

IMPROVED SOLAR ENERGY COLLECTOR SYSTEM:

By

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ABSTRACT

One method of collecting solar energy is the absorption of light by a metal surface. Heat can be removed from the metal by means of water, thereby creating a solar collector. Experimental research was conducted in an attempt to improve solar collectors for northern regions by concentrating light onto a metal surface. Investigations were made on the type of metal and surface coating which would give the best temperature rise. Light, concentrated by means of magnifying lenses, was focused onto nineteen 1/2" diameter treated copper surfaces connected in series. Water, passing through the copper cylinders, was used as a heat collecting fluid.

The lens solar concentrating system was feasible as a collector for northern regions. Water was heated to boiling even during winter months by this collector. A rate of heat gain of up to 264.83 Kcal/hr-m² was obtained for a flow rate of 22.5 litres/hr. at an ambient temperature of 27°C.

Current research and development activity on solar collectors is reviewed. Topics include solar flux, selective coatings, fundamentals of a flat plate collector and a view into different types of collectors.

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NOMENCLATURE

Q	Heat gain
W	Watts
M	Metre
F	Flow rate
L	Latitude
C _p	Specific heat of water
ΔT	Temperature difference between inlet and outlet of collector
LMTD	Log mean temperature difference

1 - INTRODUCTION

Our ever increasing energy demands are consuming our fossil fuel reserves. One method of decreasing our consumption of increasingly expensive fossil fuels as a source of energy would be the use of solar energy.

In the past solar collectors were designed for southern climates where water was heated in a square box. A certain volume was heated by means of a collector surface in contact with the water. For northern climates a glass plate was added in front. This type of simple collector was not a good design since heat losses were too great in winter. Therefore a collector design that will function effectively for our climate is needed. By utilizing a high concentration of solar rays upon the surface of a collector, the effectiveness of such solar devices are generally considerably increased, and the scope of their practicable uses is widened.

A reduction in energy consumption is important since it would give more time to develop renewable sources of energy.

The sun is the source of wind, hydro, biomass energy and many others. It can provide non-polluting energy. By harnessing solar radiation it will be possible to heat and cool buildings. Solar heating can also be used for water heating, agricultural drying, production of industrial process heat, production of steam for electrical generation, fusion of metals, smelting of high melting materials to mention a few possible uses. Photovoltaic or solar cells also have many potential uses because they can convert sunlight directly to electricity.

In solar heating systems better collectors are needed to reduce the storage space and area of collection. Because of increasing interest in solar heating, collectors are undergoing rapid development. For practical reasons it is necessary to have efficient and cheap collectors.

The sun's rays are free; however, the accumulation of solar energy for man-made needs is not free. There are costs for equipment, repairs, depreciation and operation. For solar equipment to be useful it must not only be feasible but must also be economical. Although the application of solar energy seems simple, the number of the alternative systems, shapes and types of material required makes the utilization of solar energy a complex problem.

On sunny days, concentrating solar energy collectors can obtain higher surface temperatures and greater efficiencies than non-concentrating collectors. However, concentrating collectors must track the sun for optimum operating conditions. The amount of tracking needed depends on the type of concentrating system. Some collectors only need seasonal tracking while others need constant tracking of the sun.

2. LITERATURE SURVEY

The availability of the sun's rays as a source of energy has been recognized for a long period of time but the knowledge about it has not been developed fully. It is now being attempted.

It is useful to consider the nature of solar radiation. One third of the radiation bombarding the earth is reflected into interplanetary space. The radiation absorbed by the earth's atmosphere or the surface itself heats up the earth and causes the rain and the wind. The plants absorb considerably less than one percent of the solar energy and the human population indirectly utilizes even less in the form of food and fuel.

Most data concerning the intensity of the solar flux is for a horizontal collecting surface. In order to obtain the maximum quantity of radiation the collectors need to be on a non-horizontal surface. Therefore it would be useful if more solar flux data were available for solar insolation by inclined surfaces. Information about solar radiation should be available not only with regard to non-horizontal surfaces, but should also include direct, sky diffuse, and radiation reflected from adjacent objects. Especially useful would be the direct solar flux data for the winter months.¹

In the northern hemisphere the available solar energy is at its lowest level on December 21st, which is the shortest day of the year. The hourly insolation increases in the morning to a maximum around noon and then decreases in the afternoon. The typical data for a clear day is given in Figure 1² for January 21st at various latitudes.

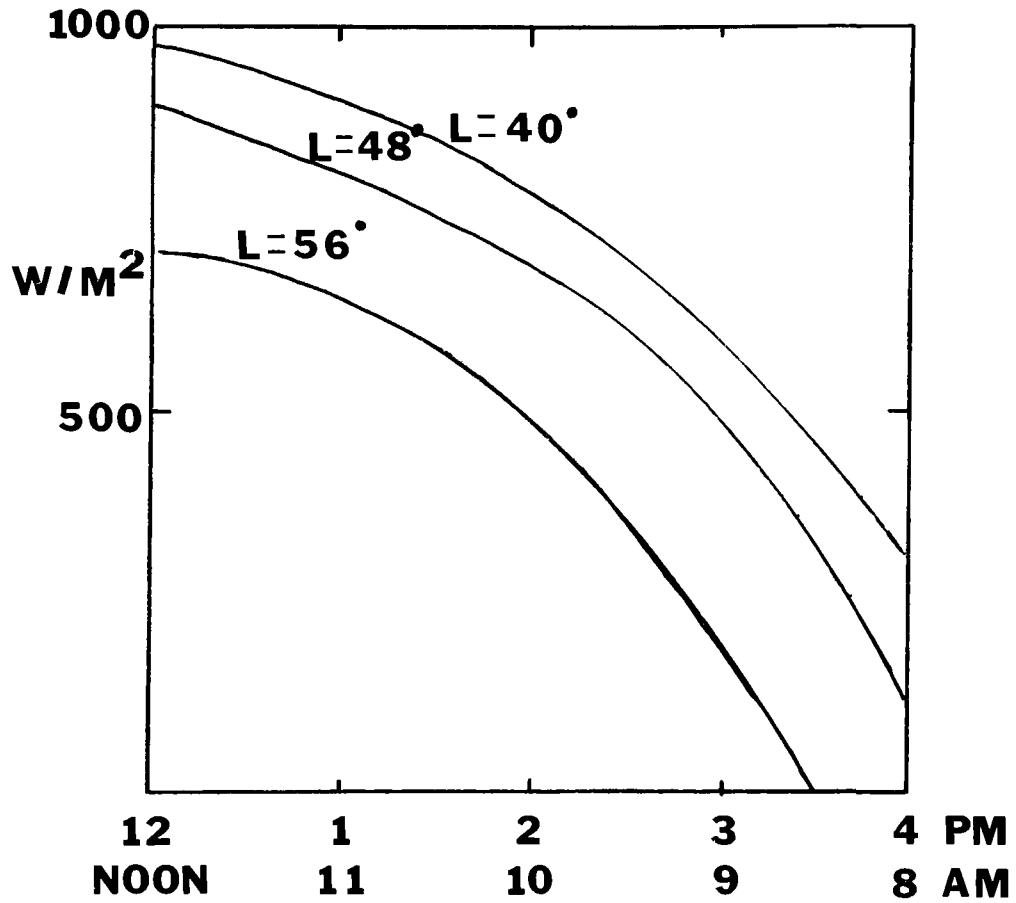


FIGURE 1: Insolation data on January 21
for a south-facing collector
tilted at $L + 20$ for various
Latitudes

The availability of a clear day during the daytime influences the effectiveness of solar collecting equipment. Since weather is also very unpredictable solar energy has not been used as much as it could be. For best effectiveness solar collecting equipment should therefore be installed where the probability of clear days is maximum.³

The solar flux striking a steeply sloping south-facing surface may not have an optimal exposure during the summer months, but may well have an optimum slope during winter conditions. During winter there is generally about 60% more direct radiation received on an optimum surface that would be received on a horizontal surface.⁴

Several types of solar radiation losses are incurred in most solar collectors. The radiation flux is partly lost by the transparent insulation protecting the collector, part is absorbed by the layers of insulation and the heating surface. The absorbed energy is converted into heat and is partly lost to the air surrounding the collector.

