAY PAVEMENT

Consider a concrete slab, 75 feet x 20 feet and 20 inches thick, of the design shown in Figure 4.1. The amount of reinforcing steel which is required to prevent temperature-change cracks from opening in a 1-foot section normal to the 75-foot dimension is 0.60 in^2/ft. The heat pipes contribute 1.33 in^2/ft of steel cross-section and the welded wire fabrics contribute 0.11 in^2/ft for a total steel area of 1.44 in^2/ft. In a 1-foot section normal to the 20-foot dimension, the required amount of reinforcing steel is 0.16 in^2/ft. The wire fabrics contribute 0.22 in^2/ft steel area, and there is obviously no contribution from the heat pipes. In both directions, sufficient steel is present to resist the forces of friction developed between the slab and the cement treated base course (coefficient of friction used = 1.5) when the slab contracts (concrete put under tension) as a result of a fall in slab temperature.

Stresses also develop as a result of temperature gradients which may exist across the slab thickness. These are called warping stresses. When the surface of the slab is warmer than the surface against the base course, the pavement surface is in compression and the base course surface is in tension. The converse is true if the temperatures are reversed. The warping stress for the design of Figure 4.1 for a $40^{\circ}F$ linear temperature difference across the 20-inch slab thickness is about 450 psi. The usable tensile strength of the specified concrete is about 300 psi. For this magnitude and type of temperature gradient, nonreinforced pavements of the specified design will be overstressed in tension. During the winter, the pavement surface will be in tension at certain times. A prolonged cold spell of zero degree temperatures and overcast skies may subject the slab to a $40^{\circ}F$ gradient if the condition occurs before a frost line is established.

The influence (on the pavement stress profile) of the temperature gradients generated by the pavement heating system must be evaluated. The heating systems of this study are designed to purposely operate at low temperatures. For the Reference airport, the heat pipe temperature (Figure 4.1) is about $60^{\circ}F$ for a surface heat flux of 26.8 $Watts/ft^2$ (Figure 2.3). The maximum axial compressive stress developed in the heat pipe for a step temperature change of $30^{\circ}F$ is less than 6000 psi (heat pipe material yield is 35,000 psi). The bonding strength of Portland concrete

is 575 psi and the shear strength is 590 psi. Even if only a small fraction of the external heat pipe area is bonded, the developed shear between the concrete and pipe will be much less than the acceptable limit. (Acceptable design value for bond strength for nondeformed bar or pipe is 160 psi.)

In addition, the turning on of the heating system when the pavement is subfreezing will induce tension stresses in the pavement surface. Again assuming a step temperature change of 30°F, the maximum tensile stress at the surface is about 300 psi. Because there may be occasions when the allowable tensile stress may be exceeded, a welded wire fabric is placed on top of the heat pipe array (Figure 4.1) to limit the concrete tensile stresses to below the allowable value.

With consideration for the provisions and the limitations described, the rigid pavement construction can proceed in accordance with standard specifications AC 150/5370-1A and AC 150/5230-1B. Transverse and longitudinal contraction joints shall be installed in the slab as provided for on the plans. Tie-bar assemblies are to be installed along the edge of the runway to ensure that the steam or hot water trenches and pavement behave as a mechanically integrated structure.

Because of the factory construction of the heat pipes, trenches must be "formed in" before the heat pipes are installed. Actual pouring of the trench can be done after the runway is poured. The base and subbase for the trenches shall be prepared with the same care as that taken for the runway.

All heating systems include the installation of drain water trenches. These are outboard of the steam and hot water trenches and are constructed in accordance with normal construction practices.

Runway centerline, touchdown, turnoff, and high intensity lights shall be installed in accordance with the plans. The installation of transformer housings and underground electrical ducts must clear the pavement heating subsystem construction and the drainage provisions. For new constructions, this requirement can be integrated into the overall plans at the time of initial design. The problem is more difficult when a heating system is to be installed into an existing airport pavement. The heat pipes and steam or hot water trenches must be integrated physically. Therefore,

existing wire runs, transformer wells, and electrical ducts will have to be removed and relocated if there is an interference.

The heat pipes for existing construction are shown in Figure 5.2. Before they are installed, the true elevation of the grade must be established. If the grade is found to be below the true elevation, the depressions shall be filled with approved material in accordance with standard construction practices. Areas showing high spots of more than 1/4 inch, but not exceeding 1/2 inch in 16 feet, shall be marked and ground down with an approved grinding tool to an elevation where the area or spot will not show surface deviations in excess of 1/4 inch when tested with a 16-foot straightedge.

Once the proper longitudinal and transverse grades have been established, the trenches for the down legs (evaporator sections) of the heat pipes can be dug and formed. Structural steel from the existing pavement must be exposed in order to permit tie bars to be placed between the pavement and trenches.

The laying of the heat pipes on the top of the prepared grade can then proceed. Longitudinal spacer strips are placed on the heat pipes in accordance with the plans. After the heat pipes are placed in the proper position, a bituminous tack coat (2.0 gallons per square yard) will be applied and allowed to cure. When the tack coat is cured, asphalt cement (AASHO M 20) will be applied in 10-foot strips beginning from the center of the runway. The compacted thickness, as measured from the original surface, shall be 4 inches. Compaction shall always begin in the region nearest the center of the runway and proceed outward in steps as the asphalt cement strips are laid.

The remaining construction for the heating systems can proceed in accordance with the plans and standard specifications. The unique features of the systems such as solar collectors, storage reservoirs, heat pipes, steam plants, and electrical heating elements will be specified separately.

5. DESCRIPTION AND ANALYSIS OF UNIQUE SYSTEM FEATURES

There are three features of the systems described in Section 3 which are sufficiently new and unique to require further amplification. These are:

- Heat Pipes
- Solar Collectors
- Thermal Storage Reservoirs

5.1 Heat Pipes

The heat pipe is the key element of the energy distribution subsystem for both the solar and steam systems. It consists of a sealed and evacuated pipe which contains a small amount of ammonia working fluid and a capillary wick structure (Reference 10). In its pure configuration, the heat pipe is a self-contained heat transfer system utilizing the boiling and condensing process of a working fluid to transport heat from one location to another. The capillary wick structure supplies the internal pumping action needed to transfer the condensed working fluid back to the region where heat is being added (liquid is being boiled). The entire system is mechanically passive; and consequently, if rules of material integrity and compatibility are observed, the system is very reliable. Because heat transport occurs as a result of the boiling and condensing process, the heat pipe is virtually isothermal. These features, combined with the ability to achieve multiple redundance, make the heat pipe an ideal candidate for use in the energy distribution subsystem.

The heat pipe is not used in its pure form for the energy distribution subsystems of this study. The wick has been eliminated in the condenser portion (section embedded in the pavement) of the heat pipe. Two versions of heat pipe design have been substituted. For new construction, the Dynatherm loop heat pipe is used (Figure 5.1). For existing construction, the gravity-assisted heat pipe shown in Figure 5.2 is used. In either design, gravity is used to return the condensed liquid to the evaporator. In the gravity-assisted heat pipe, the condenser portion of the heat pipe follows the transverse grade

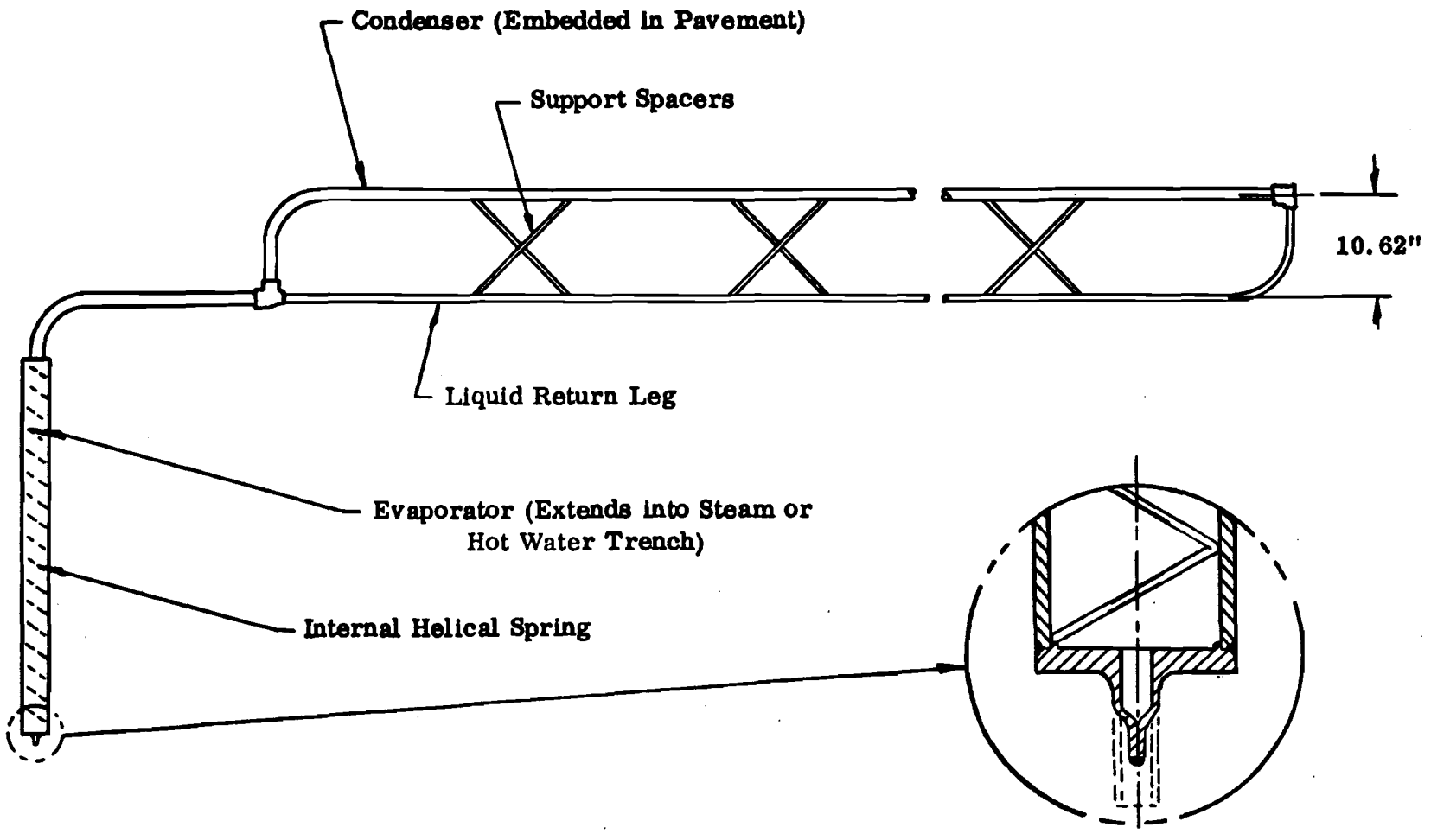


FIGURE 5.1

DYNATHERM'S LOOP HEAT PIPE

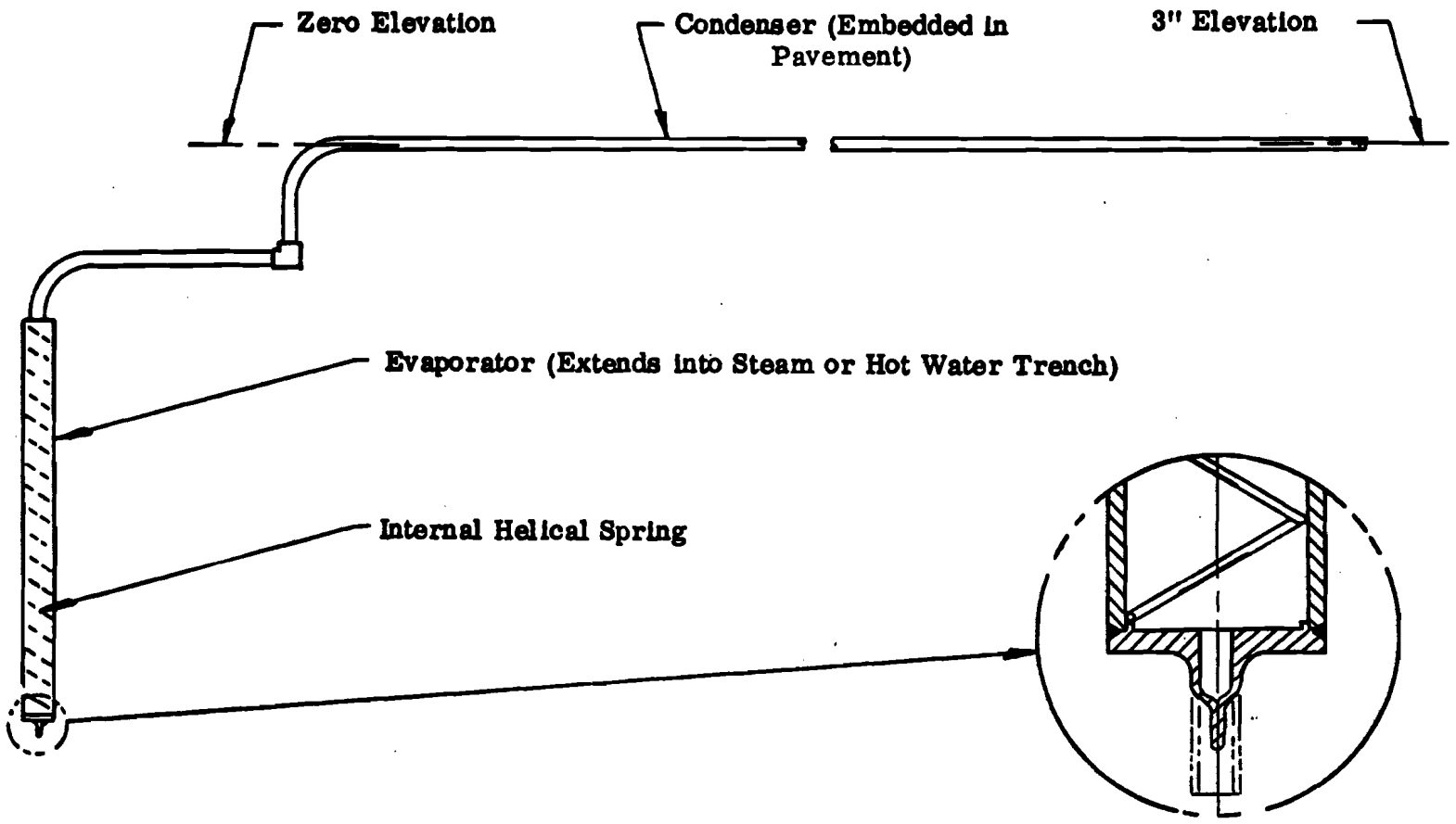


FIGURE 5.2

GRAVITY-ASSISTED HEAT PIPE

of the pavement surface. If the grade is 1% (as measured from the centerline to the edge of the runway), the far end of the condenser portion of a 75-foot long heat pipe will be elevated 0.75 foot (9 inches) above the portion of the condenser adjacent to the trench. This elevation difference provides the driving head to return the condensed liquid back to the evaporator. In the Dynatherm loop heat pipe, the pumping head is established by the separation of the condenser and liquid return sections of the heat pipe (Figure 5.1). This design is insensitive to pavement grade.

In order to evaluate the performance capability of gravity-assisted heat pipes, a computer model was developed. This model examines the hydrodynamics of heat pipe operation with "pool pumping". It considers the body forces on the liquid due to varying pool depth and inclination of the heat pipe, the frictional pressure gradient in the liquid, and the frictional and dynamic pressure gradients in the vapor. Although this program deals mainly with performance limitations resulting from heat transport capability, it is also capable of predicting the onset of entrainment and sonic vapor flows. Results of a typical calculation are shown in Figure 5.3. Shown is the predicted power carrying capability (heat transport capability) as a function of the amount of ammonia (fluid charge) initially put into a 1-inch IPS pipe having a total length of 80 feet and elevated 3 inches. Note that, with a fluid charge of 1000 grams of ammonia, the heat pipe is capable of transporting almost 6 Kilowatts. A typical Reference airport heat pipe is required to transport only 1 Kilowatt; therefore, the design has a considerable operating margin. Furthermore, a normal transverse grade of 1 degree represents an equivalent elevation of 9 inches. This larger elevation would result in a greater transport capability than shown in Figure 5.3.

The heat pipe design effort has included a pressure containment analysis. If the heat pipe of Figure 5.3 is charged with 1.2 Kilograms of ammonia, the temperature of the heat pipe could reach 770°F before the stress in a 1-inch IPS schedule 40 steel pipe would reach one-half of the material yield strength. In applying the heat pipe energy distribution subsystem to existing construction, asphalt cement (Specification AASHO M20) may be used as bituminous surface course. This material may be applied at temperatures as high as 350°F (Reference 7). This temperature is well within the design capability of the heat pipe.

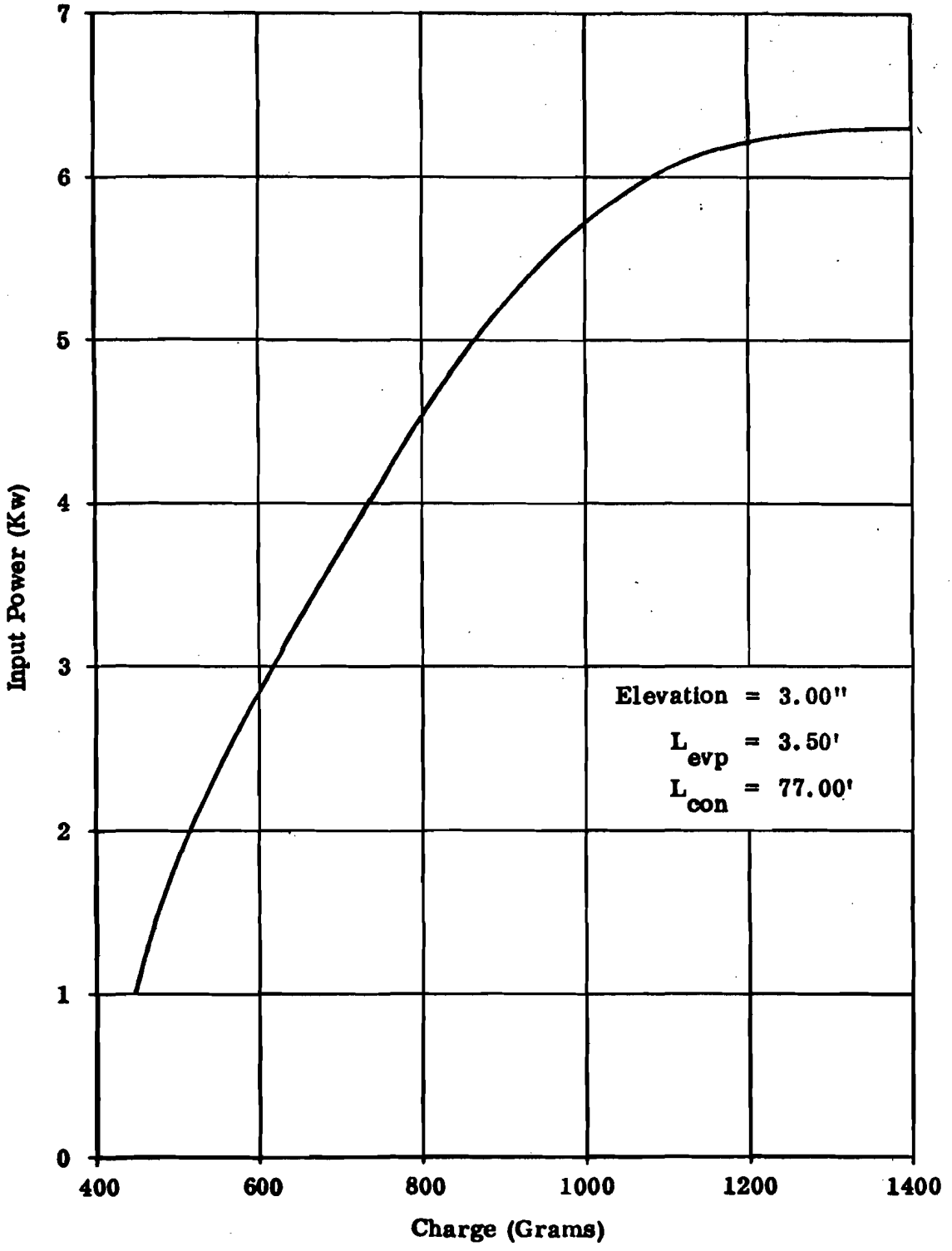


FIGURE 5.3

PERFORMANCE OF FAA HEAT PIPE VERSUS NH_3 CHARGE

The energy transfer between the heat pipe distribution subsystem and the hot water or steam trenches is accomplished at the evaporator section. Heat pipe evaporator designs were investigated for both the steam and solar systems. The study included an analysis of the effects of external heat transfer mechanisms, elimination of the boiling flux limitations in the evaporator, and techniques to provide adequate liquid distribution in the evaporator.

Gravity-assisted heat pipes utilize gravitational heads instead of capillary wicks for the return of the condensate to the evaporator. However, the performance can be improved if a wick is used in the evaporator to ensure circumferential condensate distribution. Experimental results show that if a helical spring is used in a vertical evaporator, the film coefficient in the evaporator can be increased from 60 Btu/hr-ft^2-$^\circ$F to 290 Btu/hr-ft^2-$^\circ$F (Figures 5.1 and 5.2).

In a solar system, the temperature of the storage reservoir varies between 80°F and 200°F. The heat pipe extension in the hot water trench obtains its heat input by virtue of convection in the hot water. Convection heat transfer at low reservoir temperatures is poor; therefore, the evaporator sections have been enlarged (Figures 5.1 and 5.2) to provide sufficient heat transfer area.

In a steam system, the temperature of the steam is constant and is between 150°F and 180°F higher than the equilibrium heat pipe vapor temperature. The heat transfer between the steam and heat pipe evaporator is by condensation. Consequently, the required evaporator area can be achieved with approximately a 5-inch length of 1-inch IPS pipe. This small evaporator could result in nucleate boiling within the evaporator when snow melting is required in very cold weather. By making the evaporator 1 foot long, nucleate boiling is eliminated.