Solar collectors are most often tested on clear, cloudless days. It is important to know what the spectral distribution of sunlight is. Solar cells as well as coatings on solar collectors are dependent only on certain frequency ranges in the solar spectrum. However, the solar spectrum as received on earth is variable as a result of changing conditions such as distance and angle of the sun, thickness and composition of atmosphere.⁵

As a result of the cold winters in Canada, there is a large demand for low temperature heating, that is at temperatures below 100°C. Solar energy is ideally suited to produce heat at these temperatures.

The main parts in a solar energy collecting system are the collector, circulating fluid for transferring the heat, and the heat storage system. The key component is the collector. Its cost, efficiency and temperature output are very important and dictate the selection of design.

Solar collectors used for the application of heating and cooling of buildings as well as for heating swimming pools are the subject of a great deal of interest. For such systems solar flat plate collectors are mostly used even though collector designs vary from simple flat plate collectors to ones fairly sophisticated in design used to produce steam.

There are many types of collectors and several will now be mentioned with a brief description of each.

Flat plate collectors are,^{6,7,8,9,10} as the name implies, flat and contain water passages in which the water is indirectly heated by the sun. These collectors are usually made of aluminum or copper. Aluminum is cheaper but its main disadvantage is that it corrodes very fast as a result of attack by water.¹¹ Coatings on copper, on the other hand, have generally an inadequate thermal stability.

Water trickle collectors are so named because water trickles over the surface being heated. The efficiency is less than that for the flat plate design. However, one advantage of this type of collector is that at night the water can be easily drained to prevent freezing during cold weather.

Honeycomb collectors are a variation of the flat plate collectors which have a particular design in which an attempt is made to suppress the free convective heat loss between cover and collector plate. The

addition of honeycombs and other cellular structures of a cell size of approximately one centimetre increases the efficiency in the flat plate collector by reducing heat losses.^{12,13,14,15,16}

The V-groove type of collector is of a flat plate design with V-grooves built in to trap the solar radiation. The groove angle is usually about 30 degrees. The principle of operation entails the repeated reflection, and subsequent absorption of the solar radiation with a high efficiency.^{17,18}

Evacuated collectors have been designed in such a way that the free convective and gaseous conduction heat losses are eliminated because of the absence of air or gas.^{19,20,21} The radiative loss is reduced by using selective coatings. In the same family of collectors are the partially evacuated collectors which do not have the ultra-low vacuum.²² In those collectors free convection is eliminated but gaseous conduction still exists.

Concentrating or focusing collectors are capable of providing high temperatures. In concentrating collectors, the solar rays are concentrated onto a smaller surface which in turn reduces the heat loss and increases the efficiency. Seasonal or diurnal tracking is usually necessary and in most cases the diffuse radiation from cloudy days cannot be collected. Sun tracking systems increase the cost and maintenance problems of this type of collector system.

In the parabolic trough collector a large parabolic mirror concentrates the light onto a tube at its focal line at which a fluid passes through a pipe to be heated. In this system the collector needs

to be provided with a tracking device to ensure that the radiation strikes the collector at the proper position for absorption.

Compound parabolic concentrators (C.P.C.)^{23,24,25,26,27,28} are similar to the V-groove type except that the reflective side-walls are parabolic rather than flat. At a concentrating ratio of 2 the difference is slight. One is concerned with the added heat loss along the reflective side walls. The absorber area needed in a C.P.C. is half or less than needed for flat plate collector. This reduced surface area decreases the heat loss. To minimize the cooling fin effect of the reflectors, high temperature polyurethane insulation can be used as the structural material with aluminized mylar as the reflector material. These collectors can concentrate light up to a factor of 10 without diurnal tracking of the sun. Even though these collectors are inexpensive to construct and operate they can produce process heat and have the potential to help in achieving energy independence. It is estimated that the C.P.C. with a concentrating ratio of about 9 can produce steam at temperatures of up to about 315°C. If this collector tube is evacuated and has a highly selective surface, temperatures as high as 600°C can be obtained. With the C.P.C. little or no tracking is needed and diffuse sunlight is utilized.²⁹ The C.P.C. combines the best features of a flat plate collector and the tracking parabolic trough collectors.

Other collectors which concentrate solar rays usually do so with the use of circular glass disks, cylindrical glass lenses, fresnel lenses or mirrors. One disadvantage of these collectors is that energy is absorbed or even scattered by the system. The glass concentrators have a

disadvantage of cost and weight. The fresnel lenses³⁰ have a much smaller mass but still diurnal tracking is required. Plastic lenses may not be as stable as glass ones but their stability is greater than the reflective surfaces on a C.P.C. or V-groove collector. When parabolic mirrors are used the surface collects rays parallel to its axis and focuses them into a spot. Graduated mirrors³¹ are also produced which offer a greater concentration than a simple parabolic mirror. A large number of plain mirrors can be used to reflect radiation from a large area of the earth surface onto the top of a tower.³² This arrangement is expensive but it can generate steam to produce electricity. Large areas of land and mirrors are needed to achieve the required heat output but much less than for a normal hydro dam. Coatings are generally used on collectors to enhance the absorbtivity of the surfaces. The type of coating needed is one wih a high solar absorbtivity, above 0.9, and low emissivity to minimize heat losses. The increased performance of solar resulting from the use of selective surfaces is well known.

A selective surface increases the efficiency of a collector by suppressing its thermal radiation.^{33,34,35,36} They are most beneficial to systems of low or intermediate concentration, but will still produce economic savings at high concentration ratios needed, for example, in solar boilers.

Since for operating conditions above 40°C, the heat losses are mostly the result of radiation, selective coatings are used to minimize radiation above 4 μ from the surface while not affecting the radiation reaching a collector below 3 μ which therefore increases the efficiency

of the collector. The problem of highly selective surfaces is that many are thermally unstable.