5.2 Solar Collectors

The conversion of solar radiation to heat through the use of flat-plate collectors is receiving widespread attention throughout the United States. Cost, conversion efficiency, and ease of integration into structures are considerations being emphasized. Flat-plate collectors utilizing heat pipes have been selected as the design for the solar

system (Reference 9). This design utilizes gravity-assisted heat pipes to transport the collected heat to the upper edge of the absorber panel. At this edge, the heat is transferred to the fluid collection loop.

When properly oriented, gravity-assisted heat pipes behave as thermal diodes. Heat is transferred to the fluid collection loop, but it cannot be transferred from the collection loop to the absorber panel. Therefore, shaded or damaged collector panels are automatically eliminated from the collection loop and they cannot contribute to system losses. The use of heat pipes in solar collectors result in the following additional advantages:

- The heat pipe panel is a factory-sealed system. Materials and working fluids are selected to provide long-term corrosion free operation.
- During the winter, the solar collector must be capable of operating during intermittent sunshine. The working fluid selected for the solar collector will not freeze during this kind of operation.
- The selection of heat pipe solar collectors permits easy installation and removal of individual collector panels. Thermal attachment to the collection loop is made by simple mechanical attachment.

The heat pipe absorber panel is shown in Figure 5.4. It consists of a two-piece bonded plate containing expanded heat pipe channels. The channels are interconnected at the bottom of the plate at which place there is a lead-out for a fill tube. This construction eliminates thermal resistances between the heat pipe and absorber surface, permits close heat pipe spacing, and is compatible with modern low-cost mass production manufacture.

The heat pipe absorber panel of Figure 5.4 is assembled into the solar collector panel shown in Figure 5.5. Two tempered-glass cover plates, separated by a 3/8-inch air gap, are placed over the absorber panel. These glass plates serve to trap the solar radiation and minimize thermal losses. The glass plates and absorber panel are mounted on a treated-wood frame. Appropriate sealing and insulation are provided to make the assembly watertight and reduce parasitic thermal losses. The back of the absorber panel is covered with 3 inches of neoprene insulation.

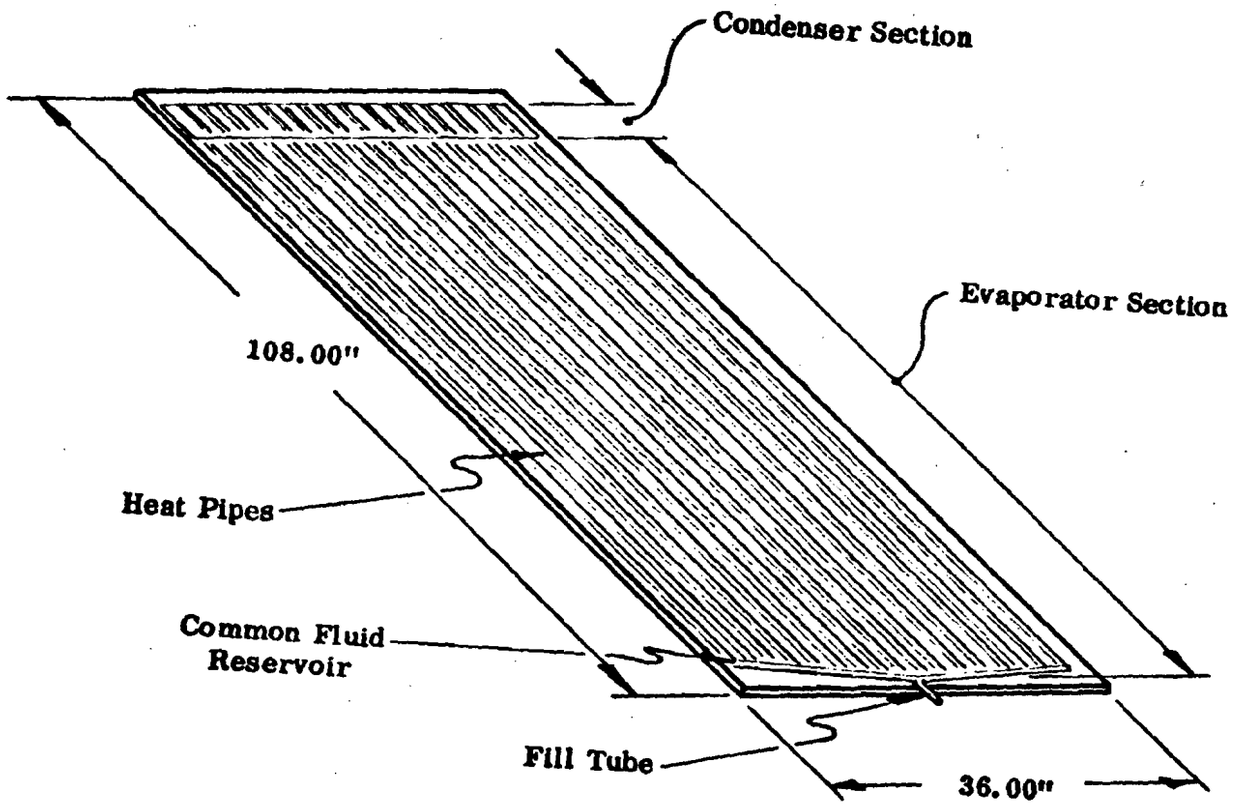


FIGURE 5.4
HEAT PIPE ABSORBER PANEL

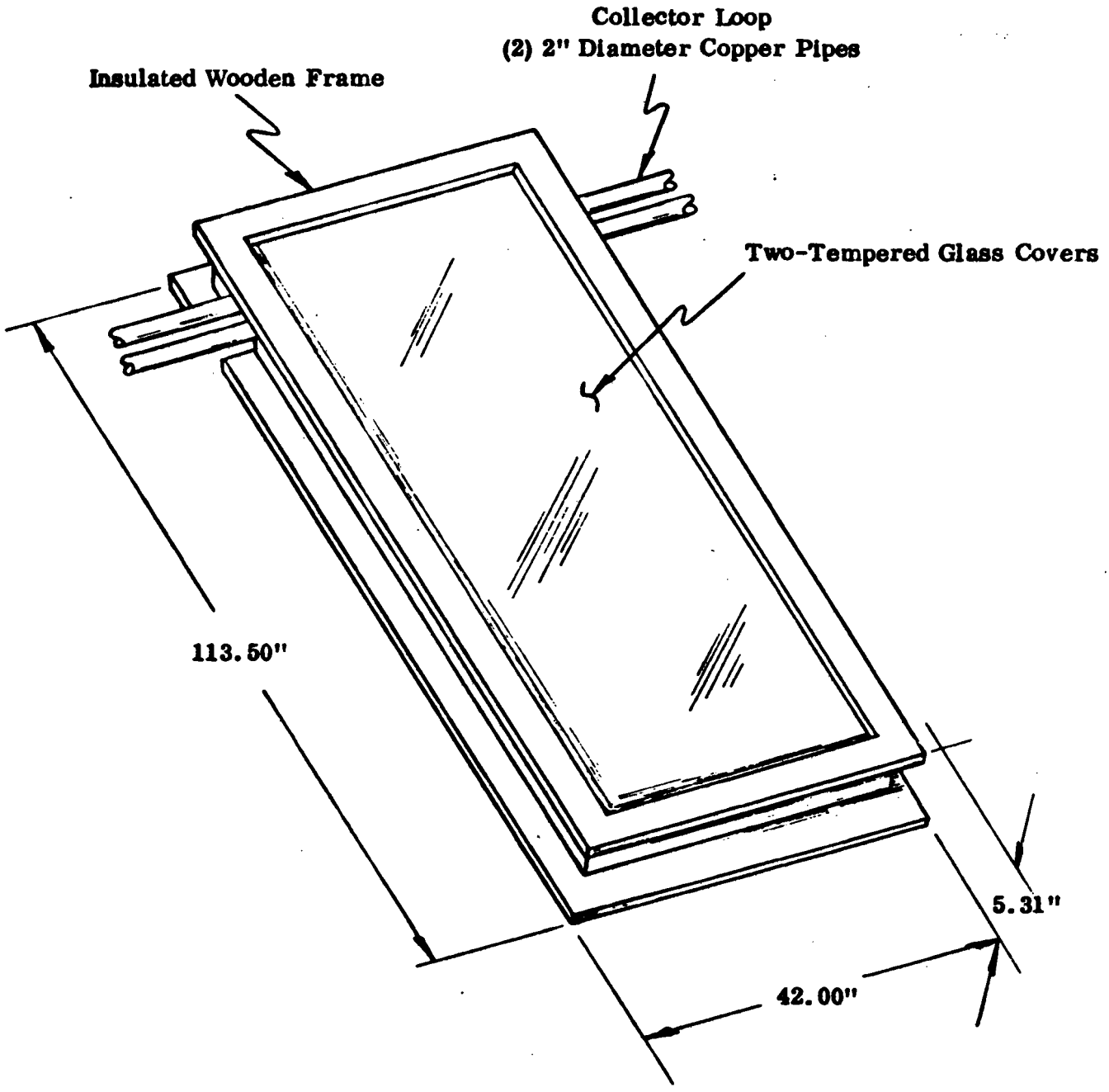


FIGURE 5.5

SOLAR COLLECTOR PANEL

At the collection loop interface, an extruded saddle is bonded to the backside of the absorber. This is directly behind the heat pipe vapor chambers (condenser section, Figure 5.4). The saddle, which has two semicircular grooves, is mechanically clamped to the two 2-inch copper pipes comprising the collection loop.

The design of the thermal interface between the collection loop and the solar collector panel is crucial to the performance of the energy collection subsystem. The heat flux at this interface is approximately one order of magnitude higher than the solar flux. The thermal flux levels are compatible with the heat transport capabilities of heat pipes, and collected heat is transported to the collection loop area with very small temperature loss.

In the collection loop area, the collected heat must be transferred through the mechanical clamps and into the collection loop water. The collection loop flow arrangement is shown in Figure 3.7. This is a series-parallel arrangement. The arrangement is necessary in order to achieve an adequate water flow velocity in the two 2-inch pipes (Figures 3.8 and 5.5). The velocity selected results in a water film coefficient of 1200 Btu/hr-ft^2-^{o}F and a 10°F water temperature rise for 2000 ft^2 of serviced collector area. The pumping power, which in this case is a trade-off against heat transfer, is 10 horsepower which is reasonable. The various collector banks are manifolded to a 12-inch common header which serves to equalize the flow through the banks.

5.3 Thermal Storage Reservoirs

Water was selected as the heat transport and thermal storage fluid because it is a good heat transfer fluid, has a high specific heat capacity, and is inexpensive. The solar energy collected throughout the year is stored as heated water in the thermal storage reservoirs. The solar system for the Reference airport requires a total storage capacity of 800,000 ft^3. Figure 5.6 shows a view of one reservoir (five are required).

Construction of the reservoir begins with excavation and subgrade preparation. The subgrade must have uniform bearing properties; and, where soft spots exist, these must be excavated, backfilled with suitable materials approved by the Engineer, and re-

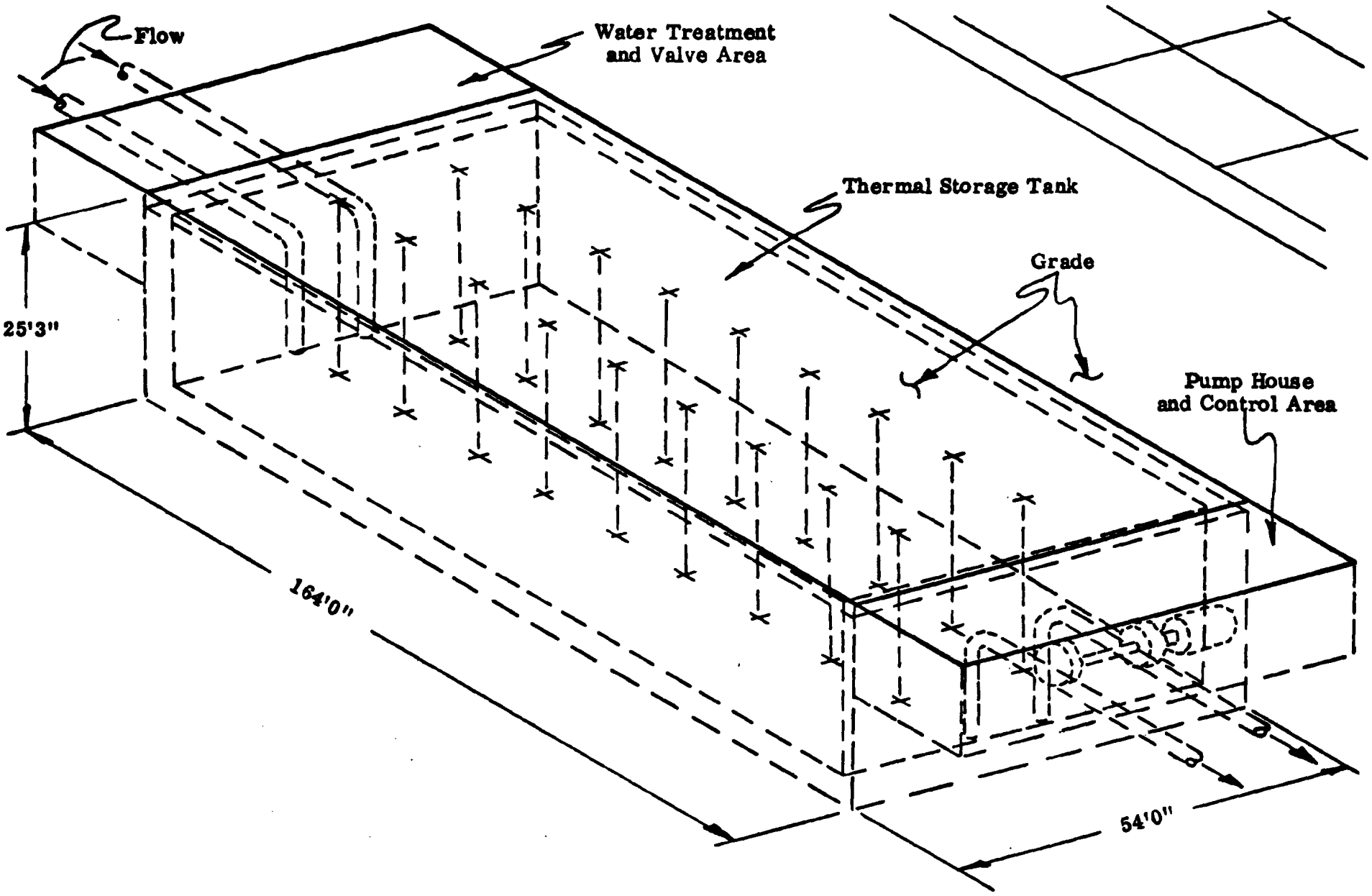


FIGURE 5.6

THERMAL STORAGE RESERVOIR

compacted. After the subgrade has been established, 18 footings shall be set for the Lally column roof-support structure. The remaining construction proceeds in accordance with the most logical sequence for the construction methods employed.

The base and walls of the reservoir consist of 12-inch thick reinforced concrete. These shall be covered with 12-inch thick urethane foam insulation. For moisture tightness, the urethane is covered with a vinyl liner.

The roof structure is supported by the walls of the reservoir and by the 18 Lally columns. It will consist of 50-foot long, 12-inch deep open web roof joists. These will be set on 2-foot centers and boxed in (top and bottom) with sheets of suitable plastic, treated wood, or protected metal material. The area between the top and bottom sheets will be filled with 12 inches of urethane foam insulation. This roof design is capable of supporting normal environmental loads but will not support heavy equipment loads.

At the ends of the reservoir are small areas containing the necessary pump and water treating equipment (Figure 5.6). This construction can be prefabricated and structurally supported by the end walls of the reservoir.

6. ANALYSIS OF SOLAR SYSTEM

The sun radiation falling on a fixed surface varies constantly. To determine this sun radiation (solar insolation), the following must be known:

- Time of Day
- Time of Year
- Latitude
- Cloud Cover
- Environmental Pollution
- Orientation of the Fixed Surface

The solar collector converts this radiant energy into usable heat. The conversion efficiency of practical solar collectors is less than 100%. The conversion efficiency is affected by:

- Ambient conditions such as air temperature, wind speed, etc.
- Temperature at which heat is being collected
- Dust, dirt, etc., which exist on collector glass covers

The solar system selected for this study collects solar energy throughout the entire year and stores this energy (in the form of heated water) in underground storage tanks. The temperature of the stored water varies from 200°F in November to 80°F in March.

The analysis of a solar system must adequately consider the relationships of many interdependent variables. To evaluate these variables, a computer program was developed which simulates the collection and storage characteristics of the solar system as a function of collector size, storage volume, thermal reservoir insulation, and orientation of the collector surface. This program utilizes average hourly solar insolation data for each month and determines the collected energy each month as a

function of the collection fluid temperature, ambient temperature, and collector conversion efficiency. The collected energy for each month is combined with the thermal losses from the storage reservoir and the energy requirements of the system for snow melting for the month being analyzed. The result is the determination of the monthly variations in storage temperature. Initially, a reservoir storage temperature must be selected to start the calculational procedure. The program iterates until an annual energy balance is obtained.

Figure 6.1 illustrates the results of a typical analysis for a full runway system. Shown is the monthly collected solar energy, the energy utilized for snow melting, and the storage water temperature (O'Hare International airport). The total storage water volume used in the analysis was 2,000,000 ft^3, collector surface area was 170,000 ft^2, the solar collectors were tilted at an angle of 41.8 degrees toward the sun, and the insulation thickness in the storage reservoirs was assumed to be 12 inches of urethane. The latitude of O'Hare is roughly equivalent to the assumed collector tilt angle. The tilt angle was made approximately equal to the latitude to provide for maximum winter collection. As will be observed from Figure 6.1, the selected collector surface area was more than sufficient to permit saturation of the reservoir temperature prior to the winter season; and, therefore, the choice of this tilt angle resulted in the optimum collection situation. It is possible that a better optimum collector surface area and tilt angle combination could be obtained. This would have involved parametric studies which are beyond the present scope.

Figure 6.2 shows the results of additional analyses for the Reference airport. The collector area (75,000 ft^2) and the storage volume (800,000 ft^3) are considerably smaller than those used for O'Hare. The annual energy requirements for the Reference airport are approximately 50% of those for O'Hare.

For both O'Hare and the Reference airports (Figures 6.1 and 6.2), the maximum storage temperatures were limited to 200°F in order to avoid boiling at the exit lines from the solar collectors. The minimum storage temperatures were limited to 80°F in order to provide sufficient thermal driving head (for the design selected for the energy distribution subsystem) to provide the specified pavement surface heat fluxes.