Selective coatings may perform well at the beginning but may deteriorate at high temperatures in an oxidizing atmosphere. By producing a vacuum atmosphere near the selective surface two effects are observed: the coating is protected, and heat losses are greatly reduced. However, some metal oxide coatings tend to deteriorate in vacuum at high temperatures since metal and oxygen will separate and deteriorate the coating.³⁷

A thin black coating can be placed on a bright polished metallic surface to produce a selective radiation surface.³⁸ The selective coating can be produced by spraying an aqueous solution of a metallic nitrate on the metal surface followed by heating to produce the metal oxide film.³⁹ For the oxide to produce satisfactory low-temperature performance the surface must initially be a good reflector. If a surface is sandblasted before coating in an attempt to increase absorptivity and bonding, the emissivity rather than absorptivity will be increased by 40% or more.

Most surfaces used to collect concentrated solar energy should withstand operating conditions above 500°C and also be useful at 100°C. The metal oxides, CuO and Co₃O₄, deposited on nickel, silver and platinum collectors are stable at the high temperatures obtained with focusing collectors.⁴⁰

Cupric oxide will start dissociating at temperatures in excess of 700°C while cobalt oxide and nickel oxide are stable in air well above

1100°C.⁴¹ Black paint, organic matter and sulfides which can create good absorptive coatings, oxidize at 500°C.³⁷

A second method of producing selective coatings is by electroplating a metal on a polished metallic surface and oxidizing the metal film at 1100°C in the presence of air. A third method of producing a coating is by chemical vapour deposition in which the metal surface to be coated is placed into a hot zone in a furnace and is then exposed to a gas mixture containing a gaseous component of the material to be deposited. The compound breaks up through the transfer of thermal energy at the surface of the hot substrate or by chemical reduction and leaves behind the desired portion of the molecule as a solid thin film.³⁷

There are many selective coatings. Some coatings that have not been mentioned yet are molybdenum oxide compounds, oxidized and chlorinated surfaces, nickel-zinc-sulfide, chromium-nickel-vanadium alloys, zirconium films ($Zr O_x N_y$) etc...^{42,43,44,45}

The selective coating helps to make the solar system advantageous by decreasing the heat loss and increasing the heat gain by 22% or more.^{46,47} It has to be kept in mind that the insolation rate, the efficiency of the collector and cost of conventional energy are factors that determine if a solar collector is economically feasible. A solar energy system becomes viable only if the value of the energy produced exceeds the cost. Therefore, the cost of the coating is a definite factor in the economic picture. The extra energy needed for producing selective coatings is usually repaid in extra energy absorbed within a year and sometimes in less than ten days.

There are three types of film coatings. An antireflective coating, a selective absorber coating and a transparent low emittance coating. Antireflective and antifogging coatings are used on covers and focusing optics to increase the efficiency by increasing the solar transmittance. For example, if the inside surface of a glass cover is coated with a thin layer of indium oxide (In_2O_3),⁴⁸ the glass will act as a selective surface and heat loss will be reduced since heat will be reflected back inside.

3. EXPERIMENTAL

Studies were performed to determine the effectiveness of various surface treatments applied to aluminum and other metal collectors operated in conjunction with a lens concentrating system. The absorptivity of selective coatings is an important factor in determining the effectiveness of collectors. Data were obtained for the rates of heat absorption by different coatings and metals.

The rate of temperature increase of insulated shiny pieces of copper, aluminum, stainless steel and brass collectors of equal size were measured for essentially constant insolation intensities. A spot light and also the sun were used as a source of light. By means of a four inch glass magnifying lens the light was concentrated on one end of a half inch cylinder one inch in length. The temperature of the cylinder was measured using a copper-constantin thermocouple and a recorder. The layout of the equipment can be seen in Figure 2.

Selective coatings were produced by spraying a 0.0025 molal aqueous solution of the nitrate to a hot (approximately 200°C) polished metal surface. The solution evaporated as soon as it touched the surface so that there was no wetting of the surface. For good bonding between the coating and metal there was a waiting period of two days between spraying and baking. The coating on the metal was baked in an oven at 360°C to oxidize the nitrate for a period of half an hour. Coatings of cobalt oxide, chromium oxide, cuprous oxide and nickel oxide were applied to copper, aluminum, stainless steel and brass. A selective coating was also produced on copper by dipping it in a boiling salt solution of

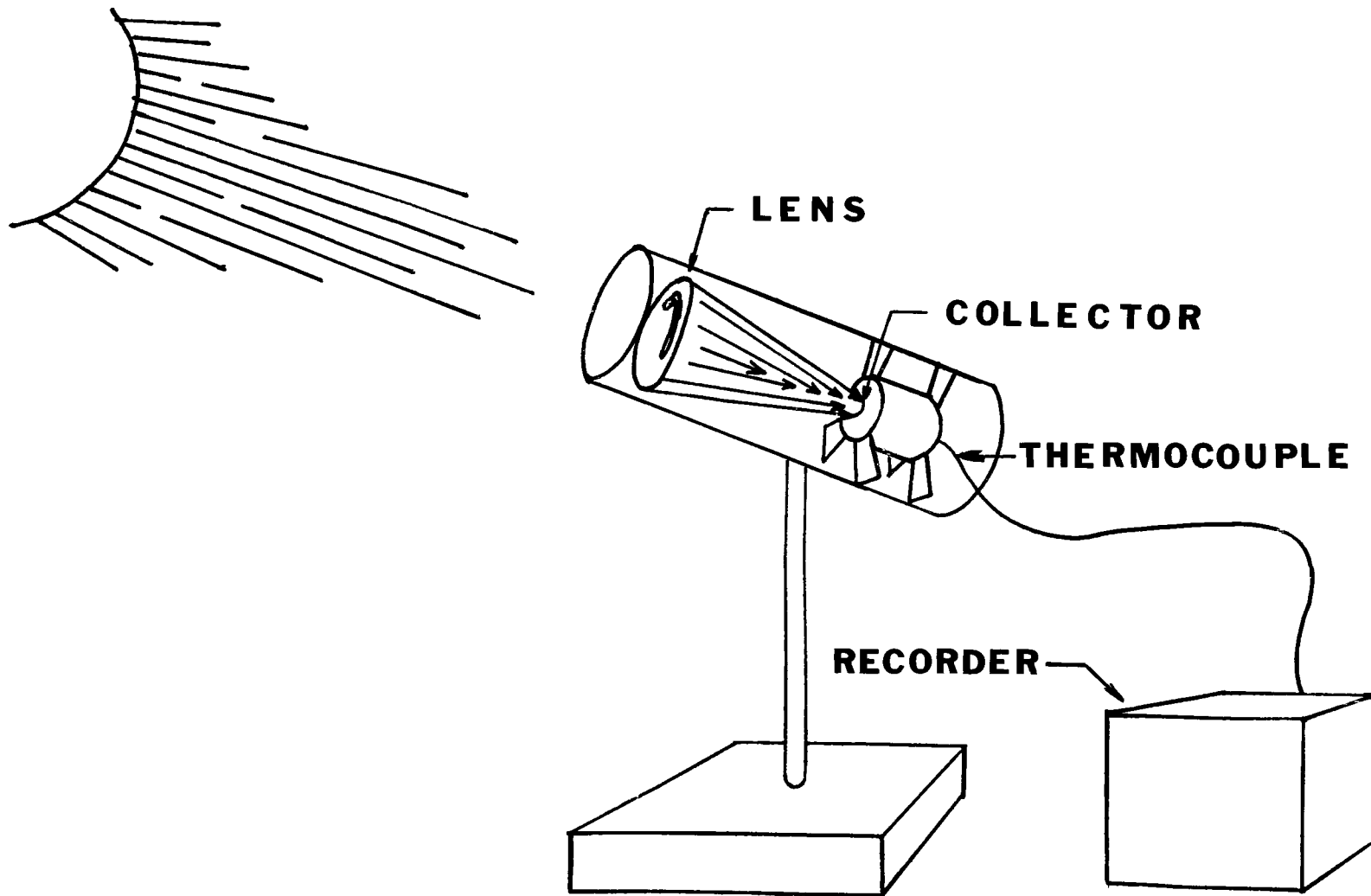


FIGURE 2

concentrated sodium hydroxide (250 gms per litre) and sodium hypochlorite solution.