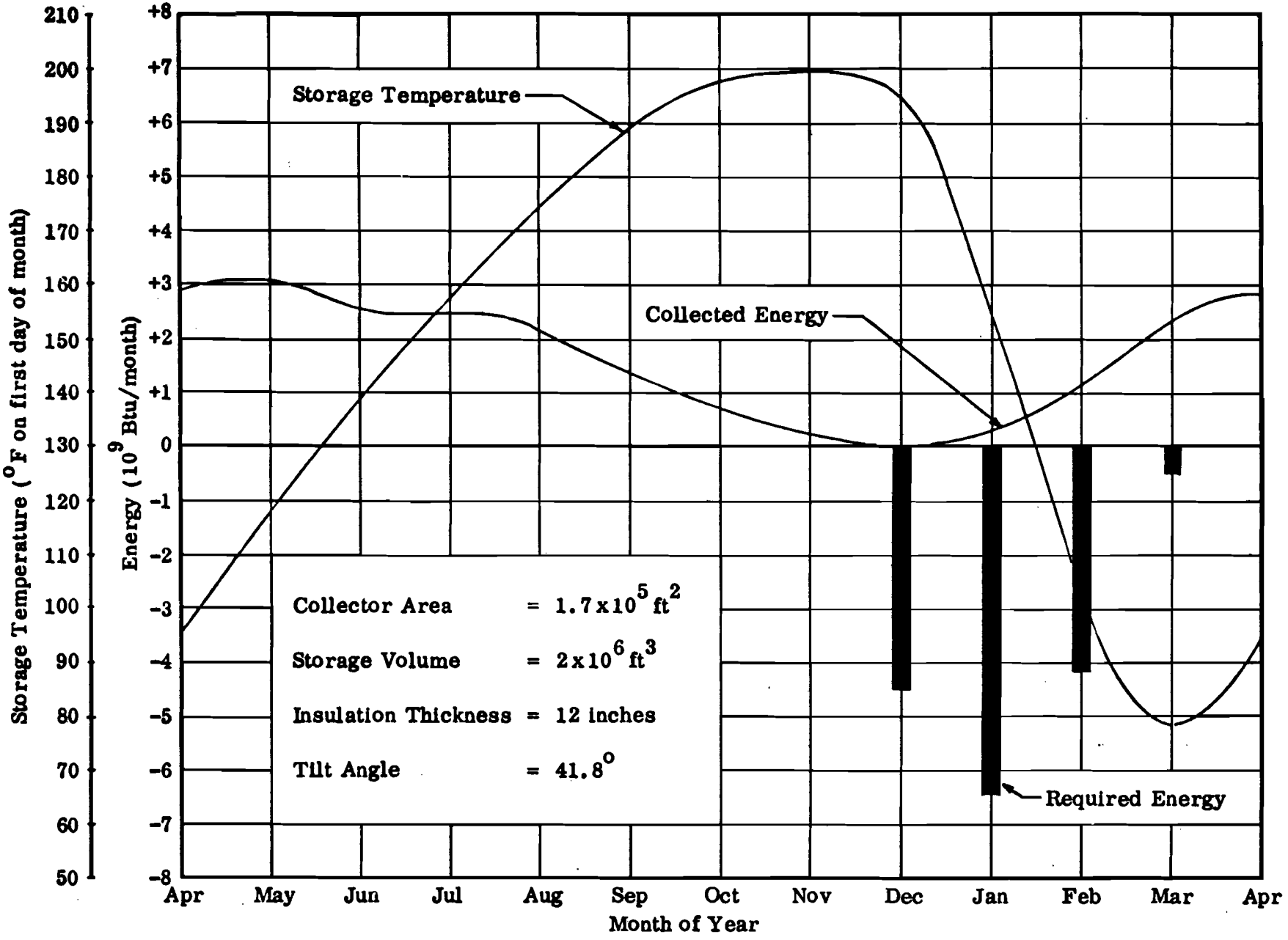


FIGURE 6.1

ANNUAL VARIATION IN STORAGE TEMPERATURE, COLLECTED ENERGY, AND REQUIRED ENERGY FOR O'HARE

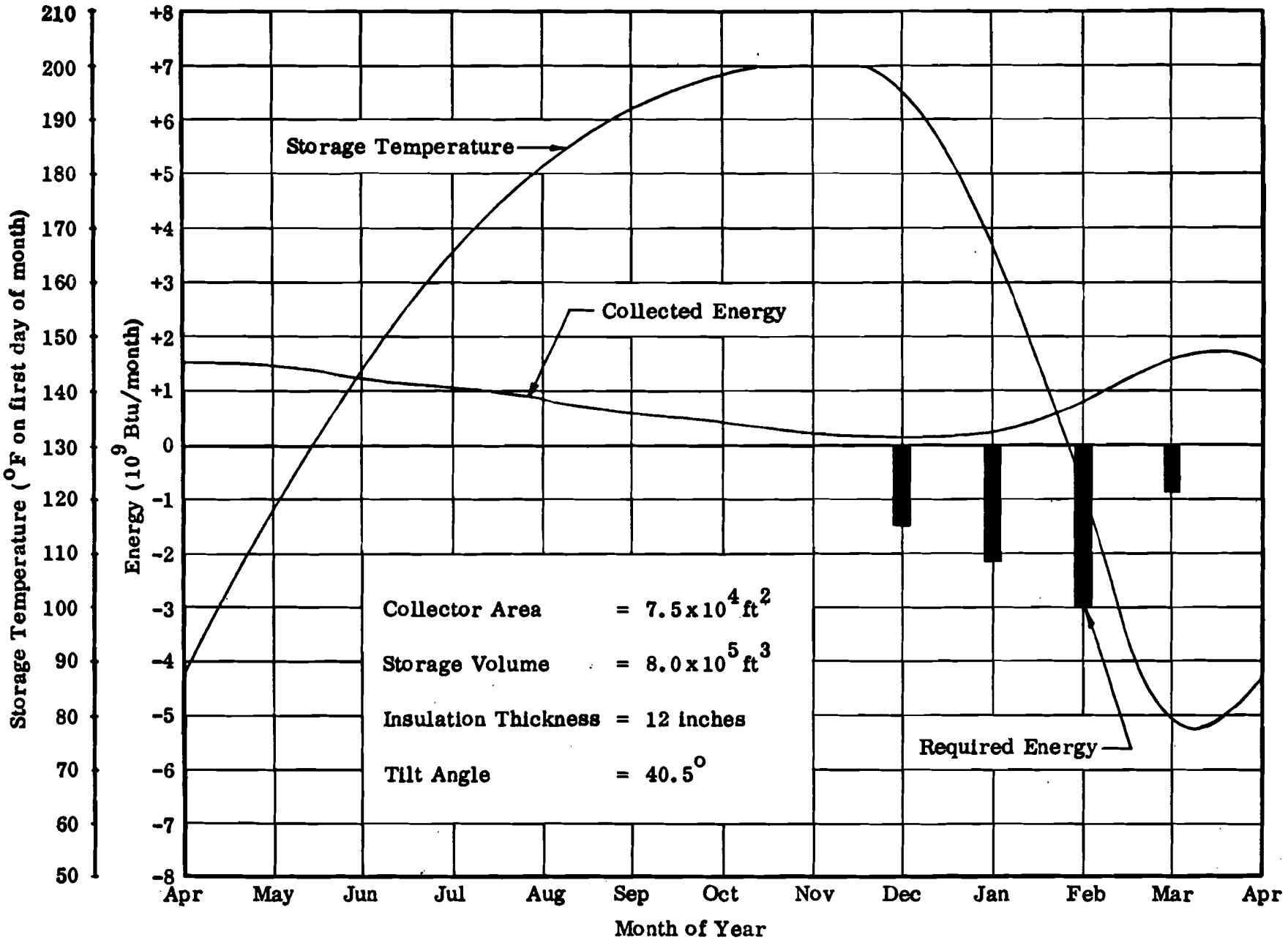


FIGURE 6.2

ANNUAL VARIATION IN STORAGE TEMPERATURE, COLLECTED ENERGY, AND REQUIRED ENERGY FOR REFERENCE AIRPORT

A study of Figures 6.1 and 6.2 shows that the collected energy reaches a minimum during the months of November and December. During these months, the storage reservoir temperature is at or near its maximum. The air temperatures during these months are beginning to fall rapidly which, when combined with the high collection temperature (storage reservoir temperature), results in an adverse effect on the collector conversion efficiency. In the northern latitudes, the available solar energy decreases during the winter months because of shorter days and frequent inclement weather (Reference 6). This further decreases the energy collected during the winter months.

Different combinations of storage insulation thickness, collector area, and storage volume have been studied. Tables 6.1 and 6.2 illustrate possible combinations of these variables for the Reference and O'Hare airports. In each case, the minimum storage volume temperature at the end of the winter season is fixed at $80^{\circ}F$. The combinations used for this study are the asterisked values on these tables. Note that as the storage reservoir insulation thickness decreases, more collector area is required to compensate for the greater thermal losses.

To complete the design analysis of the solar system, it is necessary to evaluate the heat transfer between the storage reservoir and the energy distribution subsystem. This heat transfer occurs in the hot water trench which parallels both sides of the runway and into which extensions of the pavement heat pipes penetrate. These extensions of the pavement heat pipes are termed the heat pipe evaporator sections. That portion of the heat pipes remaining in the pavement are termed the heat pipe condenser sections.

Hot water from the storage reservoir is pumped into the trench and yields thermal energy to the submerged heat pipe evaporator sections by virtue of convection heat transfer. The energy removal capability of each heat pipe depends on the local water temperature, the water flow conditions, the submerged length of each heat pipe, and the temperature of the pavement into which the heat pipes extend. Several trench designs have been investigated. In each case, the trench length has been assumed to be 2000 feet and each trench contains 4000 heat pipe evaporator sections. The pavement surface heat flux is assumed to be 26.8 Watts/ft^2 at a minimum storage water temperature of $80^{\circ}F$ (Reference airport).

Storage Tank Insulation Thickness (Inches)	Solar Collector Area (Ft^2)	Storage Tank Volume (Ft^3)
12	64,000	1,000,000
12*	80,000*	800,000*
12	102,000	750,000
8	88,000	1,000,000
8	109,000	800,000
8	132,000	750,000
4	140,000	1,000,000
4	170,000	800,000
4	200,000	750,000

TABLE 6.1

REFERENCE AIRPORT COLLECTOR AND STORAGE REQUIREMENTS FOR A MINIMUM STORAGE TEMPERATURE OF $80^{\circ}F$

Storage Tank Insulation Thickness (Inches)	Solar Collector Area (Ft^2)	Storage Tank Volume (Ft^3)
12	148,000	3,000,000
12*	174,000*	2,000,000*
12	240,000	1,500,000
8	189,000	3,000,000
8	206,000	2,000,000
8	309,000	1,500,000
4	262,000	3,000,000
4	270,000	2,000,000
4	411,000	1,500,000

TABLE 6.2

O'HARE AIRPORT COLLECTOR AND
STORAGE REQUIREMENTS FOR A
MINIMUM STORAGE TEMPERATURE OF 80°F

Perhaps the simplest concept, one may consider, is to pump the hot water into one end of the trench and take it out at the far end. This produces a horizontal water flow along the length of the trench. Because the water flows at a relatively high velocity, heat transfer from the water to the heat pipe is also relatively good. As the heat pipes extract heat from the water along the length of the trench, the bulk water temperature drops uniformly until it exists at a minimum temperature at the end of the trench. If one assumes that the pavement is at a uniform temperature along the length of the trench, the consequence of a drop in trench water temperature is a drop in pavement surface heat flux. At the inlet of the trench, where the water temperature is high, the pavement surface heat flux is excessive. Typically, at a storage reservoir temperature of 80°F, the heat flux is excessive by 20%; and, at a storage temperature of 200°F, the heat flux is excessive by 60%. This excessive heat flux is wasteful of energy. For an energy sensitive system like the solar system, this design approach is therefore unacceptable.

The above concept can be modified by introducing heat pipe extensions which have variable-length evaporator sections. This approach offers an important advantage. By independently controlling the mass flow rate (amount of water pumped through the trench) and the water level in the trench, it is possible to achieve a uniform pavement surface heat flux condition. The heat pipe extensions in the trench would vary from 2.5 feet at the inlet to 3.6 feet at the exit of the trench. The disadvantages of this concept are the increased manufacturing cost attendant with nonstandard heat pipes and the complex system control requirements.

Several concepts were suggested to minimize or eliminate the temperature gradient associated with longitudinal trench flow. Periodically reversing the flow in the trench was investigated. Technically, this approach would work. System design and operation, however, are complicated because a system of valving would be required to achieve the required reversing action; and the rate of reversing would be dependent on the existing environmental conditions. A listing of trench-flow heat transfer designs and the associated system implications are given in Table 6.3.

The preferred trench-flow heat transfer design is listed last in Table 6.3. This design, which is hybrid of the other designs listed, consists of a trench with a

Trench Design Concept	Type of Trench Flow	Type of Heat Pipe Evaporator	Control in Trench	Surface Flux Variation Along Runway
1	Longitudinal	Constant	Depth of Water Mass Flow	10
2	Longitudinal	Variable	Depth of Water Mass Flow	0
3	Longitudinal and Reversing	Constant	Depth of Water Mass Flow	Average = 0
4	Longitudinal Counter Flow	Constant	Depth of Water Mass Flow	0
5	Transverse	Constant	Mass Flow	0
6	Hybrid Transverse	Constant	Mass Flow	0

TABLE 6.3

COMPARISON OF TRENCH FLOW DESIGNS
FOR SOLAR RUNWAY HEATING SYSTEM

perforated dividing wall down its center (Figure 3.9). One side of the trench is used as a fill channel for water coming from the storage reservoir, and the opposite side contains the heat pipe extensions and is connected to the return side of the storage reservoir. Mass transfer between the trenches is accomplished by small flow channels (transfer tubes) located near the bottom of the dividing wall (Figure 3.9). Because heat is not extracted from the fill channel, it serves as a heat source of constant temperature. This design supplies constant temperature water to each heat pipe and has the additional advantage of providing good heat transfer because of the axial flow in the heat pipe portion of the trench.

The performance of the selected trench design is governed by the mass transfer between the two sides of the trench. The local mass transfer is a function of the local pressure head between the two sides of the trench. To control the mass transfer rate along the trench length, a large pressure head is intentionally incorporated between the two sides of the trench. This minimizes the effects of fluid flow on stagnation and static pressures within each side of the trench. To accomplish this, it is necessary to restrict the flow area for mass transfer while, simultaneously, providing sufficient area for axial mass flow.

The trench design shown in Figure 3.9 is capable of providing uniform heat pipe heat flux at the specified design conditions. The evaporator length of the heat pipe extension is 3.5 feet. The combined area for axial flow of both sides of the trench is 15 ft^2. It is important that the dividing wall be located such that the same axial flow resistance exists in both sides of the trench. This is necessary to minimize static head differences between the two sides along the length of the trench.

The transverse flow path through the dividing wall consists of one 0.50-inch diameter tube (transfer tube) spaced at 2.1-foot intervals along the length of the entire trench. Each tube is 1 foot long which results in a head difference at the maximum flow conditions of 1 foot.

As described in Section 3.3, system control is accomplished by controlling the mass flow rate. This control method varies the water temperature to which the heat pipes are exposed. When the pavement surface flux requirement is low and/or

when the storage temperature is high, the axial mass flow rate and the mass transfer between the two sides of the trench is reduced. Under this condition, the pressure head supported by the transfer tubes is lowered and the flow areas of the fill channel and heat pipe channel are no longer equal. Although this will cause a variation in liquid level height difference between the two sides of the trench, the head difference will not significantly affect the performance of the system.

7. DETERMINATION OF CAPITAL AND OPERATING COSTS OF THE SYSTEMS STUDIED

Throughout this study of pavement heating systems, capital and operating costs were of utmost concern. On several occasions, design effort was redirected when it became obvious that the cost of a given approach would be too high. After all iterations were completed, the resulting systems (see Section 3) were judged to be the best compromise between performance and economic considerations.

In preparing the capital cost estimates, commercially available prices were used for such items as electric cable, pipe, valves, boilers, and electrical heating elements. Standard pricing practices were used for items such as steam and water troughs, drain troughs, and buildings for housing equipment. Extrapolations from current costs were used for new technology items such as heat pipes and solar collectors. Commercial production facilities for these last items are not yet available.

The capital costs do not include the costs associated with the preparation of plans and specifications. The pavement heating systems are of a nature that plans and specifications can be standardized. These standards will apply universally and only minor site-peculiar accommodations will be required.

In addition, the capital costs do not include the costs normally associated with the laying of new pavement or the topping of existing pavement. The costs associated with laying and positioning of the heating elements, however, are included in the capital costs.

Several terms are used in this section which have been used in various ways in the literature. To avoid confusion, the terms as used here are defined as follows:

- Annual Operating Costs: Includes only those costs associated with operating the system such as maintenance labor and material costs, fuel costs, and salaries of operators.

- Total Annual Costs: Includes, in addition to annual operating costs, depreciation and interest charges.

- Capital Costs: Includes all material, labor, insurance, spares, and start-up costs which when expended will result in an operating system

capable of performing its intended function in accordance with stated performance specifications.

- Useful Service Life: Defined as the time period over which a system may be operated and still be able to perform within specifications without exceeding the budgeted maintenance costs.

- Depreciation Charge: For purposes of this study, the depreciation charge is the capital cost of a system divided by its useful life. The useful life is taken as 20 years, and residual value of the system after 20 years is considered to be zero.

- Interest Charge: A simple interest of 6% on the undepreciated capital balance was used in this study. In order to obtain a constant yearly interest charge, the total 20-year interest cost was divided by 20. This decision is not intended to imply any particular method of financing the construction of the pavement heating system.

- Demand Charge: This term is only used for electrical systems. The utility bills customers a charge for every kilowatt, in excess of 60, used in any given month. The usage is determined by a meter which checks the kilowatts being used twice every hour.

Capital and operating cost estimates for pavement heating systems were prepared for Chicago's O'Hare airport and for the Reference airport. Two pavement area sizes were evaluated -- a full 150-foot wide by 10,000-foot long runway and a ramp area of 60,000 square feet. Three pavement heating system types were investigated -- electrical, steam, and solar. The capital cost breakdown by subsystem elements is given in Table 7.1 for O'Hare airport and in Table 7.2 for the Reference airport.

Note that the capital costs for O'Hare are higher than those for the Reference airport. The annual snowfall for O'Hare is 8 inches more than for the Reference airport, and the average winter temperature for O'Hare is $6^{o}F$ lower. This requires a higher pavement power intensity for O'Hare than needed for the Reference airport (37.5 watts/ft^2 versus 26.8 watts/ft^2). Furthermore, the annual energy requirement for O'Hare is also higher (3.07 Kw-hrs/ft^2 versus 1.49 Kw-hrs/ft^2). The more severe O'Hare weather affects each of the three systems differently.

The capital cost of the energy source subsystem of the electrical pavement heating system is unaffected by small differences in weather severity. Increased capacity is

COST ELEMENT		RUNWAY COSTS ($)			RAMP COSTS ($)		
		Electrical	Steam	Solar	Electrical	Steam	Solar
Energy Source Subsystem	Boilers	—	360,000	—	—	50,000	—
	Solar Collectors	—	—	1,050,000	—	—	42,000
	Collector Supports	—	—	361,700	—	—	14,471
	Water Treatment	—	100,000	100,000	—	25,000	25,000
	Boiler Building	—	375,000	—	—	50,000	—
	Boiler Vent Stack	—	225,000	—	—	75,000	—
	Thermal Storage Tanks	—	—	1,000,000	—	—	40,000
	Thermal Storage Insulation	—	—	842,000	—	—	46,000
	Thermal Storage Roof	—	—	494,000	—	—	19,760
	Water Pumps	—	—	245,000	—	—	27,000
	Control System	150,000	250,000	250,000	100,000	150,000	150,000
	Subsystem Total	150,000	1,310,000	4,342,700	100,000	350,000	364,231
Distribution Subsystem	Electrical Heating Elements	6,832,000	—	—	273,280	—	—
	Heat Pipe Elements	—	3,000,000	3,170,000	—	120,000	126,800
	Troughs/Drains	200,000	400,000	400,000	10,000	20,000	20,000
	Installation of Elements	60,000	80,000	80,000	2,400	3,200	3,200
	Subsystem Total	7,092,000	3,480,000	3,650,000	285,680	143,200	150,000
Transport Subsystem	Material	450,000	741,065	480,000	38,240	89,200	101,652
	Labor	300,000	270,000	200,000	46,520	49,800	50,348
	Subsystem Total	750,000	1,011,065	680,000	84,760	139,000	152,000
Installation Supervision		100,000	100,000	100,000	30,000	30,000	30,000
Total System Capital Costs		8,092,000	5,901,065	8,772,700	500,440	662,200	696,231

TABLE 7.1

RUNWAY AND RAMP PAVEMENT HEATING SYSTEMS
CAPITAL COST ANALYSIS FOR O'HARE AIRPORT

COST ELEMENT		RUNWAY COSTS ($)			RAMP COSTS ($)		
		Electrical	Steam	Solar	Electrical	Steam	Solar
Energy Source Subsystem	Boilers	—	300,000	—	—	40,000	—
	Solar Collectors	—	—	480,000	—	—	19,200
	Collector Supports	—	—	165,000	—	—	6,622
	Water Treatment	—	100,000	100,000	—	25,000	25,000
	Boiler Building	—	375,000	—	—	50,000	—
	Boiler Vent Stack	—	225,000	—	—	75,000	—
	Thermal Storage Tanks	—	—	400,000	—	—	16,000
	Thermal Storage Insulation	—	—	410,000	—	—	24,000
	Thermal Storage Roof	—	—	197,600	—	—	8,000
	Water Pumps	—	—	245,000	—	—	27,000
	Control System	150,000	250,000	250,000	100,000	150,000	150,000
	Subsystem Total	150,000	1,250,000	2,247,935	100,000	340,000	275,822
Distribution Subsystem	Electrical Heating Elements	5,708,000	—	—	228,320	—	—
	Heat Pipe Elements	—	3,000,000	3,170,000	—	120,000	126,800
	Troughs/Drains	200,000	400,000	400,000	10,000	20,000	20,000
	Insulation of Elements	60,000	80,000	80,000	2,400	3,200	3,200
	Subsystem Total	5,968,000	3,480,000	3,650,000	240,720	143,200	150,000
Transport Subsystem	Material	450,000	741,065	480,000	38,240	89,200	99,452
	Labor	300,000	270,000	200,000	46,520	49,800	50,348
	Subsystem Total	750,000	1,011,065	680,000	84,760	139,000	149,800
Installation Supervision		100,000	100,000	100,000	30,000	30,000	30,000
Total System Capital Cost		6,968,000	5,841,065	6,677,935	455,480	652,200	605,622

TABLE 7.2

RUNWAY AND RAMP PAVEMENT HEATING SYSTEMS
CAPITAL COST ANALYSIS FOR REFERENCE AIRPORT

provided by the electric utility and appears as increased demand charges in the annual operating costs. Likewise, the capital cost of the transport subsystem is unaffected by small differences in weather severity because transmission of electrical energy to the pavement area is accomplished by high-voltage underground cables. The primary effect of increased weather severity occurs in the distribution subsystem. A 40% increase in required surface heat flux results in a 20% increase in the cost of the electrical heating elements and their associated electrical hardware.

For the steam system, the primary effect of increased weather severity is in the required increase in the capacity of the boilers. The transport system can accommodate nominal increases in capacity without changes in pipe diameter by simply increasing steam pressure. The transport capacity of the heat pipes used in the distribution subsystem is sufficient to handle the increased heating requirements without changing the design. For these reasons, the steam system is least affected by moderate changes in the winter climate design specifications.

Of the three systems studied, the capital cost of the solar system is affected the most by changes in winter climate design specifications. The effect shows up in the energy source subsystem. The annual energy requirement for O'Hare is 100% greater than for the Reference airport (3.07 Kw-hrs/ft^2 versus 1.49 Kw-hrs/ft^2). The energy source subsystem must collect and store twice as much energy for O'Hare as required for the Reference airport. Other conditions being equal, this results in a doubling of the required solar collector area and storage volume capacity. Actually, for a full runway (1,500,000 ft^2 of pavement area), O'Hare requires a collector area of 175,000 ft^2 and a storage volume of 2,000,000 ft^3 as compared with 80,000 ft^2 and 800,000 ft^3 for the Reference airport. The extrapolation is not exactly linear because of a number of associated factors such as a 9.5% higher annual solar flux available at the Reference airport and the greater thermal storage losses in the colder O'Hare climate.

The total annual costs and annual operating costs are summarized in Table 7.3 for the three systems studied. The costs are given for O'Hare and the Reference airports, a full runway, a ramp, and for two fuel costs. All systems were designed for a useful service life of 20 years.

The significant system-type variable in the annual operating cost is represented by the cost of electricity and oil. With the rapidly changing energy costs which have taken place in the last few years, it has been difficult to arrive at accurate projections for systems having a 20-year service life. Currently, Dynatherm is paying 4.7 cents/Kw-hr at a monthly usage rate in excess of 20,000 Kw-hrs. This cost is equivalent to paying $13.8 per million Btu of thermal energy. Currently, Middle East crude oil is priced at $12 per barrel which is equivalent to about $2 per million Btu. The above costs for electricity and oil have doubled in the last five years (Reference 4). Likewise, demand charges have been increasing. Currently, Dynatherm is paying $2.67/Kw for usage in excess of 60 Kw. Five years ago this demand charge was $1.92/Kw. Energy and demand charges will vary from one location to another, depending on the quantity of usage and the type of service (Reference 4).

In view of these uncertainties, the annual operating costs were computed using two sets of electricity and oil costs (Table 7.3). The electricity costs and demand charges are the best 1976 and 1986 estimates for high voltage service at the usage level represented by a full runway. The cost of oil was assumed to double on a 10-year cycle, and the cost of electricity was assumed to double on a 5-year cycle. Because energy costs were assumed constant for various values of pavement area, the annual operating costs for the ramp are somewhat understated.

It should be noted that general inflation will result in an offsetting increase in revenues. Therefore, the selection of appropriate energy costs becomes of primary importance when economic comparison between system types are made.

In every case, the annual operating cost of the solar system is the lowest of the three systems studied (Table 7.3). Because the solar system's annual operating cost is independent of energy costs, this conclusion obtains for fuel costs equal to or greater than the lowest set of energy costs used in this study.

The total annual cost (Table 7.3) includes depreciation and interest charges. These charges are directly related to the capital cost of the system. For the large systems (full runway) and more severe weather environments (O'Hare), the capital cost of the steam system is considerably less than the capital costs of the electrical

		COST	O'HARE AIRPORT			REFERENCE AIRPORT		
			Electrical	Steam	Solar	Electrical	Steam	Solar
RUNWAY	1.25¢/Kw-Hr $2/10^6$ Btu	Total Annual Cost	1,129,922	591,385	741,816	894,817	566,328	574,235
		Annual Operating Cost	482,562	119,300	40,000	337,377	99,044	40,000
	5¢/Kw-Hr $4/10^6$ Btu	Total Annual Cost	1,498,358	630,685	741,816	1,118,526	585,372	574,235
		Annual Operating Cost	850,998	158,600	40,000	561,086	118,086	40,000
RAMP	1.25¢/Kw-Hr $2/10^6$ Btu	Total Annual Cost	68,557	84,564	74,333	59,152	82,938	68,454
		Annual Operating Cost	28,503	31,568	20,000	22,694	30,762	20,000
	5¢/Kw-Hr $4/10^6$ Btu	Total Annual Cost	83,296	86,112	74,333	68,101	83,700	68,454
		Annual Operating Cost	43,242	33,136	20,000	31,643	31,524	20,000

Demand Charges are $1.8/Kw (@ 1.25¢/Kw-Hr) and $2.67/Kw (@ 5¢/Kw-Hr)

TABLE 7.3

SUMMARY OF TOTAL ANNUAL COSTS AND ANNUAL OPERATING COSTS FOR TWO LEVELS OF FUEL COSTS AND RAMP AND RUNWAY PAVEMENTS FOR O'HARE AND REFERENCE AIRPORTS

and solar systems (Table 7.1) and, consequently, the total annual cost of the steam system is also the lowest of the three systems. For milder climates (Reference airport) and for the large systems, the difference in capital costs between the three systems is relatively small and, therefore, the total annual cost is controlled by the energy costs. For the higher energy costs, the solar system exhibits the lowest total annual cost.

As the system size is reduced (ramp), system capital costs predominate in the total annual cost evaluation (Table 7.3). For the lower set of energy costs, the electrical system has the lowest total annual cost of the three systems studied. As the energy costs increase, the solar system becomes competitive with the electrical system especially as the winter environment becomes more severe (O'Hare). The annual operating cost of the solar system is the lowest for both sets of fuel costs, large and small systems (at least down to pavement areas of 60,000 ft^2), and for both O'Hare and Reference airport winter climates.

8. DETERMINATION OF AIRPORT DELAY COSTS RESULTING FROM SNOW, SLUSH, AND ICE

Prior to studies conducted under this program, it was assumed that the costs of removing snow and ice from pavement surfaces increased as the winter weather became more severe. As a corollary to this assumption, it was thought that the more severe the winter weather, the greater would be the disruptions of airport operations. Consequently, disruptions and the associated delay costs were assumed to increase with weather severity (Reference 1). The analyses of snow and ice delay costs reported in the following paragraphs contradict this conclusion.

A study was made by the FAA Systems Analysis Division of the costs of disruptions (delays, diversions, and cancellations) of aircraft arrivals (landings) associated with a number of Category II and III weather situations (Reference 2). This study was conducted for some of the major airports in the United States. The costs were computed with and without the estimated value of passenger time. E. Bromley (Reference 3) and others have catalogued disruptions for airports located in the United States by weather type (i.e., snow and ice, fog, thunderstorms, etc.). Finally, studies show that disruptions due to snow and ice are predominately classified as delays (Reference 1). The procedure used to determine the delay costs associated with snow and ice follows.

Airports were selected in snow and ice regions which had at least one ILS runway with a Category II capability. Because snow and ice result primarily in delays, only the Category II costs that are tabulated in Reference 2 were used. During calendar 1971, snow and ice caused 10.1% of all traffic delays (30 minutes or longer) throughout the United States (Reference 3). This percentage increases to 12.8% if only delays due directly to weather conditions are considered (i.e., if delays due to equipment failures, excessive traffic density, etc., are eliminated).

Of all weather types, snow and ice are considered predominately regional. Of the population of the United States, 28% is located in heavy snowfall regions, 31.2% in moderate snowfall regions, and 9.8% in slight snowfall and icing regions. In all of these regions, snow and ice contributed to delays at a proportionally higher percentage (18.5% versus 12.8% on a national average). If fog associated delays are eliminated (because

of the seasonal nature of this weather type) from the percentage calculations in the snow and ice regions, the percentage of snow and ice delays with respect to all remaining weather-associated delays varies between 22.7% and 26.6%. Because of the approximate nature of these assumptions when applied to a specific airport, a constant percentage of 25% was selected. This percentage was applied to Category II delay costs (less fog) for airports in snow and ice regions.

The Category II costs for weather conditions other than fog (Reference 2) were multiplied by a factor of two to account for delays in departures in addition to delays in arrivals. Twenty-five percent of the resulting cost was taken as the delay cost associated with snow and ice. Extrapolated cost values for 1976 were used for all airports. The selected airports and the snow and ice delay costs, with and without the value of passenger time, are listed in Table 8.1.

As can be seen by studying Table 8.1, there is a wide scatter in the cost data. It is difficult to use this data (as presented) in the design of pavement heating systems. The cost of building and operating a pavement heating system is related directly to the severity of the winter weather. Therefore, several attempts were made to relate the airport snow and ice delay costs to winter weather. The final results of this effort are given by the correlation plots shown in Figures 8.1 and 8.2. The values for the average number of hourly operations (between the time period 07:00 and 22:00), average winter snowfall, and average winter temperature that were used in these correlation plots are listed in Table 8.1.

The average number of hourly operations have been extrapolated to 1976 but have not been seasonally adjusted. The average winter snowfall is averaged over an extended period usually between 20 and 30 years. The average winter temperature is also averaged over an extended period and is the average temperature over the months during which a significant snowfall occurs.

The correlation plots were made by taking the product of the average number of hourly operations and the inches of annual snowfall and dividing this product into the annual delay costs associated with snow and ice. The resulting number was plotted against the average winter temperature for each of the selected airports. Figure 8.1 shows the

AIRPORT	Average Number Hourly Operations	Average Winter Snowfall	Average Winter Temperature	Snow/Ice Delay Costs	
				Passenger	No Passenger
	07:00-22:00	inches	^{o}F	$\$ \times 10^3$	$\$ \times 10^3$
Baltimore	26.0	25.3	37.3	425	112
Birmingham	8.8	1.5	44.0	8	2
Boston	42.6	41.7	32.8	603	185
Buffalo	18.4	86.5	29.4	218	68
Chicago	105.6	38.3	29.8	787	233
Cleveland	28.6	50.5	32.7	185	59
Columbus	15.2	28.6	32.8	53	15
Dallas	48.2	2.3	45.9	108	29
Denver	32.6	58.3	35.3	79	25
Detroit	38.0	31.7	31.8	360	95
Hartford	17.4	55.0	29.2	135	36
Indianapolis	15.4	20.3	32.5	103	30
Kansas	24.4	20.2	38.1	423	92
Louisville	14.6	17.9	37.6	32	9
Milwaukee	17.6	43.8	29.7	185	52
Minneapolis	25.2	43.5	24.8	73	22
New York - JFK	48.4	29.8	35.7	1608	427
New York -LaGuardia	49.2	29.8	35.7	376	108
Newark	34.2	24.0	35.6	391	112
Philadelphia	37.0	21.7	35.1	355	102
Pittsburgh	35.2	46.2	33.3	242	74
Salt Lake City	14.2	54.7	33.4	37	12
Seattle	21.4	14.7	38.2	137	37
St. Louis	36.4	17.2	36.0	197	61
Washington-Dulles	17.2	25.3	35.4	323	90
Washington-National	38.0	18.3	37.6	227	64

TABLE 8-1

ESTIMATED 1976 SNOW/ICE DELAY COSTS
AND OTHER DATA FOR REPRESENTATIVE AIRPORTS

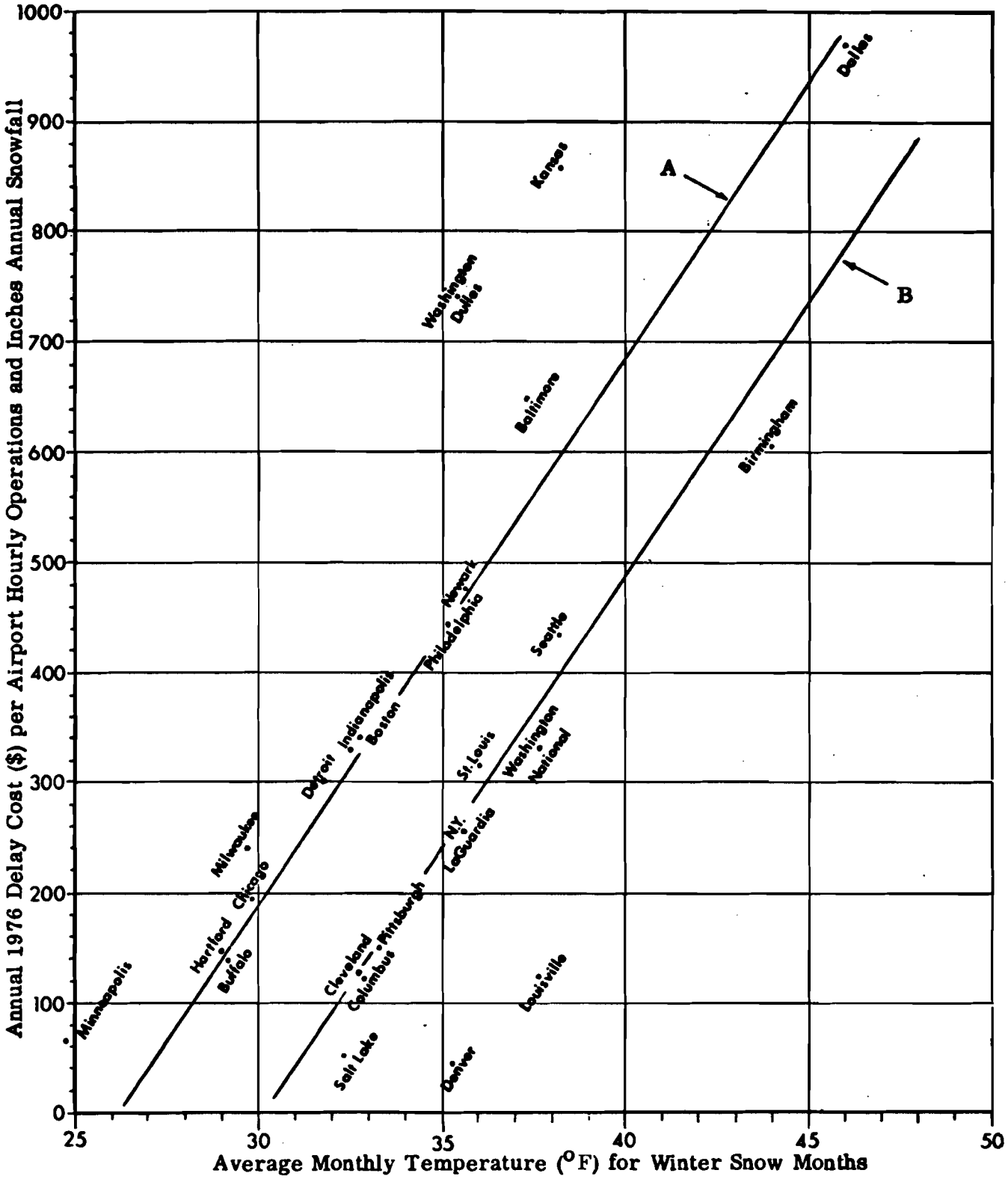


FIGURE 8.1

CORRELATION PLOT - PASSENGER DELAY COSTS INCLUDED

results of this plotting with the value of passenger time included, and Figure 8.2 shows the results without including the value of passenger time. Generally, the airports fall into two classifications which are designated A and B on Figures 8.1 and 8.2. Attempts were made to reconcile these classifications with other weather parameters such as humidity, wind speed, solar flux, and winter snowfall spectrum but no definable association could be discovered. Attempts were also made to determine whether or not geographical influences such as elevation of airport, proximity to bodies of water, and proximity to large energy sources such as cities would explain the classifications. The classifications represent an average winter temperature difference of only $4^{o}F$. Again, no explanation was found.

Perhaps one explanation for the classifications A and B may be found by examining the methods and equipments used by airports to handle snow and ice. A study of this type was beyond the scope of the present effort, although differences between airports are known to exist.

The correlation plots of Figures 8.1 and 8.2 can be expressed by:

$$\left.\begin{aligned} \text{Cost (A)} &= NS\,(13.5\,T_{avg} - 345) \\ \text{Cost (B)} &= NS\,(13.5\,T_{avg} - 404) \end{aligned}\right\} \text{passenger value not included}$$

$$\left.\begin{aligned} \text{Cost (A)} &= NS\,(50\,T_{avg} - 1315) \\ \text{Cost (B)} &= NS\,(50\,T_{avg} - 1510) \end{aligned}\right\} \text{passenger value included}$$

where the costs are the annual snow and ice delay costs in dollars, N is the average number of hourly operations at the airport between the hours of 07:00 and 22:00, S is the average winter snowfall at the airport in inches, and T_{avg} is the average monthly temperature during the winter snow months. The costs with the value of passenger time included are a factor of 2.7 higher than the costs without the value of passenger time included.

The significance of these correlation plots is illustrated by Figure 8.3. This figure shows a plot of the following expression:

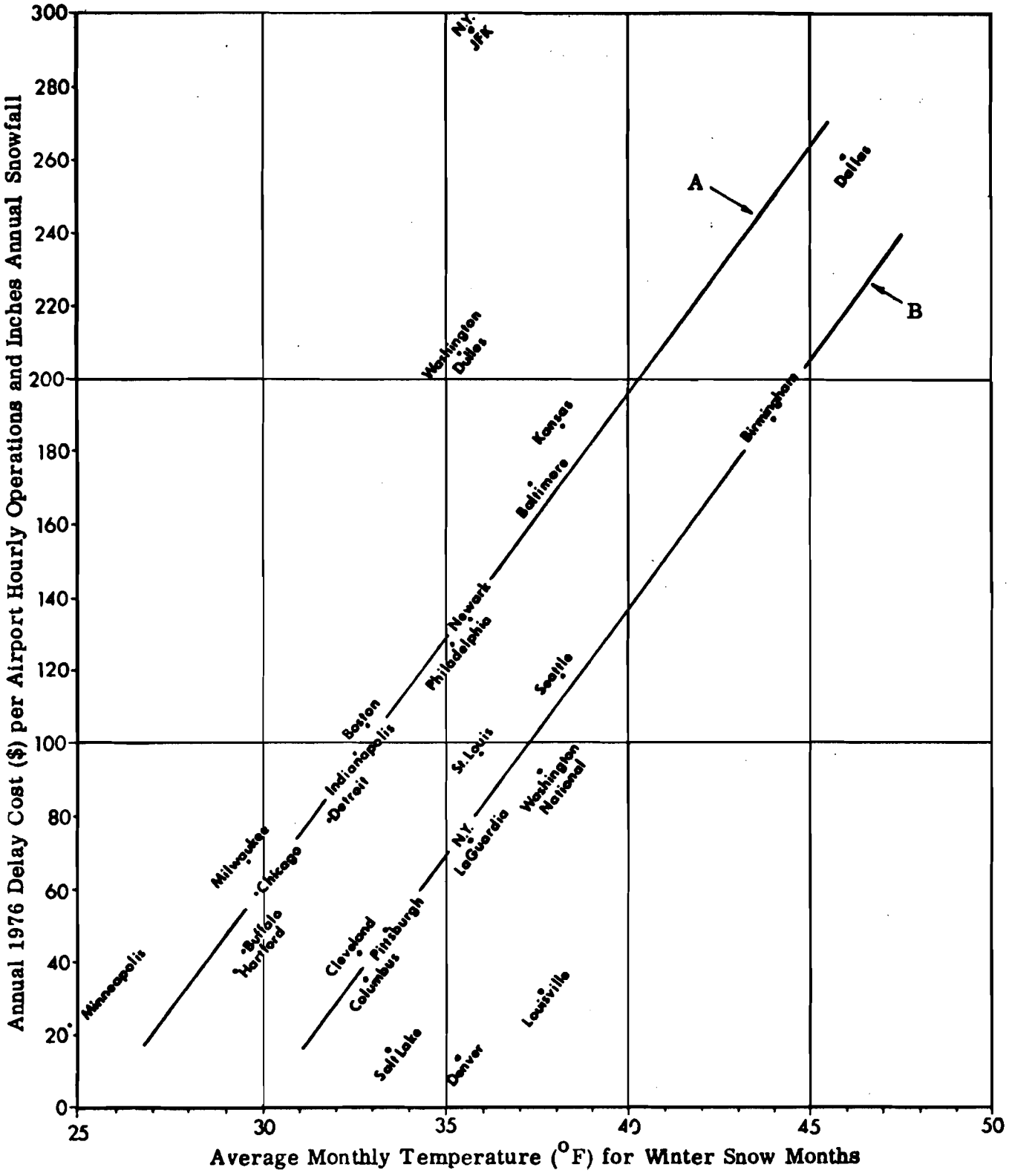


FIGURE 8.2

CORRELATION PLOT - PASSENGER DELAY COSTS NOT INCLUDED

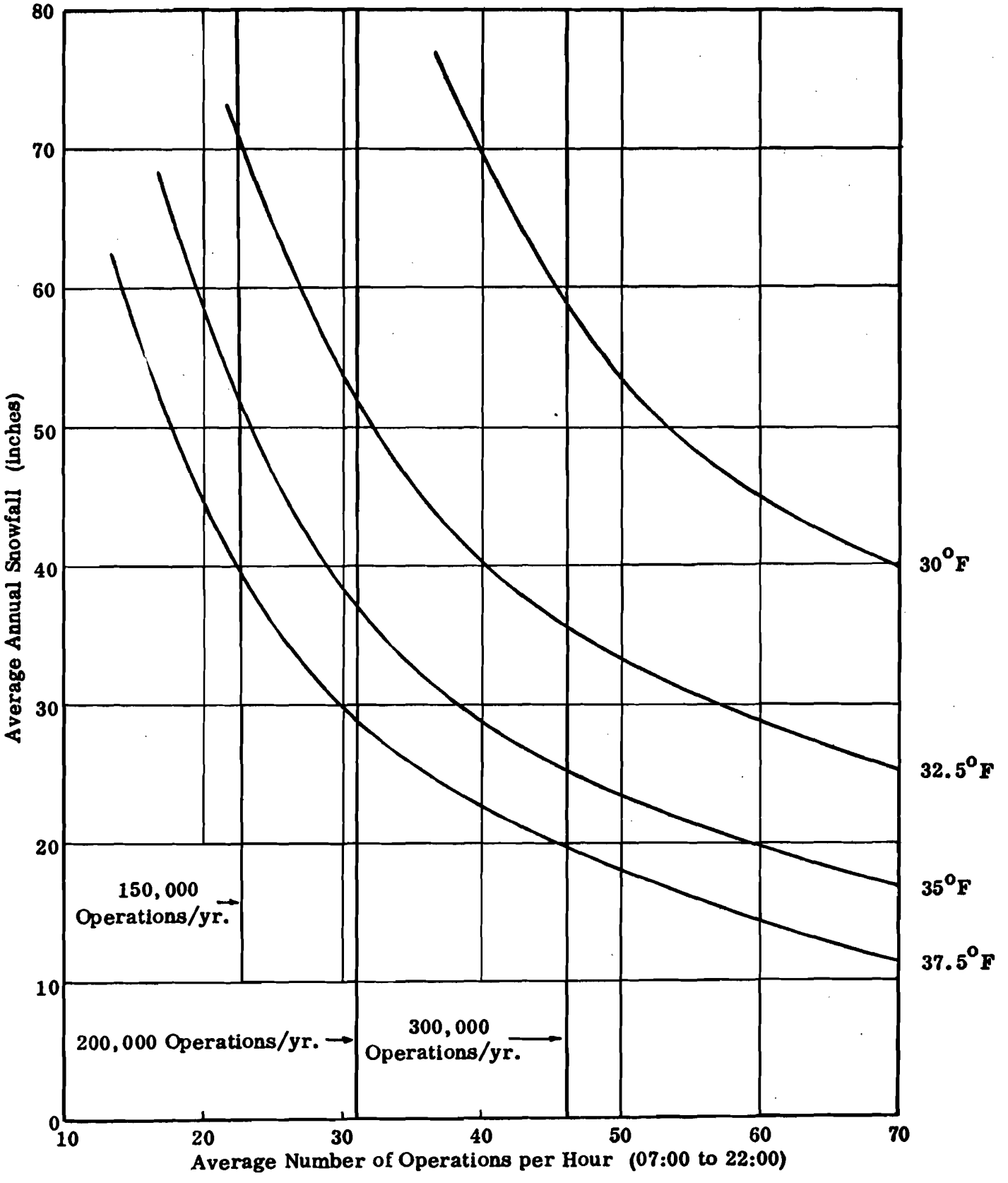


FIGURE 8.3

AVERAGE WINTER TEMPERATURE PROFILES FOR A FIXED $500,000 SNOW/ICE DELAY COST INCLUDING IMPUTED PASSENGER VALUE AS A FUNCTION OF ANNUAL SNOWFALL AND NUMBER OF AIRPORT OPERATIONS

$$N = \frac{\text{Cost (A)}}{S(50\,T_{avg} - 1315)}$$

for a constant cost of $500,000 per year. Figure 8.3 shows that, as the annual snowfall increases for any given value of average winter temperature, the traffic density of the airport decreases for a constant value of annual snow and ice delay cost ($500,000). This conclusion is intuitively obvious. What is not obvious, however, is that, as the average winter temperature increases, the average snowfall decreases for a constant value of annual snow and ice delay cost. Practically, as the average winter temperature increases the annual snowfall decreases and eventually becomes zero.