The maximum temperature attainable by means of the selective surfaces was measured. The maximum temperature was generally attained in less than one half hour.

Utilizing the data obtained with the coatings, work was done to design a solar collector using magnifying lenses. A sketch of the collector can be seen in Figure 3. The collector was built with sides thirteen inches in length which gave the top a surface area of 439.1 square inches (0.283 m^2) exposed to solar radiation. Styrofoam insulation, two inches thick was used on the sides and bottom. Plexiglass was used to hold the nineteen four inch magnifying lenses in position. The coated surfaces of the metal cylinders were placed at the focal point of the lenses which in this case was ten inches below the lenses. The metal cylinders were insulated on the sides with asbestos and at the bottom with plexiglass. Water which was used as the heat collecting fluid passes through a tube soldered into each cylinder in succession, in a spiral configuration starting close to the walls where the heat losses to the atmosphere were considered to be a maximum and finishing at the center of the collector bank. The layout of the solar collecting system can be seen in Figure 4. The temperatures were measured in the solar collector at inlet, first, thirteenth and nineteenth cylinder and at the outlet of the collector. Temperatures of the water in the surge tank and ambient temperatures were also measured. The solar radiation was measured using solar cells to give a basis of comparison among insolation intensities for the various days of testing.

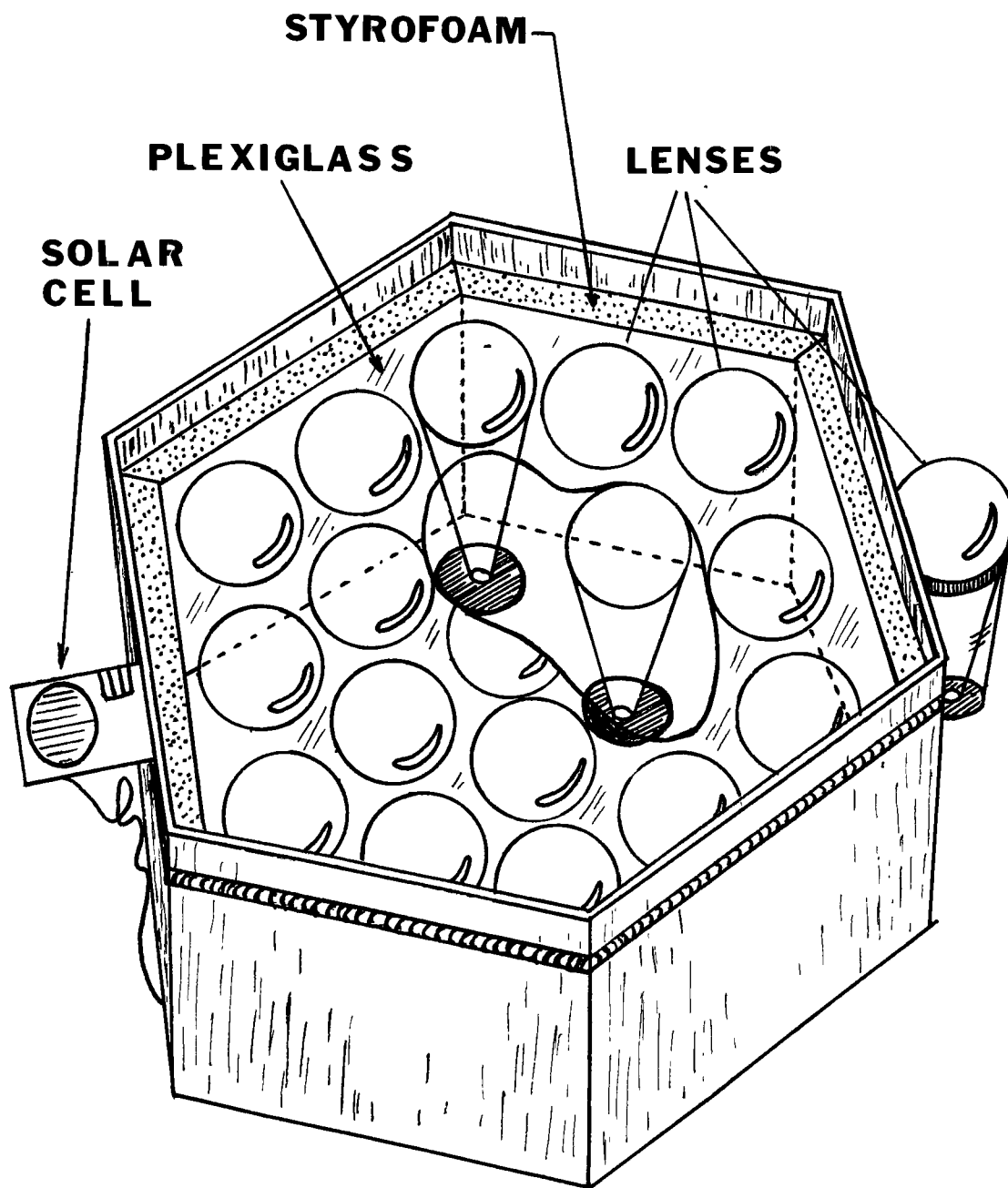


FIGURE 3

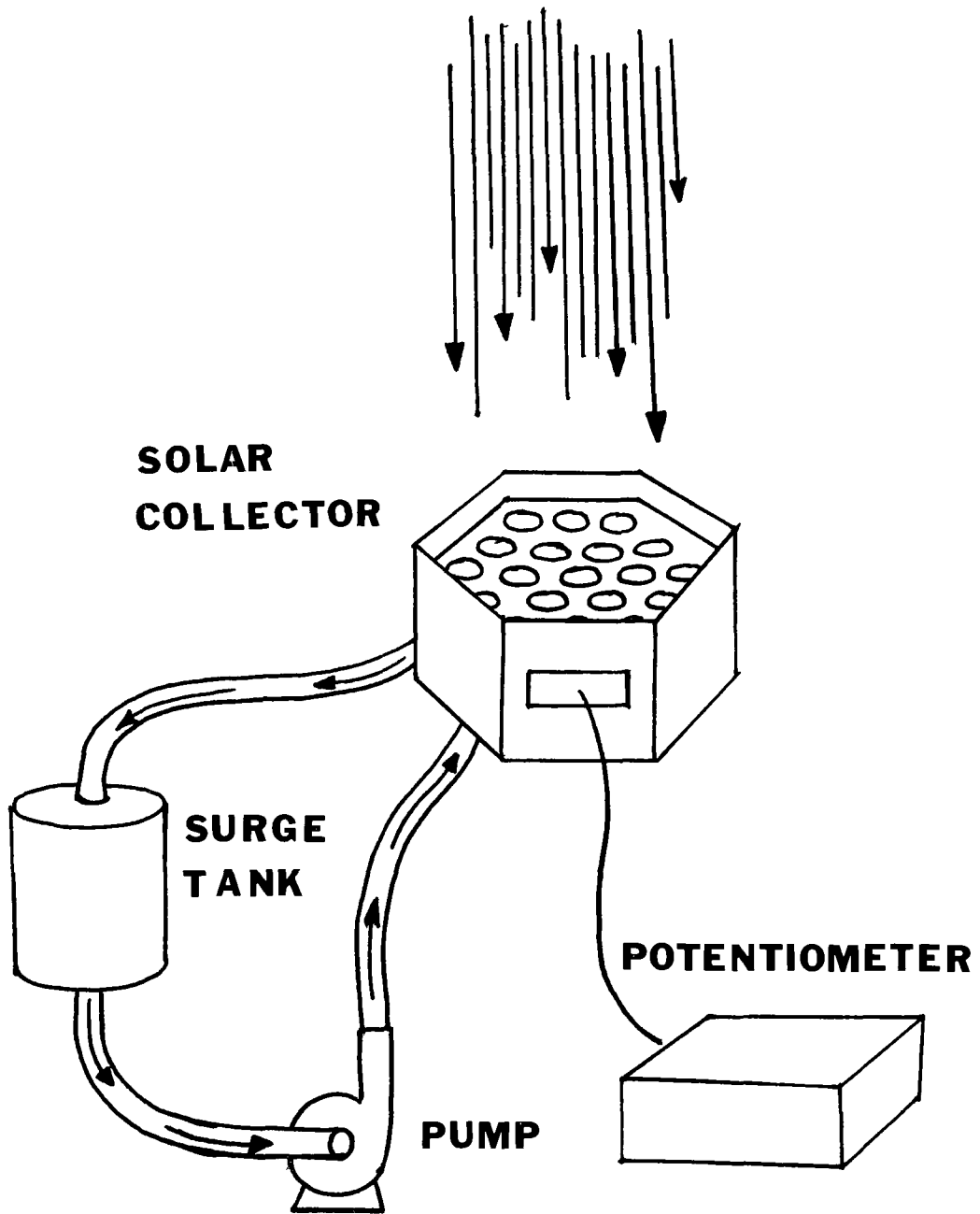


FIGURE 4

The solar collector had to track the sun. It was, therefore, mounted on a steel base designed to tilt and rotate the collector. The collector system was installed on the roof of Colonel By Hall.

Tests were made on clear sunny days for different water circulation rates. Some data were also obtained on some cloudy days. During each test, temperatures and flow rate data were recorded for the collector system using time intervals of five to fifteen minutes.

Heat loss experiments from the solar collector system were also measured outside and under a controlled environment inside the Engineering building. Heat loss experiments were performed by using hot water initially in the surge tank and then by measuring the rate of temperature drop while the water was being circulated.

The rate of heat gain (Q) of the collector was obtained by using Equation (1).

$$Q = F \times C_p \times \Delta T \quad (1)$$

where F is the flow rate, C_p is the specific heat of water, and ΔT is the temperature difference between inlet and outlet.

4. RESULTS AND DISCUSSIONS

The radiation absorption data obtained using the shiny flat surfaces of stainless steel, copper, brass and aluminum collectors is recorded in Figure A-1 and Figure A-2. From these results it may be observed that stainless steel is a good absorber while aluminum is a poor one. From these two figures it was possible to compare the radiation obtained by means of a spotlight and that obtained from the sun. It was observed that the radiation from a spotlight was not as intense as the radiation from the sun.

The effects of selective coatings is a major factor in solar collector efficiency. The increased radiation absorption as a result of selective coatings on stainless steel and on copper can be observed in Figure A-3 and on Figure A-4. The cobalt oxide shows a good absorptivity on both metals. The selective coating produced by the hot concentrated salt solution was the best coating on copper.

The selective coatings of cobalt oxide and chromium oxide seemed to give the best oxide coatings and their effects on different metal surfaces can be observed in Figures A-5 and A-6. From these results it looked as if aluminum would be the best metal to coat and use. The cuprous oxide and nickel oxide had an inferior bonding to the metal and tended to flake off easily. Coatings on copper, obtained by exposing the collector to the hot salt solution, were stable and the surface could be easily recoated. In Figure A-7 the absorptivities are compared for the coatings of cobalt oxide on aluminum and for the coating on copper from the salt solution. The first attempt at coating copper with the salt

solution produced a good selective surface but inferior to that of cobalt oxide on aluminum. In the second attempt at coating copper the surface was washed with distilled water after coating to remove the salt from the surface. This produced an even better coating yet still not the best. By experimenting with the immersion time of the copper in the salt solution, a dipping of 15 seconds produced a coating as good as, or better than, cobalt oxide on aluminum.

A temperature of approximately 500°F was obtained at about 1/8 of an inch from the surface of a copper cylinder coated using the salt solution.

Data showing the variation of solar flux that was observed on a particularly sunny day is recorded in Table 1 and is plotted in Figure A-8. This data was obtained by means of a calibrated solar cell and a recorder. It is similar to the variation in solar insolation as reported by Martin S. Stein¹ as shown in Figure 1. In most experiments the solar output varied between 950 and 1000 W/M².

The numerical data for the rate of heat absorption by the collector in the experiments are recorded in Tables 2 to 23 for flow rates from 0.94 litres/hr. to 22.5 litres/hr. The results are slightly scattered but this was expected as a result of the variation in the weather which included variations in wind velocity, clouds, haze, solar flux and ambient temperatures, as well as to the physical changes made to the collector. The heat gain of the collector at start up was not constant. This was the result of the transient nature at start up since it takes at least 25 minutes for the metal collector to warm up to its optimum temperature. After start up, the heat gain was generally approximately

constant when the wind velocity, ambient temperature and solar radiation were fairly constant. To illustrate this, some heat gain results for sunny days from Tables 2, 4, 12 and 18 were plotted in Figure A-9 to A-12. The heat gain results at a flow rate of 2.724 litre/hr. for an overcast day, Table 13, and for a sunny day, Table 12, were plotted in Figure A-13.

The effect of flow rate on the heat gain was recorded in Table 24 and plotted in Figure A-14 for sunny days. When calculating the average heat gain ($Q_{avg.}$), the transient data at start up and during the bad weather conditions, such as that obtained during cloudy or windy days, were not included. There was a greater heat gain observed as the flow rate of circulating water was increased. The effect of the ambient temperature on the rate of heat gain by the collector was small in comparison to the effects of wind velocity and intensity of the solar radiation as can be observed by inspection of the data in Table 24 and illustrated in Figure A-15. For example there was a difference in heat gain of only 5 to 7 Kcal/hr. for an ambient temperature difference of 30°C at a flow rate of 2.069 litres/hr. while there was a difference of 33 Kcal/hr. at a flow rate of 2.724 litres/hr. at approximately the same ambient temperature, but under different weather conditions. It may be estimated from this data that the collector is capable of providing a heat gain of about 45 Kcal/hr. even at an ambient temperature of -40°C when using a water circulation rate of 2.069 litres/hr.