The validity of this conclusion is supported by analysis of the monthly delays due to snow and ice, as reported in Reference 3. Approximately 3/4 of all such delays occur during the months of March and April. These are months during which significant warming occurs throughout the United States. In conjunction with this, the acceptable runway tolerance for wet snow or slush is 1/2 inch and for dry snow the tolerance is 2 inches (as reported in the Air Transport Association Handbook). The estimated average snowfall size throughout the United States is 1.5 inches on days when a storm occurs (Reference 1). This is within the 2-inch allowable tolerance for dry snow but exceeds the 1/2-inch allowable tolerance for wet snow. The colder climates will have a greater percentage of dry snow during any given winter; and airports located in these climates will, therefore, experience a smaller percentage of delays for average snowfalls.

As stated previously, the costs of building and operating a pavement heating system increase as the conditions for which the system is designed become more severe. These studies show that the benefits to be derived from a pavement heating system decrease as the winter weather becomes more severe. During the program, it became obvious that the Benefit/Cost ratio would optimize for airports located in relatively mild climates. Consequently, the original program was redirected and the airport located at Juneau, Alaska, was eliminated from further study. In its place, a hypothetical Reference airport was substituted and assigned a relatively mild climate which is

representative of Mid-Atlantic Eastern cities. The snow delay costs of the Reference airport were selected to correspond to Curves A of Figures 8.1 and 8.2 as represented by the appropriate expressions previously given.

9. BENEFIT/COST RATIOS FOR O'HARE AND REFERENCE AIRPORTS

Removal of snow and ice by means of heated pavements is a necessary step toward the goal of achieving an "all-weather" airport. Whether or not this goal is technically and economically feasible has been the subject of much debate. This report addresses this question for the weather area of snow and ice.

The annual operating and total annual costs of airport pavement heating systems are developed in Section 7. The airport delay costs associated with snow and ice are outlined in Section 8. The delay costs are determined for two cases -- costs which may be recovered as a result of increased revenues from airline users, and costs associated with the capital investment which saves passenger waiting time by minimizing or eliminating delays. This latter cost, which results in a nonrevenue benefit (improved service), must be partly or entirely subsidized.

The benefit of an improvement in terms of annual revenue dollars divided by the cost of financing, maintaining, and operating this improvement in dollars per year is a dimensionless ratio which is a convenient index that is used to judge the economic feasibility of the improvement. This is termed the Benefit/Cost ratio. When the ratio is exactly one, the improvement costs are said to be break-even with the resulting revenues generated by the improvement. When the ratio is greater than one, the revenues exceed the costs; and, when the ratio is less than one, the costs exceed the revenues and the improvement is not economically feasible.

Two types of Benefit/Cost ratios are evaluated in this section:

- Operating Benefit/Cost Ratio: The benefits are those that can produce revenues from increased flight fees. Increases in flight fees are justified because of reduced airline delays and reduced aircraft maintenance costs. The costs are those associated only with the maintenance and operation of the pavement heating system.

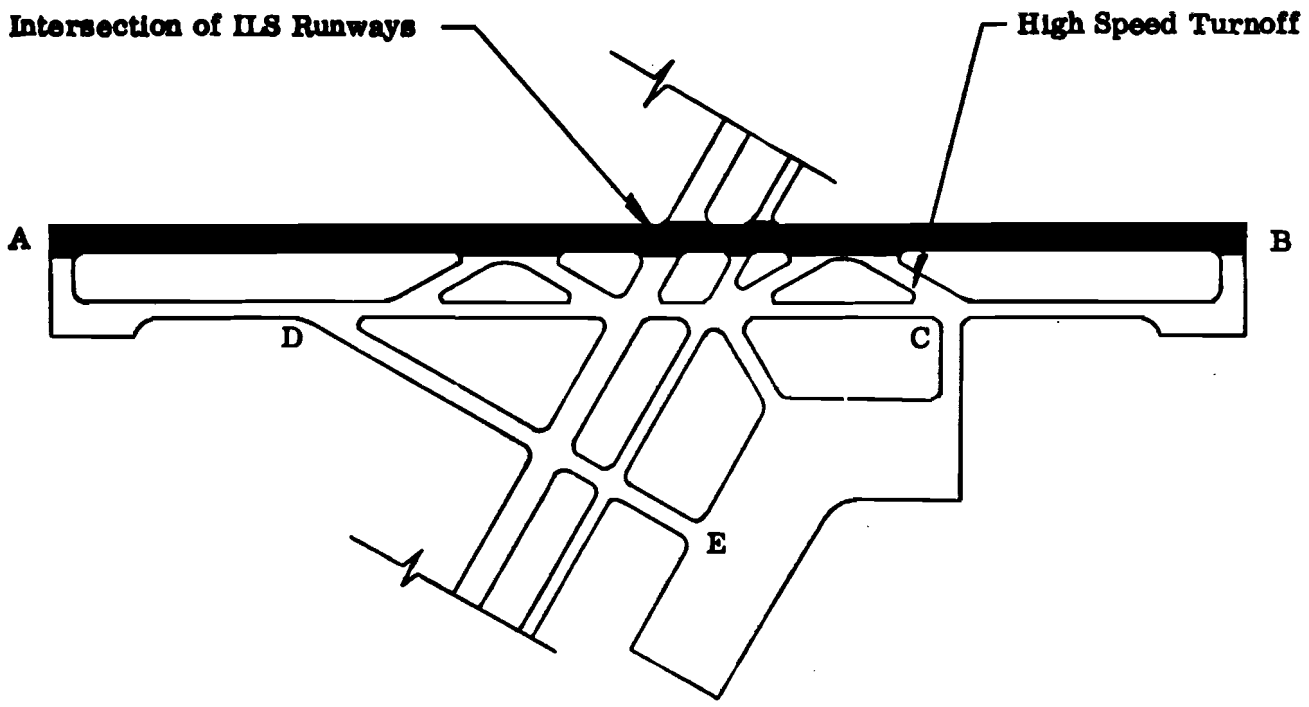
- Total Benefit/Cost Ratio: In addition to the revenue producing benefits, there are those benefits associated with improved service which saves time of passengers. Reference 2 assigns a dollar value to the passenger time. It is this dollar value which when added to the realized revenue results in the total benefit value used here. The pavement heating system is an investment which must be financed. The

depreciation and interest charges of this investment are added to the operating costs to yield the total cost used in this ratio.

The pavement heating system represents an investment of $4 to $6 per square foot of pavement area for large systems and approximately $11/ft^2 for small systems. This large investment is utilized for only 1/3 of the year. For the remaining 2/3 of the year, the investment sits idle and does not contribute to improving airport service. For this reason, airport operators are reluctant to consider pavement heating systems for snow and ice removal. The general attitude has been that, if the system does not interfere with airport operations and if someone else provides it, the airport will operate it provided that the costs of operation can be recovered through increased revenues (operating Benefit/Cost ratio equal to one or greater). The airport operator's position is understandable; however, the general public (either local or federal) cannot be asked to finance an improvement unless either a case can be made for overall economic feasibility (total Benefit/Cost ratio equal to one or greater) or other considerations such as safety, fuel conservation, etc., can support the case for an otherwise uneconomical improvement.

A Benefit/Cost analysis has been made for the Reference airport for selected pavement heated areas. To illustrate the procedure, consider the heating of a full 150-foot wide, 10,000-foot long runway. To determine the benefit, it is first necessary to establish the reduction in delay that will be experienced with the chosen heated pavement location. It is assumed that the existing mechanical snow and ice control equipment is capable, with proper programming, of clearing the necessary pavement areas in a 15-minute period (Reference 1). During the time the equipment is programmed, the airport is closed down for a minimum time of 15 minutes.

A layout of the Reference airport indicating the heated runway area is shown in Figure 9.1. The types and quantities of mechanical snow removal equipment and the transit times between designated locations are also indicated in Figure 9.1. Normally, equipment groups #1 and #2 (Figure 9.1) are both required to clear the runway (A to B) during the time interval of 7.5 minutes. Obviously, during this time interval, the airport must be closed down because the equipment is on the runway.



EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				

FIGURE 9.1

REFERENCE AIRPORT LAYOUT WITH HEATED RUNWAY

With the heated runway, the sweepers (S), plows (L), large plows (PL), and high speed blowers (BH) of equipment groups #1 and #2 can be reprogrammed to maintain the high speed turnoffs and taxiways free of snow and ice. Without the requirement for airport shutdown for runway clearance of snow and ice, there now exists the incentive to reprogram the freed equipment in such a way as to avoid any shutdown and, consequently, eliminate any delay. Using the approaches developed in Reference 1, several combinations of equipment movement can be formulated which will eliminate delay.

With delay eliminated, the costs associated with delay become the benefit. For the Reference airport, the following expressions which were developed in Section 8 can be used to determine the dollar value of the benefits:

$$\text{Cost (A)} = NS\,(13.5\,T_{avg} - 345)$$

$$\text{Cost (A)} = NS\,(50\,T_{avg} - 1315)$$

where the first expression does not include the value of passenger time and the second expression includes the value of passenger time. For the Reference airport, S = 30 inches of snowfall per winter, N = 31.5 operations per hour, and $T_{avg} = 35.7^{o}F$. Making these substitutions, the annual delay cost (Benefit) without including the value of passenger time is $129,418 and including the value of passenger time is $444,150. The pavement system total annual and annual operating costs for the Reference airport are given in Table 7.3. Therefore, the operating benefit/cost ratio for the low fuel cost case for the electrical system becomes:

$$\frac{\$129,418}{\$337,377} = 0.384 \text{ or approximately } 0.38$$

Likewise, the total Benefit/Cost ratio for the low fuel cost case for the electrical systems becomes:

$$\frac{\$444,150}{\$894,817} = 0.496 \text{ or approximately } 0.50$$

Repeating these steps for the other cases, the Benefit/Cost ratios listed in Table 9.1 are obtained.

An examination of Table 9.1 discloses that none of the three systems have a total Benefit/Cost ratio (1976 benefits) approaching break-even. The operating Benefit/Cost ratios for the steam and solar systems are above one; however, the steam system is sensitive to fuel costs and may approach break-even if fuel costs increase beyond the values assumed. Of the three systems studied, the Benefit/Cost ratios for the electrical system are clearly unacceptable (heated runway).

A studied of projected delay costs given in Reference 2 indicates that by 1981 increases of 50 to 65% can be expected in costs not including the value of passenger time and increases of 60 to 90% can be expected in costs including the value of passenger time. These increases are anticipated as the result of historical price escalations and increases in traffic density. Therefore, the total Benefit/Cost ratios for the steam and solar systems will exceed one before 1981 (for systems constructed in 1976). Of course, if these assumptions continue to be valid, this break-even projection can be made for any similar period in the future.

Pavement heating systems can be used to remove snow and ice from airport problem areas. In discussions with personnel at the Baltimore-Washington International Airport and from published documents, several airport problem areas have been identified:

- High Speed Turnoffs
- Intersection of ILS Runways
- Central Taxiway

The economic feasibility of pavement heating systems applied to localized pavement areas was investigated. As before, the Reference airport having the proper type and amount of mechanical snow removal equipment to achieve a 15-minute delay capability (Figure 9.1) is used as the evaluation standard. Each problem area was analyzed (Appendix A) to determine by how many minutes the 15-minute delay time could be reduced if the heating system was used in that area. The procedures outlined in Reference 1 were used as a guide and the following time savings were obtained:

Type of Pavement Heating System	Operating Benefit/Cost Ratio		Total Benefit/Cost Ratio	
	Low Fuel Cost	High Fuel Cost	Low Fuel Cost	High Fuel Cost
Electrical	0.38	0.23	0.50	0.40
Steam	1.31	1.10	0.78	0.75
Solar	3.09	3.09	0.77	0.77

TABLE 9.1

OPERATING AND TOTAL BENEFIT/COST RATIOS FOR REFERENCE AIRPORT RUNWAY FOR LOW AND HIGH COST FUELS

- ILS Runway : 15 minutes
- High Speed Turnoffs (4) : 5 minutes
- ILS Runway Intersection : 4 minutes
- High Speed Turnoffs (1) : 3 minutes
- Central Taxiway : 2 minutes

These time savings are mutually exclusive. The maximum benefit that can be achieved corresponds to a time saving of 15 minutes (zero delay). For the case of four high speed turnoffs, the benefit would be 5/15 or 1/3 of the maximum possible. In this manner, the benefits can be determined for the other areas.

The capital, total annual, and annual operating costs for these smaller pavement heating systems were determined in the same way as these costs were determined for the ramp (Section 7). The results are summarized in Tables 9.2, 9.3, and 9.4 for the electrical, steam, and solar systems. An examination of these tables reveals that the total Benefit/Cost ratio improves for all systems as the pavement area decreases. Although on a unit area basis the systems become more expensive as the pavement area decreases, the associated total benefits more than counterbalance these increases. If the value of passenger time is excluded from the benefits, the operating Benefit/Cost ratios for the electrical system increase as pavement area decreases, for the steam system they tend to be essentially constant, and for the solar system they decrease down to pavement areas of 300,000 square feet and then remain constant. These ratio variations are shown more clearly in Figures 9.2 and 9.3. As stated previously, both Benefit/Cost ratios will improve with time as the systems are operated. The improvement will be the greatest for the solar system and the least for the electrical system because of the influence of fuel costs.

Similar analyses can be performed for O'Hare airport. O'Hare is a large airport with a high traffic density (see Table 8.1) and a complex pavement system. Heating a single runway at O'Hare would not result in a 15-minute delay saving as it did for the Reference airport. Therefore, the full benefits (Table 8.1) would not be realized for the total annual and annual operating costs listed in Table 7.3.

PAVEMENT IDENTIFICATION	System Definition		Cost		Benefit/Cost Ratios	
	Pavement Area (Ft^2)	Capital Cost ($)	Annual Operating Cost ($)	Total Annual Cost ($)	Operating	Total
ILS Category II Runway	1,500,000	6,968,000	337,377	894,817	0.38	0.50
4 High Speed Turnoffs	316,700	1,130,684	82,704	178,158	0.52	0.83
Runway Intersection	180,000	902,792	47,964	120,187	0.72	0.99
Central Taxiway	37,500	309,450	12,933	37,689	1.33	1.57

TABLE 9.2

REFERENCE AIRPORT BENEFIT/COST COMPARISONS FOR SELECTED PAVEMENT LOCATIONS HEATED WITH ELECTRICITY

PAVEMENT IDENTIFICATION	System Definition		Cost		Benefit/Cost Ratios	
	Pavement Area (Ft^2)	Capital Cost ($)	Annual Operating Cost ($)	Total Annual Cost ($)	Operating	Total
ILS Category II Runway	1,500,000	5,841,065	99,044	566,382	1.31	0.78
4 High Speed Turnoffs	316,700	1,267,000	39,064	140,460	1.10	1.06
Runway Intersection	180,000	1,016,000	32,286	113,566	1.07	1.05
Central Taxiway	37,500	510,000	15,476	42,776	1.11	1.39

TABLE 9.3

REFERENCE AIRPORT BENEFIT/COST COMPARISONS FOR SELECTED PAVEMENT LOCATIONS HEATED WITH STEAM

PAVEMENT IDENTIFICATION	System Definition		Cost		Benefit/Cost Ratios	
	Pavement Area (Ft^2)	Capital Cost ($)	Annual Operating Cost ($)	Total Annual Cost ($)	Operating	Total
ILS Category II Runway	1,500,000	6,679,935	40,000	574,235	3.09	0.77
4 High Speed Turnoffs	316,700	1,221,870	25,000	122,750	1.72	1.21
Runway Intersection	180,000	937,000	20,000	94,960	1.73	1.25
Central Taxiway	37,500	357,019	10,000	38,560	1.72	1.54

TABLE 9.4

REFERENCE AIRPORT BENEFIT/COST COMPARISONS FOR SELECTED PAVEMENT LOCATIONS HEATED WITH SOLAR ENERGY

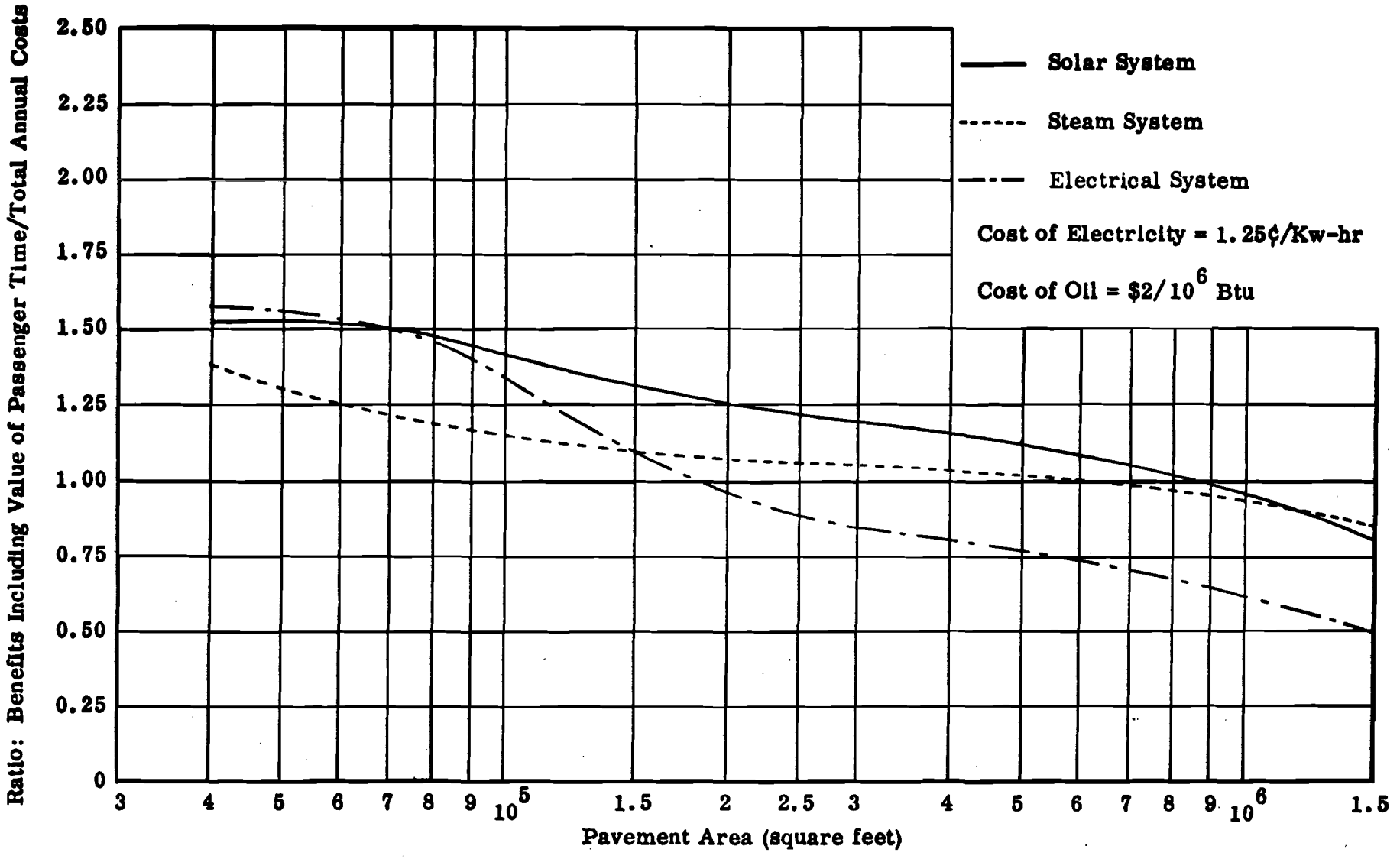


FIGURE 9.2

BENEFIT TO COST RATIO INCLUDING ALL BENEFITS AND ALL COSTS AS A FUNCTION OF AIRPORT PAVEMENT AREA FOR VARIOUS HEATING SYSTEMS

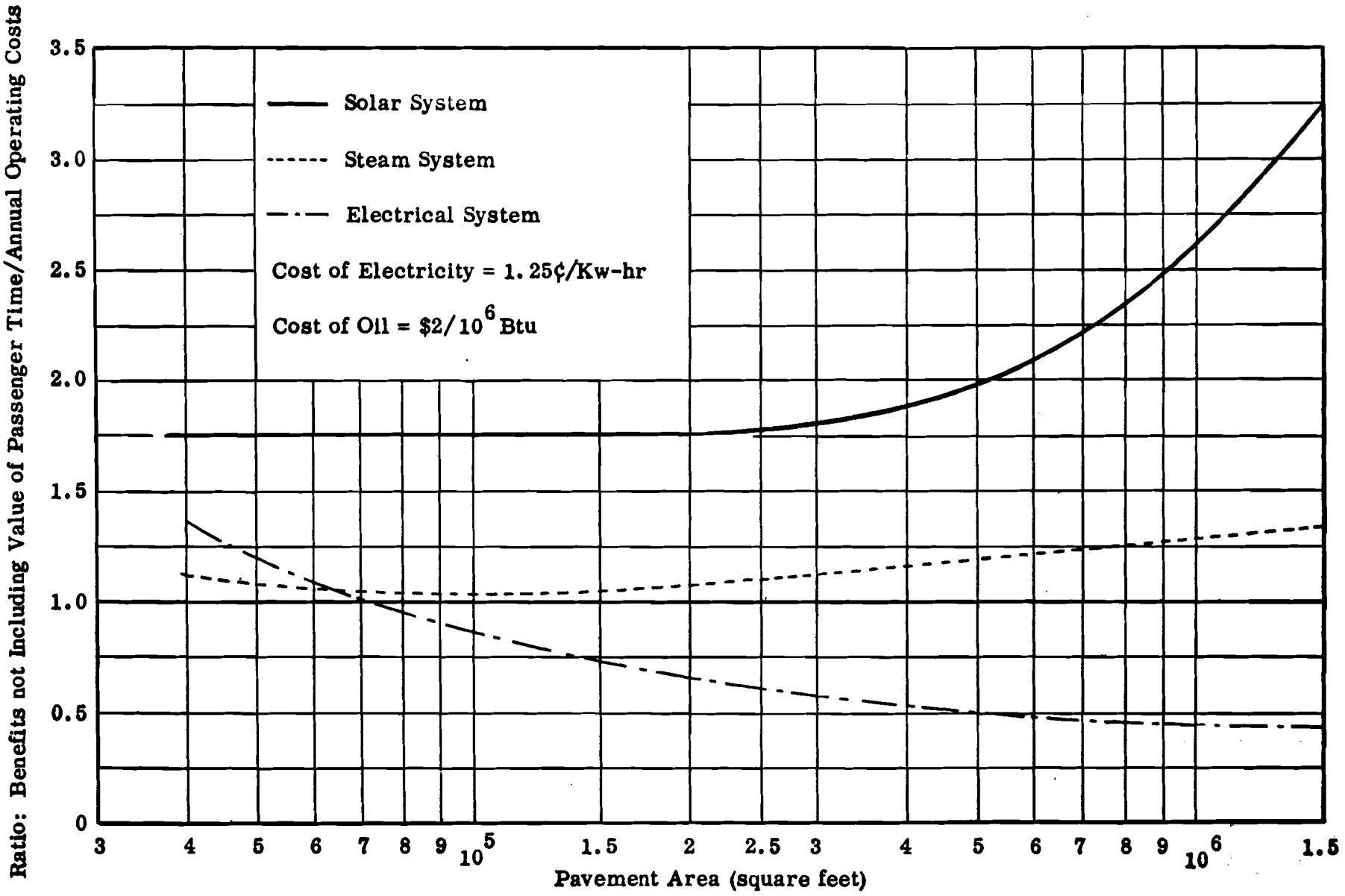


FIGURE 9.3

BENEFIT TO COST RATIO INCLUDING ONLY REVENUE PRODUCING BENEFITS AND ANNUAL OPERATING COSTS AS A FUNCTION OF AIRPORT PAVEMENT AREA FOR VARIOUS HEATING SYSTEMS

10. CONCLUSIONS

The heating of airport runways to thermally remove snow, slush, and ice is technically feasible and represents a significant step towards the objective of an "all weather" airport.