The measured rates of heat loss from the experimental apparatus were tabulated in Table 25 for outside conditions, and in Table 26 to Table 38 for inside conditions. Some heat loss results from Tables 25, 28, 30,

34, 37 are illustrated in Figure A-16. There is an appreciable variation of the data collected as can be observed by comparing Tables 32 and 33 as illustrated in Figure A-17 for the same operating conditions.

It appears that an increase in circulation rate through the collector bank tends to increase both the heat losses as well as the heat gain. However, it is advantageous to run at increased flow rate since the change of heat gain is much greater than the change of heat loss so that the total heat collected would be increased.

5. CONCLUSION

The concentrating solar collector bank clearly shows that it is possible to collect solar radiation to produce heat even during the winter months and to be able to raise the temperature of water to its boiling point. For an active solar surface collection area of 0.283 m^2 a rate of heat gain of up to $264.83 \text{ Kcal/hr-m}^2$ was obtained for a flow rate of 22.5 litres/hr . The main disadvantage of this type of collector system is that the position of the collector has to be constantly adjusted in order to "track" the sun.

6. RECOMMENDATIONS FOR FUTURE WORK

It would be desirable to have lenses (plastic or glass) that have a shorter focal length, and, at the same time, a larger surface area. This would decrease the depth of the collector, thereby decreasing the heat losses. It is suggested that the shape of the metal collector surface should be changed in the manner illustrated in Figure 5.

A new type of collector element is recommended for future evaluation. The outside of the collector should have the shape of a paraboloid and should be made of an insulating substance such as high density polyurethane so that this concentrating cone does not act as a heat dissipating fin. The inside of the parabolic fin should be of aluminized mylar, coated to reflect the direct and indirect solar radiation to the central metal cone. The central cone would absorb all the reflected rays with the help of a selective coating and would be the only surface to collect heat. Eddy currents would be reduced because of the protection afforded by the shroud surrounding the cone.

The tracking of the sun would not be as critical if lenses with shorter focal points and the parabolic collector element was used.