Heating systems are most attractive in moderate climates (average winter temperatures around 35°F, and average annual snowfalls between 25 and 40 inches). They are attractive for airports which have at least one ILS runway and a traffic density of more than 200,000 operations per year (about 31 operations per hour). In more stable colder climates, the snow is dry and easy to remove from the pavement surfaces; consequently, the costs to the airport and airlines of snow, slush, and ice are not high enough to override the costs of the more expensive heating systems required for these colder climates.

Operating costs can be recovered through the added revenues justified by the elimination or reduction in delays. The justifications for the investment required to build the heating system obtains because service and safety will be improved. Dollar savings for these improvements are difficult to assign and are the subject of controversy. However, it appears that the estimated savings resulting from these improvements must be projected forward about 5 years before a breakeven on the investment is realized. For heating systems with service lifetimes of 20 years, a breakeven projection of 5 years is considered acceptable.

Depending on the heating system, the capital costs of large systems (greater than 10^6 ft^2 of pavement area) are estimated to be in the range of $4 to $6 per square foot of pavement area. This unit cost will increase to between $8 and $12 per square foot for small systems (less than 100,000 ft^2 of pavement area).

Based on a 20-year depreciation, the total annual costs of large systems are estimated to be in the range of 40¢ to 75¢ per square foot of pavement area. For small systems, the total annual costs will increase to between 90¢ and 140¢ per square foot of pavement area.

The annual operating costs of large systems are estimated to be in the range of 3¢ to 30¢ per square foot of pavement area. The annual operating costs for small systems are estimated to be between 30¢ and 55¢ per square foot of pavement area.

Of the three systems investigated, the capital, total annual, and annual operating costs for an electrically heated runway are the highest. The capital and total annual costs for a steam heated runway are lower than for either the electrical or solar systems. The annual operating cost of the solar system is the lowest for the range of pavement areas represented by runways and ramps.

The electrical system is the least efficient and the steam system is the most efficient in the utilization of the Nation's energy resources. For the most part, the solar system does not use the Nation's energy resources. Consequently, the electrical system is the system most impacted by fuel shortages and fuel cost increases. For example, the annual operating costs of large electrical systems located at O'Hare International airport increase from 32¢/ft^2 at an electricity cost of 1.25¢/Kw-hr to 57¢/ft^2 at an electricity cost of 5¢/Kw-hr.

11. RECOMMENDATIONS

The solar system is recommended (over the electrical and steam systems) for heated runways at airports which have at least a moderate traffic density (in the order of 30 to 40 operations per hour) and which are located in moderate winter climates (about 25 to 40 inches annual snowfall and about 35°F average winter temperature). The supporting arguments for this recommendation are:

- The annual operating cost of the solar system is much lower than those of the competing systems investigated.
- The annual operating cost of the solar system is insensitive to the cost of fuel and, therefore, not subjected to escalation.
- The solar system conserves our Nation's fuel resources.
- The solar system is based on an infant technology in contrast to the more mature technologies of the steam and electrical systems. As solar technology advances, benefits promise to accrue to the solar system (Reference 11) and, thereby, increase its attractiveness.

Although the solar system performance and behavior have been characterized analytically, before a large scale operational installation is considered, it is recommended that an instrumented pilot solar system be constructed and operated. A small pilot facility would validate the various calculational assumptions and permit a more confident scale-up of the design for an airport installation.

Prior to committing a solar system for an entire runway, a smaller airport installation is recommended. This installation may be an intersection of ILS runways or a central taxiway. In addition to permitting an evaluation of heating systems under actual airport operating conditions, it would permit an evaluation of the cost effectiveness of the solar system, a judgment regarding the acceptance of heating systems by airport operations personnel, and a demonstration model that may be observed by personnel from other airports and organizations.

12. REFERENCES

1. FAA-RD-71-20, D. J. Tighe, L.A. Garland, and J. C. Caird, "An Analysis of Airport Snow Removal and Ice Control," March 1971

2. FAA-RD-71-44-1, "Potential Economic Benefits of Fog Dispersal in Terminal Area," Part I Estimating Procedure, Part II Findings, November 1971

3. Edmund Bromley, Jr., "Terminal Weather - Some Aspects of its Impact on Airport Capacity," International Conference on Aerospace and Aeronautical Meteorology, May 1972

4. DTM-70-6, Dynatherm Corporation, "Nuclear Wastes in Comparison with Other Heat Sources for Deicing of Bridges, Ramps, and Pavements," September 1970

5. FHWA-RD-75-6, W. B. Bienert, et al., "Snow and Ice Removal from Pavements Using Stored Earth Energy," May 1974

6. U. S. Department of Commerce, "Climatic Atlas of the United States," June 1968

7. AC 150/5370-1A, Federal Aviation Administration, "Standard Specification for Construction of Airports," May 1968

8. AC 150/5070-6, Federal Aviation Administration, "Airport Master Plans," February 1971

9. NSF/RANN/SE/AER 74-09164/PR/75/1, W. B. Bienert and D. A. Wolf, "Heat Pipes Applied to Flat-Plate Solar Collectors," January 1975

10. DTM-72-3, Dynatherm Corporation, "Heat Pipe Design Handbook," August 1973

11. A. Rabl and C. E. Nielsen, "Solar Ponds for Space Heating," Solar Energy, Volume 17, April 1975

12. NBSIR-74-635, "Method of Testing for Rating Solar Collectors Based on Thermal Performance," 1974

APPENDIX A

BASIS FOR TIME SAVINGS ON HEATED AIRPORT PAVEMENTS

CASE # 1

The main ILS runway is always clear of snow, slush, and ice to a width of 150'. Equipment Groups #1, #2, and #3 are assumed to be programmed on remaining airport pavement surfaces to eliminate delay.

CASE # 2

Start Equipment Group #1 in E, D, and A program and Equipment Group #2 in C, D, and A program. Departing aircraft can follow equipment to point A and hold during airport shutdown. Shut airport down when equipment arrives at point A. Total time for both Groups #1 and #2 to arrive at point A is 4 minutes.

Groups #1 and #2 clear runway to point B. Total time to clear runway is 7.5 minutes. Groups then clear taxiway B to C in a total time of 2.5 minutes. At this time the airport is opened to air traffic. The total time elapsed is the sum of 7.5 and 2.5 minutes or 10 minutes.

Group #3 must clear 20% of the ramp and the central taxiway in the interval of 10 minutes. Group #3 will have some free time. Total time saving is 5 minutes.

CASE # 3

Time saved by Equipment Groups #1 and #2 in going from A to B is 0.8 minutes. Utilize the second ILS runway as a high speed turnoff. Time saved as a result of this is 3 minutes (CASE #4). Total time saved is 3.8 minutes or about 4 minutes.

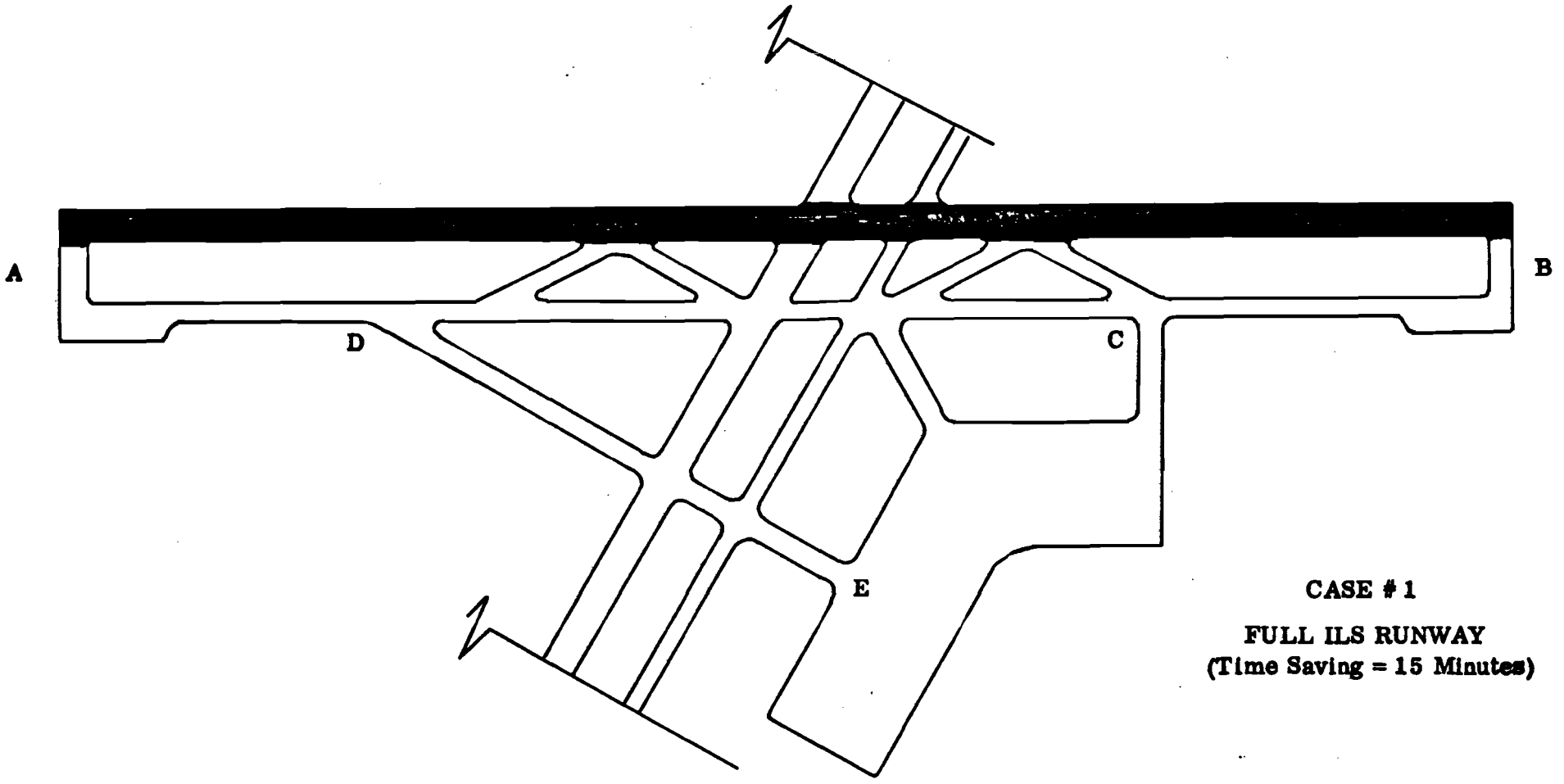
CASE # 4

Program equipment as in CASE #2 except for Group #3. Program Group #3 to start at C (after Group #2 starts) and swing through the two adjacent high speed turnoffs and then back to the C-D taxiway to one of the remaining high speed turnoffs and then return back on the other ILS runway through the central taxiway to the ramp. Since the time to clear each turnoff is 2 minutes, the total time is 6 minutes plus the travel time which is estimated to be 2 minutes.

The minimum time to clear 20% of the ramp with Group #3 is 4 minutes, thus the total elapsed time is 6 plus 4 minutes for snow clearing and 2 minutes for travel time or a total of 12 minutes. Total time saved is 3 minutes.

CASE # 5

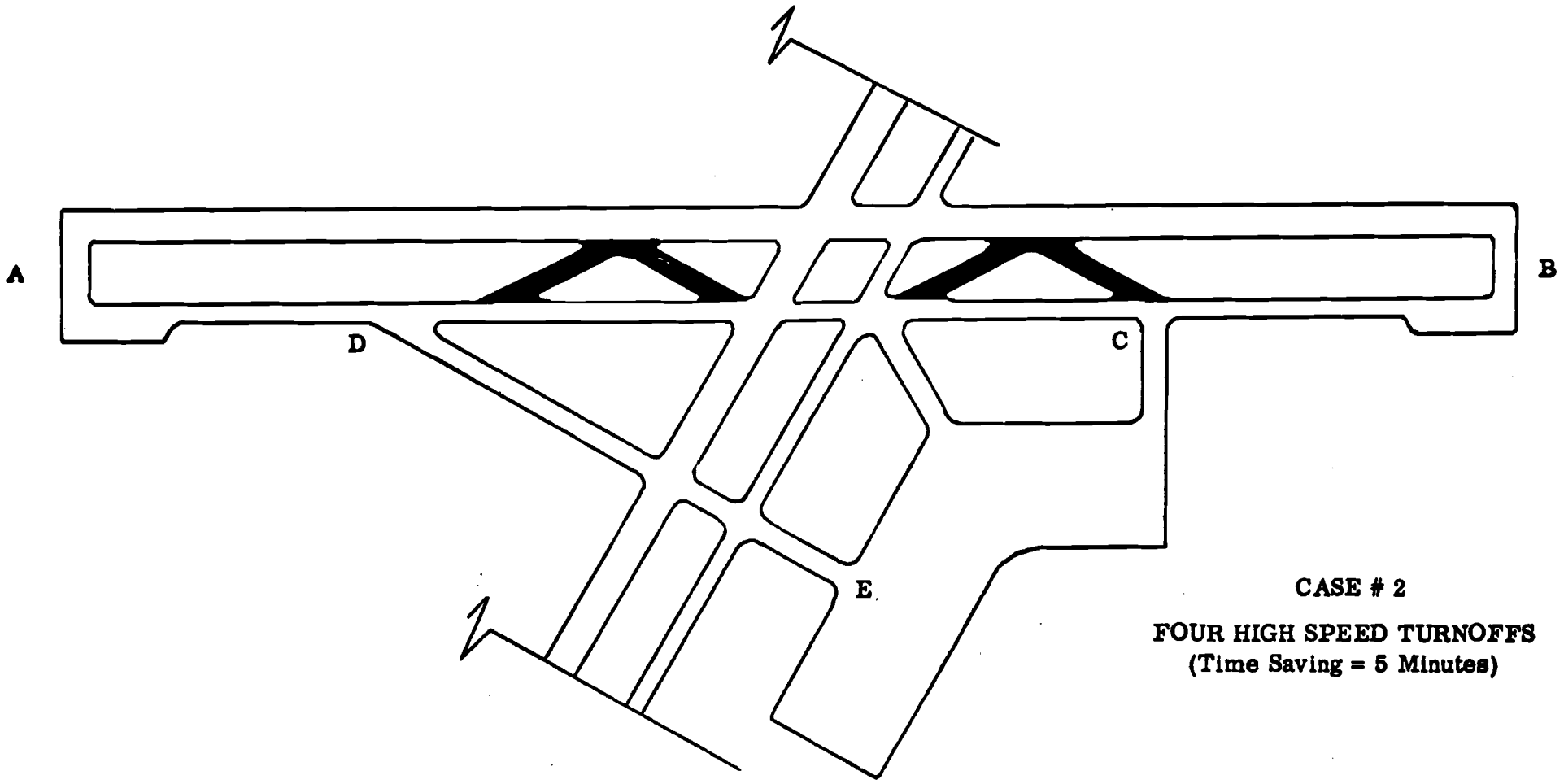
The time to clear the central taxiway is equal to the time to clear on high speed turnoff. All equipment groups are utilized in designated tasks so that this time would have to be added to the 15 minute time of the basic system. Total time saved is thus 2 minutes.



CASE # 1

FULL ILS RUNWAY
(Time Saving = 15 Minutes)

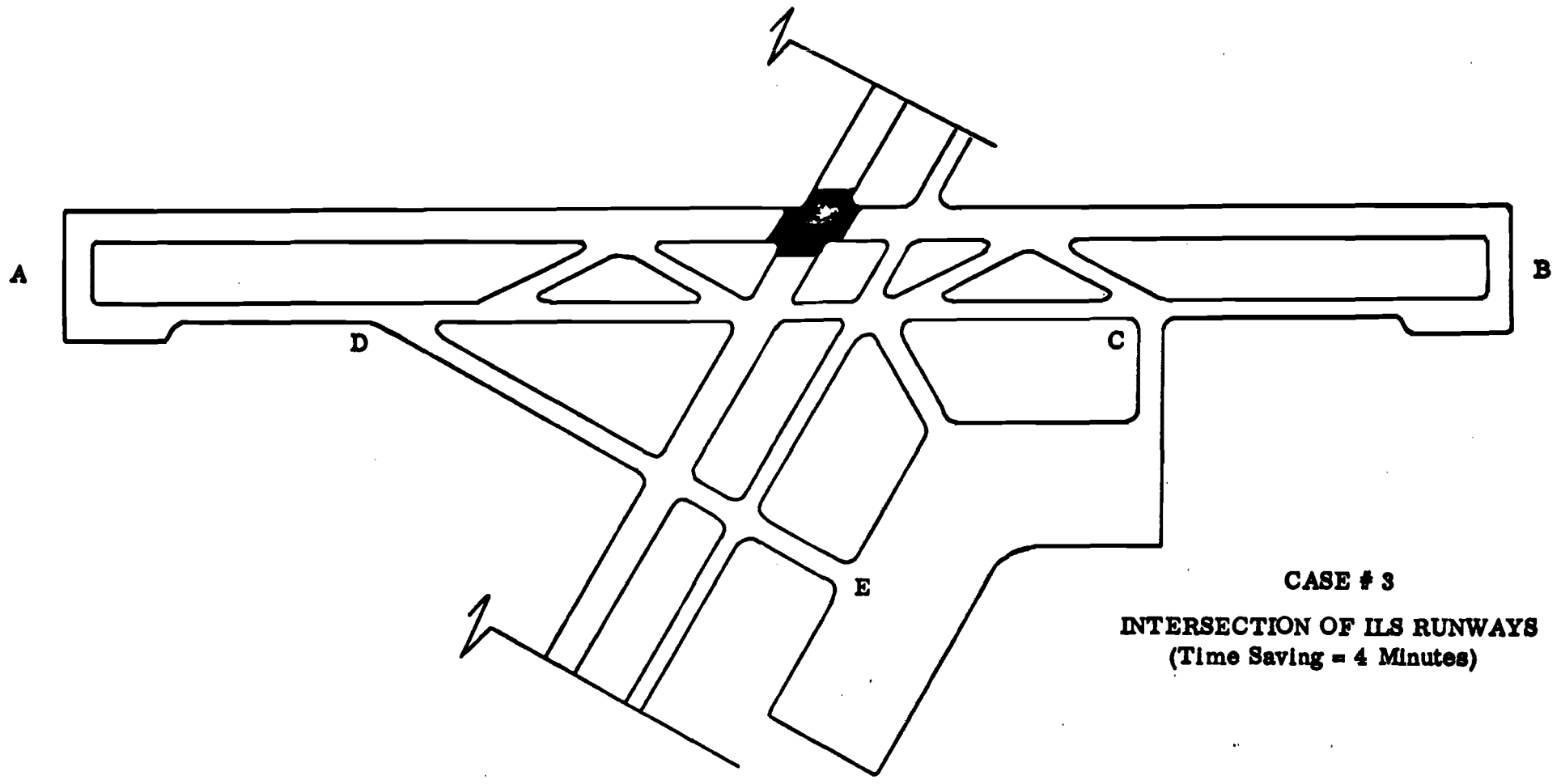
EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				



CASE # 2

FOUR HIGH SPEED TURNOFFS
(Time Saving = 5 Minutes)