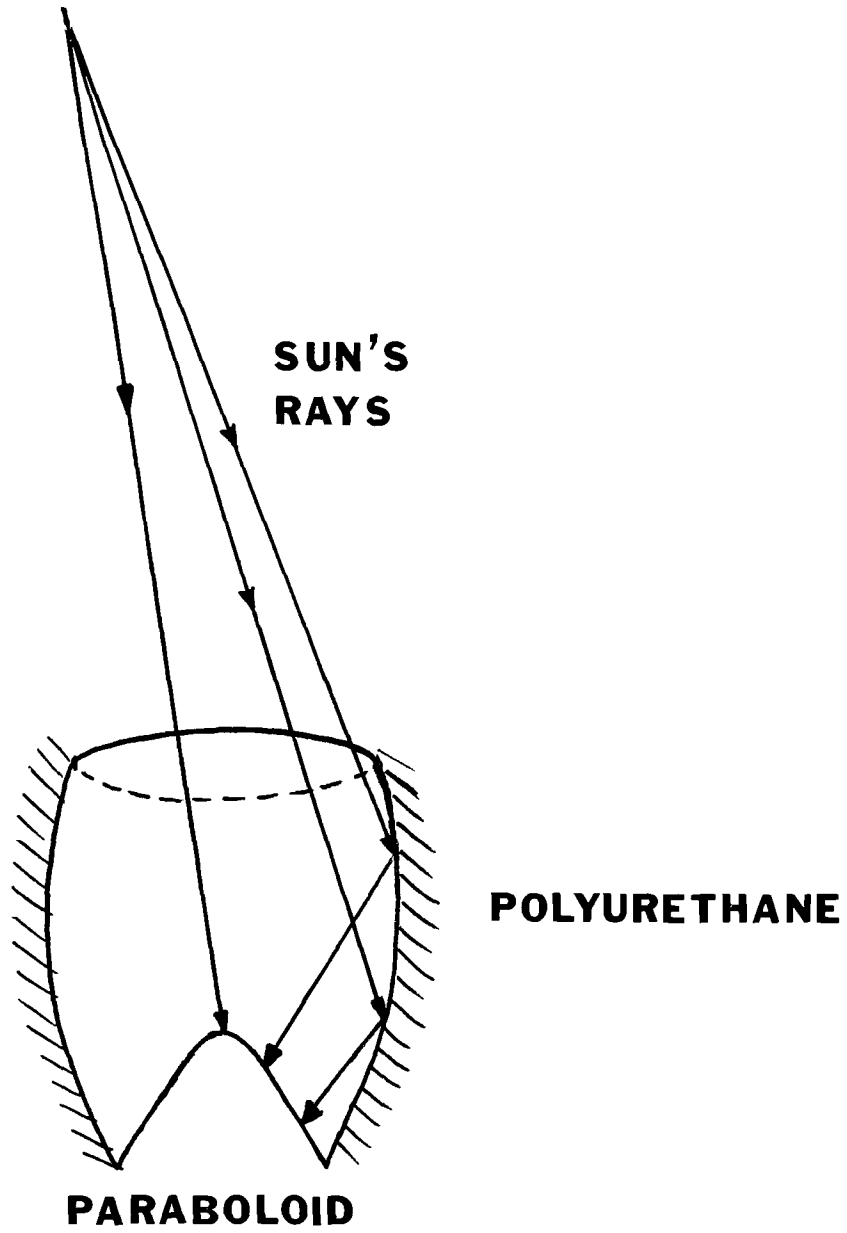


FIGURE 5

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APPENDIX - A

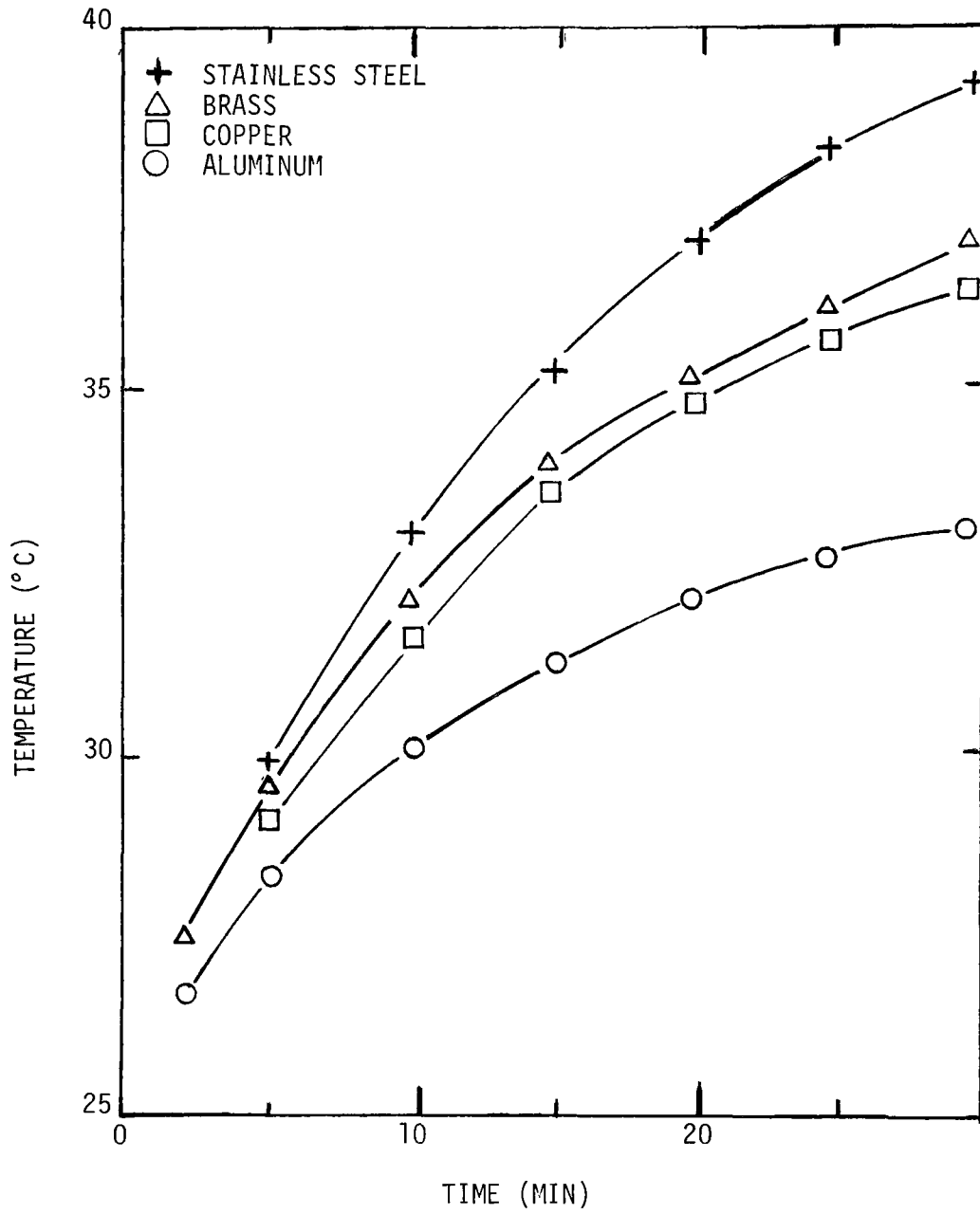


Figure A-1: Temperature increase vs. time for metal surfaces using a spot light.

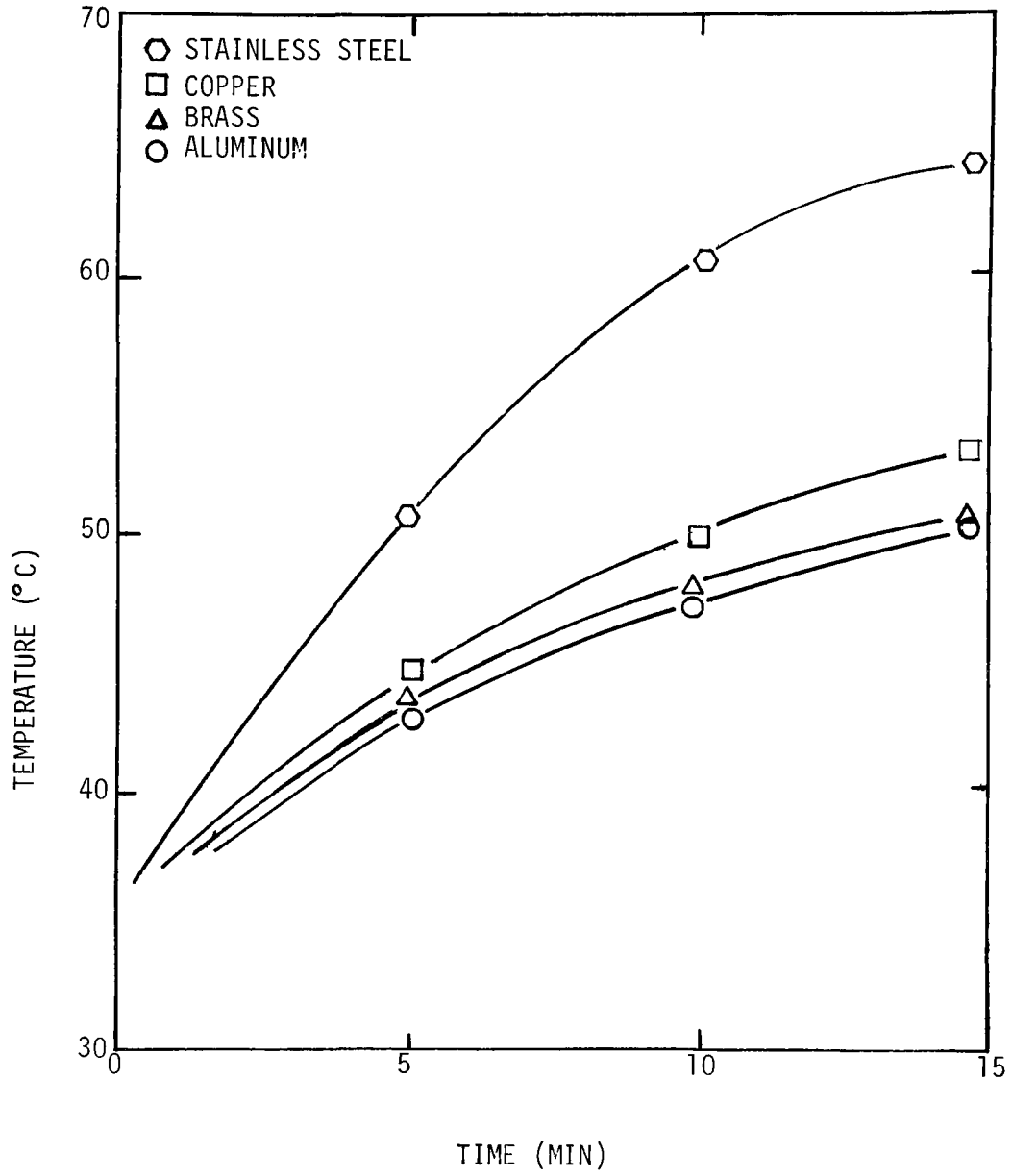


Figure A-2: Temperature increase vs. time for metal surfaces using solar radiation.