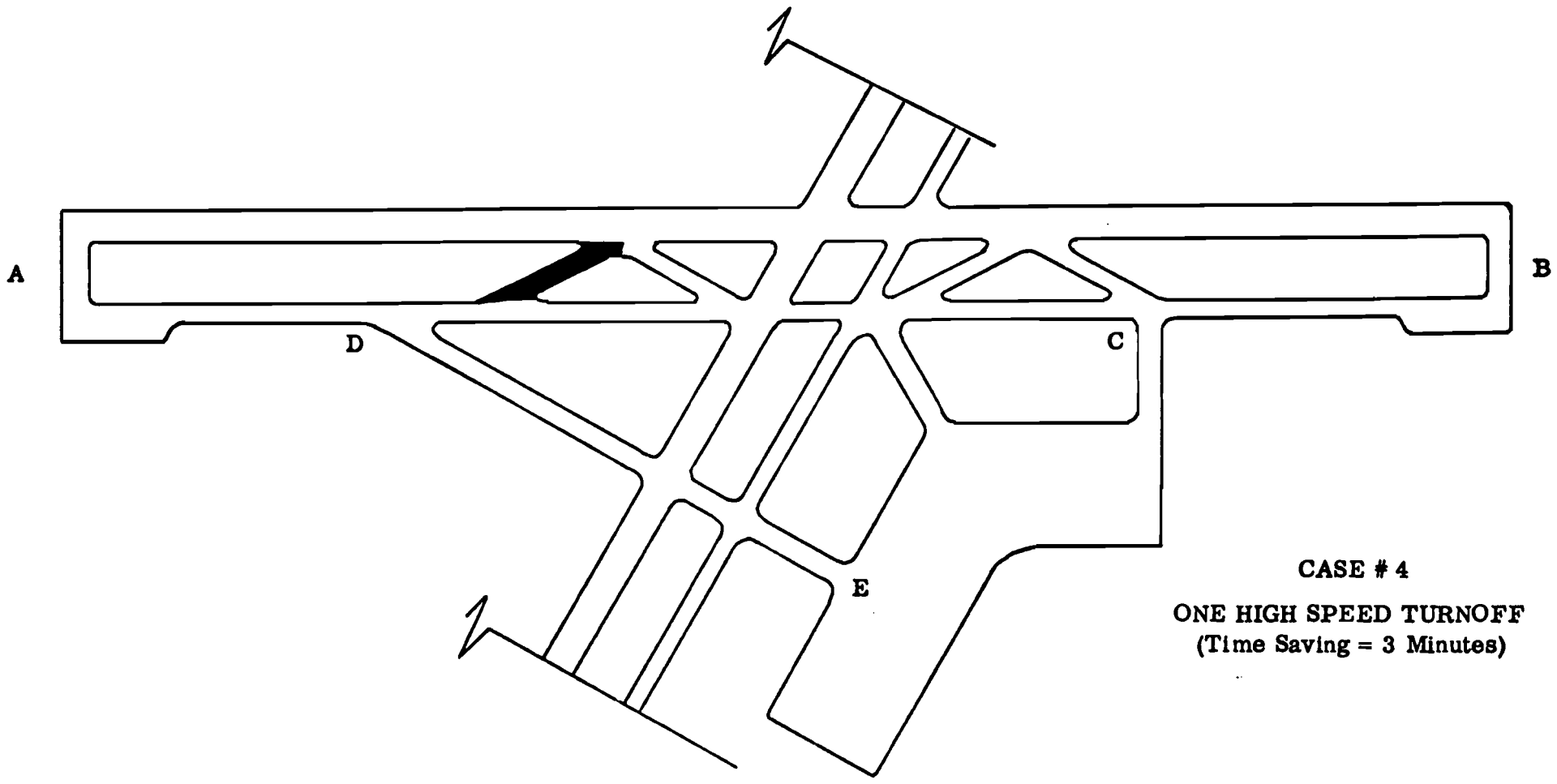
EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				



CASE # 3

INTERSECTION OF ILS RUNWAYS
(Time Saving = 4 Minutes)

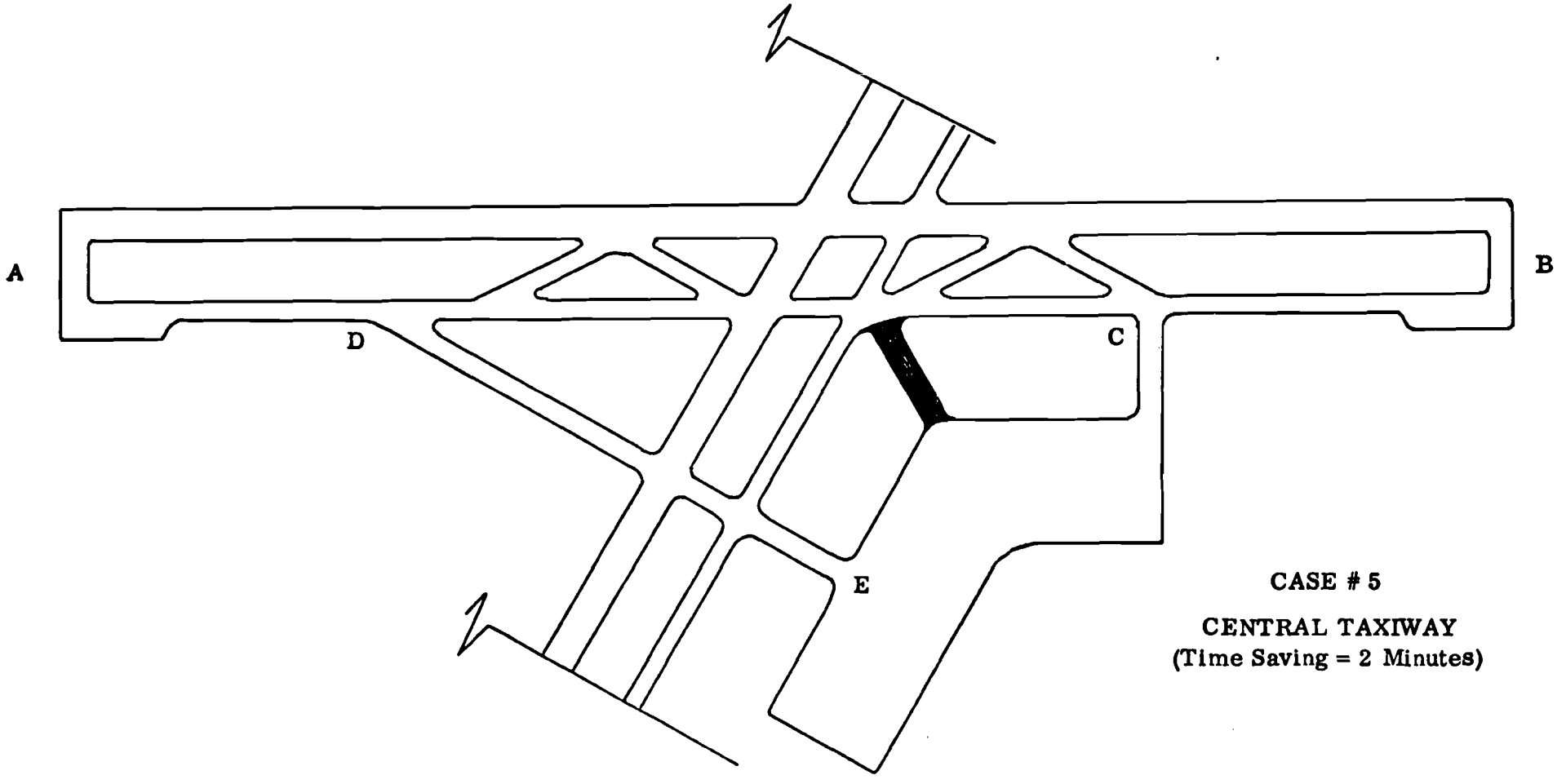
EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				



CASE # 4

ONE HIGH SPEED TURNOFF
(Time Saving = 3 Minutes)

EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				



CASE # 5

CENTRAL TAXIWAY
(Time Saving = 2 Minutes)

EQUIPMENT GROUP			TIME FOR SNOW REMOVAL		
#1	#2	#3	From	To	Minutes
S1	S5	PL3	A	B	7.5
S2	S6	PL4	C	D	3.0
S3	S7	PL5	E	D	2.0
S4	S8	PL6	D	A	2.0
P1	P2	BH3	B	C	2.5
PL1	PL2	BH4			
BH1	BH2				

APPENDIX B

GENERAL SPECIFICATION FOR
AIRPORT PAVEMENT SNOW AND ICE REMOVAL HEATING SYSTEMS

REVISIONS				
LTR	PAGE	DESCRIPTION	DATE	APPROVED

CONTRACT NO. DOT-FA74WA-3421	dynaTherm CORPORATION	COCKEYSVILLE, MARYLAND 21030
M. F. Pravda — PREPARED BY — DATE 5/3/74	TITLE	
REVIEWED/APPROVED — DATE	GENERAL SPECIFICATION FOR AIRPORT PAVEMENT SNOW AND ICE REMOVAL HEATING SYSTEMS	
APPROVED — DATE		
APPROVED — DATE		
	SIZE A	CODE IDENT. NO. 34881 — DRAWING NO. 098-1000
	SCALE:	SHEET 1 OF 25

FORM D-0103 REV. B

1.0 SCOPE

This specification outlines the general requirements for the design of airport Pavement Heating Systems for maintaining runways and taxiways free of ice, slush, and snow. This specification applies to:

- New Construction
- Existing Construction
- Rigid Pavements
- Flexible Pavements
- Surface Heating Elements
- Embedded Heating Elements
- Electrical Pavement Heat
- Thermal Pavement Heat

2.0 APPLICABLE DOCUMENTS

The following documents are cited for informational purposes except where direct reference is made within this specification, in which event they shall be applied to the extent indicated.

A/C 150/5070-6	Airport Master Plans
A/C 150/5300-6	Airport Design Standards - General Aviation Airports, Basic and General Transport
A/C 150/5320-5	Airport Drainage
A/C 150/5320-6	Airport Paving
A/C 150/5325-2	Airport Design Standards - Air Carrier Airports - Surface Gradient and Line of Sight
A/C 150/5325-4	Runway Length Requirements for Airport Design

A/C 150/5325-6	Effects of Jet Blasts
A/C 150/5330-2	Runway/Taxiway Width and Clearances for Airline Airports
A/C 150/5330-3	Wind Effect on Runway Orientation
A/C 150/5335-1	Airport Design Standard - Airports Served by Air Carriers - Taxiways
A/C 150/5335-2	Airport Aprons
A/C 150/5340-4	Installation Details for Runway Centerline and Touchdown Zone Lighting Systems
A/C 150/5340-9	Prefabricated Metal Housing for Electrical Equipment
A/C 150/5340-13	High Intensity Runway Lighting System
A/C 150/5340-14	Economy Approach Lighting Aids
A/C 150/5340-15	Taxiway Edge Lighting System
A/C 150/5340-16	Medium Intensity Runway Lighting System and Visual Approach Slope Indicators for Utility Airports
A/C 150/5340-18	Taxiway Guidance System
A/C 150/5340-19	Taxiway Centerline Lighting System
A/C 150/5340-20	Installation Details and Maintenance Standards for Reflective Markers for Airport Runway and Taxiway Centerlines
A/C 150/5345-1	Approved Airport Lighting Equipment
A/C 150/5345-9	Specifications for L-819 Fixed Focus Bidirectional High Intensity Runway Lights
A/C 150/5345-15	Specification for L-842 Airport Centerline Light
A/C 150/5345-16	Specification for L-843 Airport In-Runway Touchdown Zone Light

A/C 150/5345-20	Specification for L-802 Runway and Strip Light
A/C 150/5345-23	Specification for L-822 Taxiway Edgelight
A/C 150/5345-29	FAA Specification L-852 Light Assembly Airport Taxiway Centerline
A/C 150/5345-30	Specification for L-846 Electrical Wire for Lighting Circuits to be Installed in Airport Pavements
A/C 150/5345-37	FAA Specification L-850, Light Assembly, Airport Runway Centerline and Touchdown Zone
A/C 150/5345-38	Changes to Airport Lighting Equipment
A/C 150/5345-39	FAA Specification L-853, Runway and Taxiway Centerline Reflective Markers
A/C 150/5370-1	Standard Specifications for Construction of Airports
A/C 150/5370-4	Procedure Guide for Using the Standard Specifications for Construction of Airports
A/C 150/5370-8	Grooving of Runway Pavements
MIL-C-4921A	Cable, Power, Electrical, Airport Lighting
MIL-C-27212	Cable, Power, Electrical, Airport Lighting Control
MIL-H-22577	Heating Elements, Electric Cartridge, Strip, and Tubular Types
ANSI-C2	National Electrical Safety Code

3.0 REQUIREMENTS

3.1 System Definition

The Pavement Heating System is comprised of three subsystems:

- Energy Source Subsystem
- Energy Transport Subsystem
- Energy Distribution Subsystem

For a particular system, compatible subsystems must be selected. Furthermore, interface thermal, hydraulic, electrical, instrumentation, and mechanical parameters must be identical.

3.1.1 Energy Source Subsystem

The Energy Source Subsystem consists of the energy conversion facility and, where applicable, the fuel or energy storage facilities. Typical primary sources of energy are high voltage electricity, solar, earth heat, waste heat, and fossile fuels such as coal, oil, or natural gas. Typical forms of converted energy are low voltage electricity, heated fluids, and heated vapors. The subsystem consists of all the equipment necessary to produce the voltages, currents, temperatures, pressures, and flows required by the associated Energy Transport and Energy Distribution Subsystem.

3.1.2 Energy Transport Subsystem

The Energy Transport Subsystem consists of pipes or electrical cables which carry energy from the location of the Energy Source Subsystem to the runway or taxiway Energy Distribution Subsystem.

3.1.3 Energy Distribution Subsystem

The subsystem associated with heating the runway or taxiway pavements is termed the Energy Distribution Subsystem. The subsystem interfaces with the Energy Transport Subsystem at the edge of the runway or taxiway.

3.1.4 Subsystem Interface Definition

The interface between subsystems shall be defined in the Pavement Heating System mechanical, flow, electrical, and instrumentation diagrams.

3.2 System Functional Requirements

The spectrum of possible Pavement Heating Systems, and the variations within each system, is considerable. Each system and its variations are to be evaluated and, where necessary, adjusted to conform to manditory functional requirements. Each system and its variations are to be evaluated and, where necessary, reoptimized to achieve the best balance between the various nonmanditory requirements.

3.2.1 Safety

The objectives of the Pavement Heating System is to improve the safety and availability of airport runways and taxiways during Winter periods of ice, slush, and snow formation while maintaining current safety standards at all other times including Spring, Summer, and Fall seasons.

3.2.1.1 Catastrophic Pavement Failures

The Pavement Heating System shall not cause the pavement to fail catastrophically. The Energy Distribution System

shall not be operated at such a temperature, nor in such a manner, as to cause buckling of the pavement. Adequate analyses and/or testing shall be performed to assure that pavement buckling will not occur.

Heating elements placed on the top of pavements will be secured to the pavement and topped with a suitable cover. Epoxy or other bonding materials between the cover and the pavement may be employed but shall not be considered capable of carrying shear loads.

3.2.1.2 Undetectable System Failures

A failure analysis of the Pavement Heating System shall be performed. Modes of failure that cannot be detected by suitable methods and which degrade the safety of the system will be eliminated.

3.2.1.3 Limitations on Obstructions and Elevated Structures

The Pavement Heating System shall be designed to comply with A/C 150/5370-1A, "Standard Specifications for Construction of Airports".

Elevated structures will be located so that the vision of pilots during takeoff, landing, and taxiing will not be obstructed. The air-side view of the control tower will not be obstructed.

Solar collectors shall be designed and located to prevent glare hazards to pilots during takeoff, landing, and taxiing.

Elevated structures carrying cables or pipes shall not be used in the vicinity of runways and taxiways.

3.2.1.4 Interference with Existing Runway/Taxiway Facilities

The Pavement Heating System shall be designed so as not to interfere with the airport runway and taxiway lighting systems, A/C 150/5345-15, A/C 150/5345-16, A/C 150/5345-20, and A/C 150/5345-23. The system will not compromise the reliability of existing runway and taxiway lighting.

The Pavement Heating System will not interfere with runway and taxiway drainage, A/C 150/5320-5. Ice, snow, and slush will not be permitted to accumulate in apron areas.

3.2.1.5 Electromagnetic Interference

Electrically operated Pavement Heating Systems use large quantities of electrical energy. To minimize interference with aircraft and airport navigational and other instrumentation, shielded cables and wires shall be employed. An assessment of the potential radiation hazard to aircraft safety shall be made, and design modifications will be made where hazards are determined to exist.

3.2.1.6 Flamable/Toxic Materials

Flamable and toxic materials will not be used in the design of the Pavement Heating Systems in areas around runways and taxiways. This applies to materials which may generate toxic fumes when heated or burned.

3.2.1.7 Excessive Temperatures on Pavement Surfaces

The design of the Pavement Heating System will be

such as not to permit temperatures hazardous to the aircraft or runway and taxiway facilities. A failure mode analysis shall be conducted to verify this requirement.

3.2.2 Reliability

The Pavement Heating System must be reliable in its operation and performance of its function. Reliability will be considered in the design of the system and in the selection of components.

3.2.2.1 Component Redundancy

Where a failure analysis study shows that the system operation is critically dependent on the continued operation of a single component, redundancy will be employed to improve system reliability.

3.2.2.2 Subsystem Backup

Where a subsystem such as the Energy Source Subsystem cannot be demonstrated to have a high reliability, emergency backup subsystems shall be employed.

3.2.2.3 Component Reliability

System component selection will be in accordance with FAA, MIL, and Federal specifications in this order of preference. Where Government specifications are unavailable, good commercial practices shall be employed.

3.2.3 Maintainability

In order to conserve the initial "built-in" reliability of the Pavement

Heating System, the components and subsystems will be maintainable insofar as practical.

3.2.3.1 Open Runway Maintainability

Insofar as practical, the Pavement Heating System will be maintainable while in operation and while the runway or taxiway is in use.

3.2.3.2 Closed Runway Maintainability

Major maintenance will normally be undertaken during the summer months and during periods when the runway or taxiway is closed to air traffic. The design of the Pavement Heating System will be such that major maintenance can be done progressively during short periods of runway or taxiway closing.

3.2.4 Installation

The concept of the Pavement Heating System shall be such that it can be applied without regard to region, new or existing construction, and size of airport.

3.2.4.1 New Construction - Type I (Rigid Pavement)

Reinforced concrete (nominal thickness 20 inches) is designated as rigid pavement. Where practical, the heating elements will be self-supporting and self-locating prior to the concrete pour. The design of the heating elements will be such that precise location will not be required.

3.2.4.2 New Construction - Type II (Flexible Pavement)

It would be desirable to place the heating elements in position prior to pouring the asphaltic base and prior to applying the topping; however, the design of the heating elements must be sufficiently flexible to withstand large deformations without failure. As a minimum, the heating elements will be applied to the asphaltic base after compaction but prior to applying the topping.

3.2.4.3 Existing Construction - Type I & II

The surface of existing pavement will be corrected for damage and settlement by filling with suitable materials prior to the placement of heating elements. A minimum cover of 1-1/2 inches of asphaltic topping and 2 inches of concrete topping will be applied over the heating elements. Where required, heating element fasteners will be sufficiently long to penetrate through locally applied fill and into the original pavement.

3.2.5 Economy

Although capital and operating costs are normally budgeted separately, a cost comparison between various Pavement Heating System concepts must be based on total cost including the cost of money.

3.2.5.1 Capital Costs

Capital costs of a particular system are defined as the total material, hardware, and labor costs plus those costs associated with startup. Startup costs are those labor and material

costs incurred prior to turnover of the plant to airport operations personnel.

3.2.5.2 Operating Costs

Operating costs are those costs of labor, fuel, and materials necessary to maintain the system ready for operation and to operate the system to perform its intended function.

3.2.5.3 Total Annual Cost

The total annual cost will be computed as cents per square foot of heated pavement per year (¢/ft^2-year). The life of the system will be estimated and the capital cost will be depreciated on a straight-line basis. The cost of money on the undepreciated balance will be taken as 5% simple interest.

Note that costs associated with closing of runways or taxiways for Pavement Heating System maintenance are not included.

3.2.6 Ecology

Because large quantities of energy are required to keep the runways and taxiways free of ice, snow, and slush, each Pavement Heating System will have an impact on airport and national thermal and environmental pollution. Those systems which maintain the thermal balance (earth heat and solar) in the vicinity of the airport will have the least effect on ecology.

3.2.6.1 Level I Considerations (Airport)

The Pavement Heating System is local to the airport

and, therefore, certain system concepts will have a local impact on the ecology. Coal or oil burning Energy Source Subsystems shall be equipped with partical separators or precipitators capable of removing 99% of the particulate matter. Storage facilities for oil shall be suitably protected using ground dams to avoid general contamination from oil spillage. Nontoxic fluids and vapors shall be used in the Energy Transport Subsystem.

3.2.6.2 Level II Considerations (National)

Certain fuels have an impact on the ecology of the Nation. Coal which is mined by strip mining and used as an energy source represents an example. The objective shall be to select systems which have a minimal impact on the Nation's energy system and on energy sources that add to the ecology burden.

3.3 System Operating Requirements

The Pavement Heating System is used during the Winter and, like any system, it must be secured after winter operation is complete and then reactivated when winter operation begins. Major maintenance is scheduled for the Summer; however, the operation of the system must be verified sufficiently early to permit unexpected maintenance to be performed in the Fall.

3.3.1 System Readiness

The system readiness shall be determinable. This requires the ability to operate the system during off-season periods, and provisions must

be made for sufficient instrumentation to verify functional performance.

3.3.1.1 Check-Out Requirements

The design of the Pavement Heating System shall be such that component and subsystem operation can be verified independently. A central control panel shall be provided at the location of the Energy Source Subsystem on which is provided a diagrammatic representation of the system and indicating lights and instruments at key subsystem locations to provide a visual indication of system status. Where large pavement areas are involved, a suitable grid shall be constructed and independently indicated on the control panel.

3.3.1.2 Fuel/Energy Reserves

For those systems which depend on energy storage (either fuel or heated materials), the status of the energy storage shall be determinable from the control room.

3.3.2 System Operation

The system shall be designed to perform its intended function under normal adverse winter conditions.

3.3.2.1 Anticipating Adverse Conditions

For those Pavement Heating Systems designed to operate on demand, system effectiveness can be improved considerably by turning the system on well before the snow, ice, or slush conditions materialize. For those systems which have

built-in flexibility and operate continuously, system performance can be improved by anticipating the watts/ft^2 requirements well in advance of the adverse weather condition and then adjusting the system accordingly. Experience has shown that adverse weather conditions cannot be anticipated with a high degree of reliability and, therefore, false starts can be expected. In the interest of safety, false starts must be tolerated.

3.3.2.2 System Effectiveness Status

Generally, if the pavement surface temperature is above 32°F and is clear of snow and slush, the system can be considered to be performing its function. Pavement temperature shall be monitored in the control room. A minimum of two indications will be available for each grid section. A telephone link to the control tower shall be provided to relay runway and taxiway conditions obtainable by visual observations.

3.3.2.3 Emergency Procedures

Experience has demonstrated that the thermal capacity of the pavement system is sufficient to provide normal snow melting for a period of several hours after failure of a system previously operated in the continuous mode. Emergency operating procedures shall be prepared which shall clearly define the corrective action steps necessary to maintain the runways and taxiways in a safe condition.

3.3.3 Securing System

The Pavement Heating System will be operated during the Winter season and, quite possibly, only intermittently during this period. Experience in the operation of power plants demonstrates that most system problems occur during startup and that proper procedures in securing the system after operation can minimize these problems.

3.3.3.1 Temporary Shutdown

Procedures shall be prepared for temporary system shutdown. During the Winter season, as many as possible of the subsystems will be maintained in active standby.

3.3.3.2 Shutdown During Off-Seasons

Procedures shall be prepared for off-season shutdown. The system design shall incorporate drains at subsystem low points, standby heaters in high humidity areas, covers or enclosures for sensitive components and instruments, and standby power for equipment sensitive to cycling. Humidity control and/or air-conditioning will be employed in the control room.

3.4 System Design Requirements

The Pavement Heating System shall be designed to comply with A/C 150/5370-1A, "Standard Specifications for Construction of Airports." Fundamentally, the design shall be as simple as possible and the system shall be simple to operate.

3.4.1 System

The Pavement Heating System shall be designed to perform its

function under nominal adverse weather conditions. Extremely severe weather conditions will not be designed for; however, it is possible (if it is within the capability of the system) to operate in such a way as to take advantage of the thermal capacity of the pavement and subbase to improve performance beyond nominal system design performance.

3.4.1.1 Nominal/Abnormal Weather

Experience with pavement heating systems has demonstrated that, when weather conditions are sufficiently severe, snow and slush will accumulate on the pavement. When snowfall and drifting abate, the Pavement Heating System gradually clears the pavement. In all cases, the pavement beneath the accumulated snow and slush has been found to be ice-free.

Nominal weather conditions shall be defined as 1/3 of the recorded maximum monthly snowfall falling within a 24-hour period, at the 20-year average wind speed for the month, and at the 20-year (or greater) minimum average daily temperature. Relative humidity will be taken as the average humidity for the month averaged over a 20-year period. A 100% cloud cover shall be assumed.

Abnormal weather conditions shall be defined as 1/2 of the recorded maximum monthly snowfall falling within a 24-hour period, at twice the 20-year average wind speed for the month, and at the 20-year minimum average daily temperature minus 10°F. The remaining conditions are the same as defined for normal weather conditions.

3.4.1.2 Continuous Operation

All Pavement Heating Systems shall be capable of operating continuously during the winter months. Those systems designed to operate in the demand mode shall have sufficient fuel or energy storage to operate continuously at 1/3 demand power. The fuel or energy storage requirement may be reduced if the system is provided with feedback controls such that power is supplied to maintain the pavement surface temperature at $32^{o}F$ or higher.

3.4.1.3 Demand Operation

Pavement Heating Systems designed for demand operation shall be capable of providing specified watts/ft^2 to the pavement surface within 1/2 hour of command and shall be capable of sustaining this level for a minimum of 48 hours once each week.

3.4.1.4 Design Margins

Pavement Heating Systems utilizing energy storage shall be capable of providing design watts/ft^2 at the end of 48 hours when operated in a demand mode. Systems shall have sufficient margin to accommodate a 1-1/2 inch thick asphaltic resurfacing.

3.4.1.5 Use of Hazardous Materials

Materials hazardous to aircraft, ground vehicles, and airport personnel shall not be used in the system. Materials which emit toxic fumes when burned or heated shall not be used.

3.4.1.6 Energy Storage Requirement

Pavement Heating Systems which utilize energy storage shall have a capability of periodically replenishing the stored energy. The storage subsystem shall be subdivided in such a manner that any single failure will not degrade system performance by more than 10%. Annual degradation of the energy storage subsystem shall be adequately provided for by suitable initial overdesign.

3.4.1.7 Fuel Storage Requirement

Storage of liquid fuels shall be underground. Not more than 20% of the average annual requirement shall be stored in a single tank. Each underground tank shall have a separate fuel pump with sufficient capacity to satisfy the entire requirement of the Energy Source Subsystem.

3.4.1.8 Location of Structures

Elevated structures of any description shall not be located near the runways and taxiways. Because the location of the Energy Source Subsystems determines the length and, therefore, cost of the Energy Transport Subsystem, consideration shall be given to selecting a central location which is accessible to airport personnel.

3.4.2 Structural Requirements

The design life of the Pavement Heating System shall be 20 years. The system shall not be designed to require major structural repair or re-

placement during its design lifetime.

3.4.2.1 Dynamic Loads

The system shall be designed for dynamic loads such as wind gusts and jet blasts, A/C 150/5325-6. Maximum wind speeds shall be taken from 30-year weather data but shall not be less than 80 mph or that specified in local codes whichever is greater. The Energy Distribution subsystem shall be capable of sustaining sudden and localized loads applied by landing aircraft without failure of the heating elements.

3.4.2.2 Static Loads

The Pavement Heating System shall be designed to withstand all identifiable static loads. Covered troughs in apron areas adjacent to runways and taxiways shall be capable of supporting the dead weight of the largest aircraft which the airport is anticipated to accommodate. Covered troughs in other areas shall be capable of supporting the vehicular traffic associated with airport operation and maintenance.

Subsurface structures shall be provided with adequate foundations to support the dead weight of contained liquids and external hydrostatic loads when empty. Differential settlement, which introduces bending stress in long continuous structures, shall be minimized by adequate foundation design. Flexible joints shall be provided at intervals of not more than 250 feet unless required more frequently by thermal stress considerations.

In certain system designs, limitations may be placed on allowable static deflections in structures. When this is the case, it is understood that the structure shall first be capable of supporting all identifiable static loads with adequate safety margins.

3.4.2.3 Pressure Stress Limits

All fired and unfired pressure vessels shall be designed to the ASME Boiler Code requirements. A failure analysis will be performed to identify the maximum casualty temperatures and pressures. Piping schedules shall be selected on relief valve settings where relief valves are provided or maximum casualty pressures where relief valves are not provided.

3.4.2.4 Thermal Stress Limits

The Pavement Heating System is a thermal system, and all or substantial parts of the system are subjected to temperature changes during operation. Thermal stresses shall not exceed the yield stress either in compression or tension.

Certain adopted airport practices such as runway grooving, A/C 150/5370-8, can result in unavoidable stress concentrations. Heating elements shall be located within the pavement to minimize surface stresses and reduce the chances of spalling.

Consideration may be given to using certain types of heating elements as substitutes for reinforcing steel (rebars). If this practice is employed, the combined thermal and mechanical stresses shall not exceed the yield stress of the heating element structural material.

3.4.2.5 Fastening Devices

Components subjected to dynamic, thermal, and vibration cycling, which for reasons of maintenance must be removable, shall be secured by bolts and lock-wired to prevent loosening. This requirement shall not apply to the Energy Source Subsystem.

3.4.2.6 Failure Analysis

A failure analysis of the structural design shall be conducted. No single failure shall cause the system to become inoperative.

3.4.3 Electrical Requirements

The Electrical subsystems of the Pavement Heating System shall be designed to the requirements of the National Electrical Safety Code, American National Standard C2, unless superceded by A/C specifications such as A/C 150/5345-30.

3.4.3.1 Electromagnetic Radiation

All electrical circuits shall be grounded. Cable splicing shall not be permitted. Maximum voltage across phases

in the area of taxiways and runways shall not exceed 480 volts AC. Surface leakage shall be in accordance with the requirements of Section 4.5.2.1 of MIL-C-4921A. The power circuit frequency shall not exceed 60 Hertz and shall be free of higher harmonics.

3.4.3.2 Stray Electric Currents

Heating cables embedded in runways and taxiways shall be enclosed in a grounded metal tube. Metal structures containing electrical equipment or carrying cables shall be grounded.

3.4.3.3 Underground Cables

Underground cables shall be used in the areas of runways and taxiways. Good commercial practice shall apply for selecting and installing underground power cables.

3.4.3.4 Overload Protection

Hermetically sealed, oil-immersed and recloseable circuit breakers shall be used to protect each grid segment of electrically heated runways and taxiways. The short-circuit rating of these breakers shall not exceed the trip setting of the main breakers of the electrical substation.

3.4.3.5 Lightning Protection

All metal enclosures containing electrical equipment and electrical cables will be provided with suitable lightning protection.

3.4.3.6 Electrochemical Protection

Concrete pavements degrade when subjected to voltage gradients and chemical contaminants such as chlorides. Sheathing electrical heating elements and providing a common ground for the sheathing as specified in Section 3.4.3.2 eliminates this condition.

Cathodic protection using sacrificial electrodes shall be provided where dissimilar metals must be used in contact with each other.

3.4.3.7 Failure Analysis

A failure analysis of the electrical subsystems shall be conducted. No single failure shall cause the system to become inoperative.

3.4.4 Instrumentation Requirements

The Pavement Heating System will be provided with instrumentation to permit operating and maintenance personnel to establish system readiness, performance, fault, and corrective action conditions.

3.4.4.1 Pavement Temperature

Pavement temperature within 1/2 inch of the surface shall be measured in each grid segment. The measurements shall be made in two representative locations away from pavement edges and between adjacent heating elements. The data shall be available to the operator in the control room and red-light alarms shall be

provided to indicate abnormal temperatures.

The service life of the temperature measuring instrumentation shall be at least 20 years, and provisions in the installation shall be made to accommodate resurfacing.

3.4.4.2 Storage Energy

Pavement Heating Systems, which utilize energy storage, shall be instrumented to indicate the level of stored energy.

3.4.4.3 Line Voltage - System Power

Pavement Heating Systems utilizing utility or emergency source electrical energy shall be instrumented to indicate the incoming voltage and the power consumption of the system.

3.4.4.4 Source Temperature - Pressure

Pavement Heating Systems utilizing fossile fuel boilers shall be instrumented to indicate boiler temperature and pressure and Energy Transport Subsystem vapor pressure or, where applicable, fluid flow rate, pressure, and temperature.

INSTALLATION/ACCEPTANCE
SPECIFICATION FOR
SOLAR HEATED RUNWAY INTERSECTIONS

REVISIONS				
LTR	PAGE	DESCRIPTION	DATE	APPROVED

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FORM D-0103 REV. B

1.0 SCOPE

This specification documents the requirements for the installation of a solar energy pavement heating system for airport application. Specifically, the drawings referenced herein apply to the intersection of two existing ILS runways located in a climate typical of the Baltimore-Washington area.

The pavement heating system (DTM-098-1022) is designed to maintain the surface of the ILS runway intersection (total pavement area 165,000 ft^2) free of ice and snow except for severe blizzard conditions. The solar system collects solar energy throughout the year, stores this energy in the form of heated water, and uses the stored energy to provide heat to heat pipes which are embedded in the pavement.

2.0 APPLICABLE SPECIFICATIONS

The following documents apply to the extent indicated:

A/C 150/5070-6	Airport Master Plans
A/C 150/5300-6	Airport Design Standards - General
A/C 150/5320-5	Airport Drainage
A/C 150/5325-6	Airport Paving
A/C 150/5325-2	Airport Design Standards - Surface Gradient
A/C 150/5330-2	Runway/Taxiway Width and Clearances for Airline Airports
A/C 150/5335-1	Airport Design Standards - Taxiways
A/C 150/5340-4	Installation Details for Runway Centerline and Touchdown Zone Lighting Systems
A/C 150/5340-9	Prefabricated Metal Housing for Electrical Equipment
A/C 150/5340-13	High Intensity Runway Lighting System

A/C 150/5340-14	Economy Approach Lighting Aids
A/C 150/5345-1	Approved Airport Lighting Equipment
A/C 150/5345-9	Specification for L-819 Fixed Focus Bidirectional High Intensity Runway Lights
A/C 150/5345-15	Specification for L-842 Airport Centerline Light
A/C 150/5345-20	Specification for L-802 Runway and Strip Light
A/C 150/5345-30	Specification for L-846 Electrical Wire for Lighting Circuits to be Installed in Airport Pavements
A/C 150/5345-37	FAA Specification L-850, Light Assembly, Airport Runway Centerline, and Touchdown Zone
A/C 150/5345-38	Changes to Airport Lighting Equipment
A/C 150/5370-1	Standard Specifications for Construction of Airports
A/C 150/5370-4	Procedure Guide for Using the Standard Specifications for Construction of Airports
A/C 150/5370-8	Grooving of Runway Pavements
MIL-C-4921A	Cable, Power, Electrical, Airport Lighting
MIL-C-27212	Cable, Power, Electrical, Airport Lighting Control
ANSI-C2	National Electrical Safety Code
NBSIR-74-635	Method of Testing for Rating Solar Collectors Based on Thermal Performance
DTM-098-1000	General Specification for Airport Pavement Snow and Ice Removal Heating Systems
DTM-098-1014	Thermal Storage Tank
DTM-098-1018	Solar Panel Assembly

DTM-098-1020	Heat Pipe Assembly
DTM-098-1022	Runway Intersection - Solar Heated
DTM-098-1024	Solar Panel Installation

3.0 REQUIREMENTS

The pavement heating system consists of three major subsystems (energy source, transport, and distribution) and two supporting subsystems (electrical and instrumentation/control). The physical configuration of the pavement heating system is determined by the size and location of the pavement area to be heated and by the layout of the airport. The capacity of the pavement heating system is determined by the size of the pavement area to be serviced and by the severity of the winter climate to which the airport is subjected.

The integration of a pavement heating system into an existing airport facility is somewhat more difficult than new construction because of the possible interference with existing facilities and services. This specification addresses pavement heating systems (having a service life of 20 years) for existing pavement areas.

3.1 Energy Source Subsystem

The energy source subsystem consists of the solar panel assembly (DTM-098-1018), the solar panel installation (DTM-098-1024), and the thermal storage tank (DTM-098-1014). The physical layout of the solar panels and the thermal storage tank is shown in DTM-098-1022. The interconnecting piping and the associated pumps and valves are defined as part of the energy source subsystem.

3.1.1 Solar Panel Assembly/Installation

The solar panels (DTM-098-1018) are to be assembled and

secured to the support frame in accordance with DTM-098-1024 Panels with cracked glass covers shall be rejected. During solar insolation, each installed panel will be checked with a portable temperature measuring instrument for proper isothermal performance. Defective panels shall be removed from the assembly.

A hydrostatic pressure test (250 psig) shall be conducted on each 2-inch copper pipe loop. A pressure loss of more than 10% in one hour shall be cause for rejection.

3.1.2 Thermal Storage Tank

The thermal storage tank shall be constructed in accordance with DTM-098-1014. The subbase shall consist of 18 inches of crushed stone placed in layers not exceeding 4 inches and compacted by rolling. The floor of the thermal storage tank shall be poured monolithically and shall be free of honeycombs and voids. The floor shall be pitched 1/4-inch per foot downward toward the drain.

In-leakage of ground water shall not exceed one gallon per day. Leakage through imperfections in the vinyl liner shall not exceed one gallon per day with the tank filled with water at a temperature of not less than 200°F.

With the thermal storage tank filled with water at a temperature of 200°F, the water temperature shall not fall below 199°F after one week when the average ambient air temperature during the week is 70°F $\pm$ 10°F.

3.1.3 Pumps

Two pumps, connected in series, shall each be capable of supplying water to the solar collectors at a minimum mass flow of 1.1×10^5 pounds per hour. These pumps shall be located in the pump areas attached to the thermal storage tank and shall be thermostatically controlled.

3.1.4 Underground Piping

The piping between the solar collectors and thermal storage tank shall be protected against corrosion, insulated (losses shall not exceed 25 Btu/hr-ft), and installed in the trench in accordance with the plans. A hydrostatic pressure test (250 psig) shall be conducted on each leg of pipe. A pressure loss of more than 10% in one hour shall be cause for rejection.

3.1.5 Subsystem Testing

The collection loop of the energy source subsystem shall be tested to determine its collection efficiency. The rate of heat collection (as measured by the product of the temperature difference between the water leaving and entering the thermal storage tank, the specific heat of water, and the mass flow rate) shall be not less than 90% of that calculated in accordance with the Standards for Rating Solar Collectors. The calculation shall be based on the specified heat loss coefficients and effective absorptivity-transmissivity products for the solar panel assembly (DTM-098-1018). This test will be conducted on a clear day between the hours of 10:00 and 14:00 and with the tank temperature at 200°F.

3.2 Energy Transport Subsystem

The energy transport subsystem consists of the large piping (and associated thermal expansion joints) connecting the thermal storage tank to the hot water trenches, the hot water trenches themselves (DTM-098-1022), and the associated pumps and valves. The energy transport subsystem is activated only during those times when pavement heating is desired.

3.2.1 Pumps

Water shall be pumped into the hot water trenches by a single pump located in the pump area attached to the thermal storage tank (DTM-098-1014) and having a pumping capacity of 1.5×10^6 pounds per hour. Water shall be pumped out of each hot water trench by a pump located on the exit end of the trench by a pump having a pumping capacity of 0.75×10^6 pounds per hour. These pumps shall all be activated from the control room.

3.2.2 Underground Piping

The piping shall be protected against corrosion, insulated (losses not to exceed 60 Btu/hr-ft), and installed in the trench in accordance with the plans. A hydrostatic test (50 psig) shall be conducted on this piping. A pressure loss of more than 10% in a period of 15 minutes shall be cause for rejection.

3.2.3 Hot Water Trenches

The hot water trenches are located on each side of the main ILS runway as shown in DTM-098-1022. The trench excavation must pro-

ceed at night, especially in the area of the second ILS runway. Temporary trench covers shall be used to avoid air traffic disruptions.

The trench and trench covers shall be insulated. The conductance of the trench covers shall be between 1.42 and 1.60 Btu/hr-ft^2-^{o}F. The conductance of the walls and bottom of the trench shall not exceed 0.06 Btu/hr-ft^2-^{o}F.

The trench grade along its length shall be such that the elevation difference does not exceed 4 inches.

3.2.4 Subsystem Testing

A subsystem test shall be conducted at night when the air temperature is 60°F or less. The water temperature in the thermal storage tank shall be 200°F. The main circulating pumps shall be activated and pavement temperature readings shall be recorded. The test shall be conducted for 8 hours during which period the difference between the highest and lowest pavement temperature readings (see DTM-098-1022 for thermocouple locations) shall not exceed 3°F.

3.3 Energy Distribution Subsystem

The energy distribution subsystem consists of heat pipes (DTM-098-1020) which extend from the hot water trenches to and into the runway pavement. The subsystem, furthermore, consists of the heat pipe and pavement installation. For existing construction, the subsystem consists of the heat pipe and pavement overlay installation (DTM-098-1022). Prior to the installation of the heat pipes, the trench construction must be completed to the extent indicated on the plans and the proper grade of the

existing runway surface must be established.

3.3.1 Establishing Proper Runway Grade

If the grade of the existing runway surface is found to be below true elevation, the depressions shall be filled with approved material in accordance with the plans. Areas showing high spots of more than 1/4 inch, but not exceeding 1/2 inch in 16 feet, shall be marked and ground down with an approved grinding tool to an elevation where the area or spot will not show surface deviations in excess of 1/4 inch when tested with a 16-foot straightedge.

3.3.2 Heat Pipe Grade

The heat pipes for existing pavement installations shall be pitched uniformly a minimum of 1/8 inch per foot toward the hot water trench. The vertical portion of the heat pipe (evaporator) shall be true to within 5 degrees.

3.3.3 Heat Pipe Installation

The heat pipes shall be placed on the prepared runway surface in accordance with the plans. Longitudinal spacer strips shall be clipped to adjacent pipes to hold horizontal positions during the application and rolling of the bituminous concrete overlay. After the heat pipes are placed in the proper position, a bituminous tack coat shall be applied and allowed to cure. When the tack coat is cured, asphalt cement (AASHO M 20) shall be applied in 10-foot strips beginning from the center of the runway. The compacted thickness, as measured from the original surface,

shall be a nominal 4 inches. Compaction shall always begin in the region nearest the center of the runway and proceed outward in steps as the asphalt cement strips are laid.

3.3.4 Subsystem Testing

The subsystem testing outlined in Section 3.2.4 applies.

3.4 Electrical Cable Installation

Electrical cables and cable runs shall be in accordance with the plans. All electrical cable home runs shall be installed underground in ducts or conduits as specified in AC 150/5370-1A and in the plans.

3.5 Instrumentation and Control

The pumps shall be controllable from the control room through magnetically operated circuit breakers located at the pump site. Control circuit wire shall be underground and shall not be less than No. 12 AWG and shall be insulated for 600 vac. The installation of control cable home runs shall be in accordance with AC 150/5370-1A and the plans.

The instrumentation cable shall be electrically shielded and shall be placed underground in conduit.

3.6 Pavement Heating System Functional Test

The final acceptance test of the assembled system shall be conducted on a clear night when the air temperature is 60°F or less. The water temperature in the thermal storage tank shall be 200°F ± 10°F. The test shall be conducted from the control room, and the period of testing shall be 8 hours.

The test shall proceed in accordance with the written operating procedure for the system and shall be under the direct supervision of the Engineer. All subsystems shall perform properly in accordance with their intended functions. The test shall proceed without adjustments to valves, pumps, circuit breakers, instrumentation, etc. Temperature measurements in accordance with Section 3.2.4 shall be recorded every 15 minutes. Air temperature, wind speed, and humidity shall be recorded every hour. The system shall be accepted when the testing sequence can be reproduced without incident and when temperature readings on pavement thermocouples are as specified in Section 3.2.4.