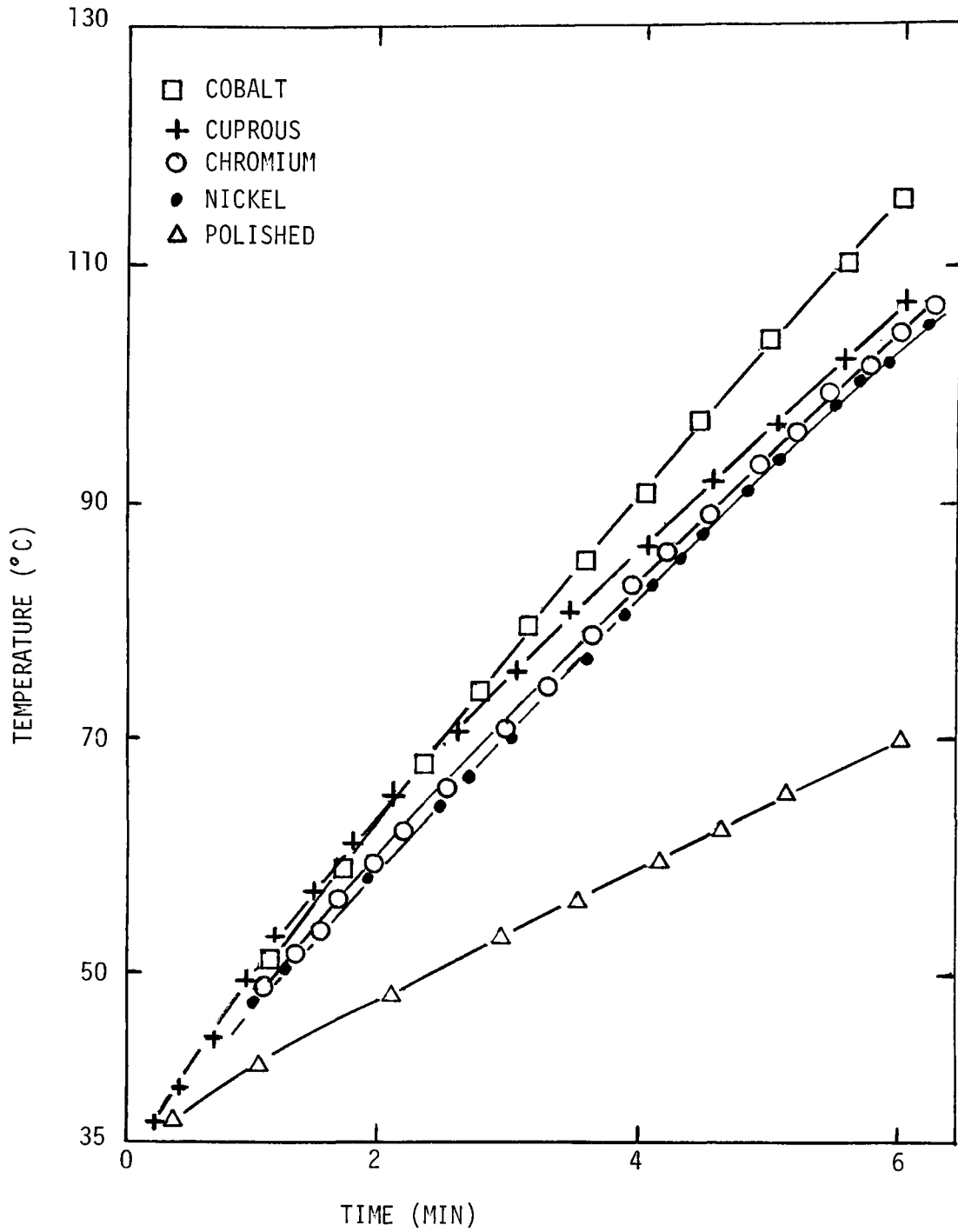


Figure A-3: Temperature increase vs. time for different coatings on stainless steel.

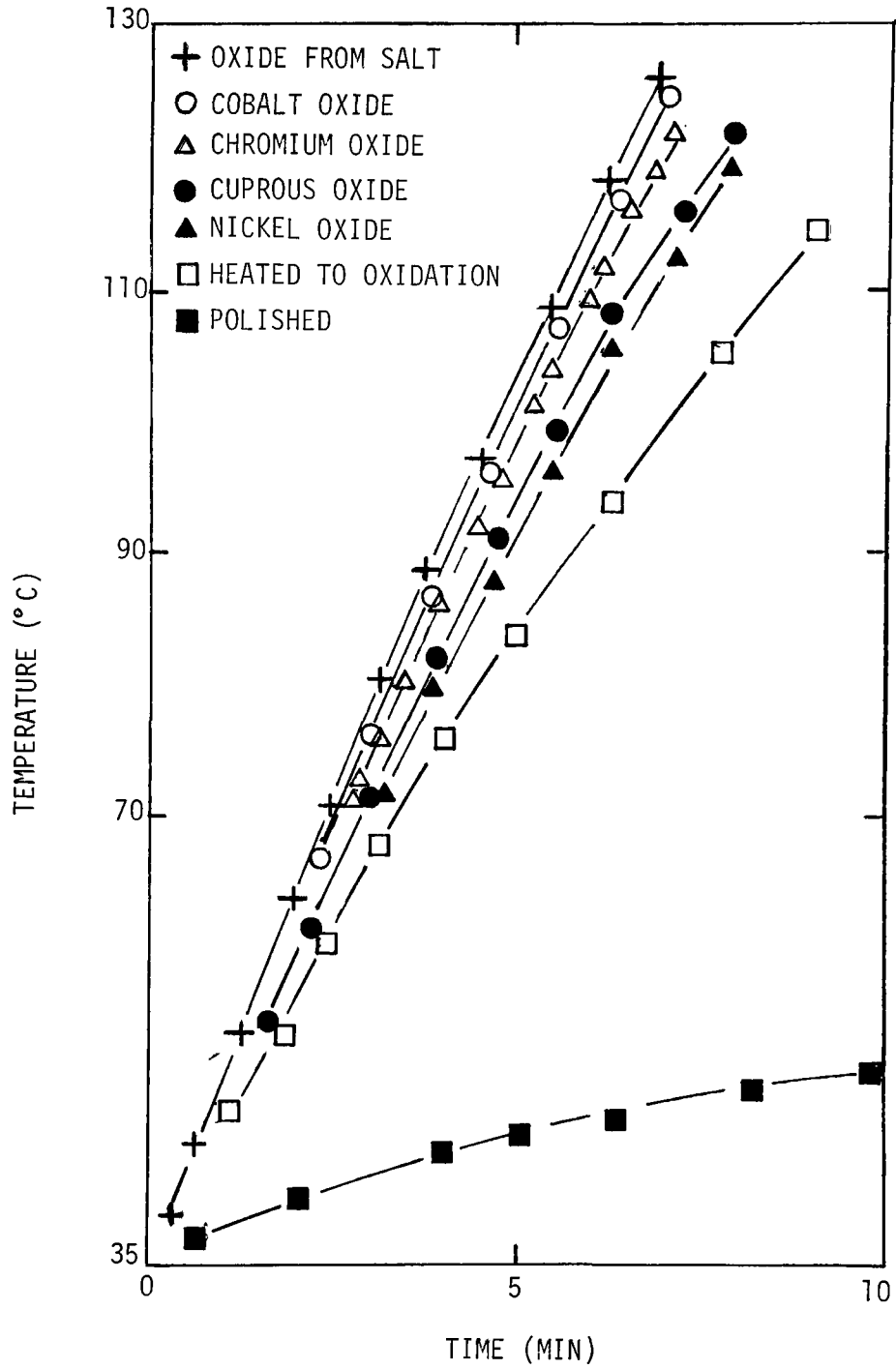


Figure A-4: Temperature increase vs. time for different coatings on copper.

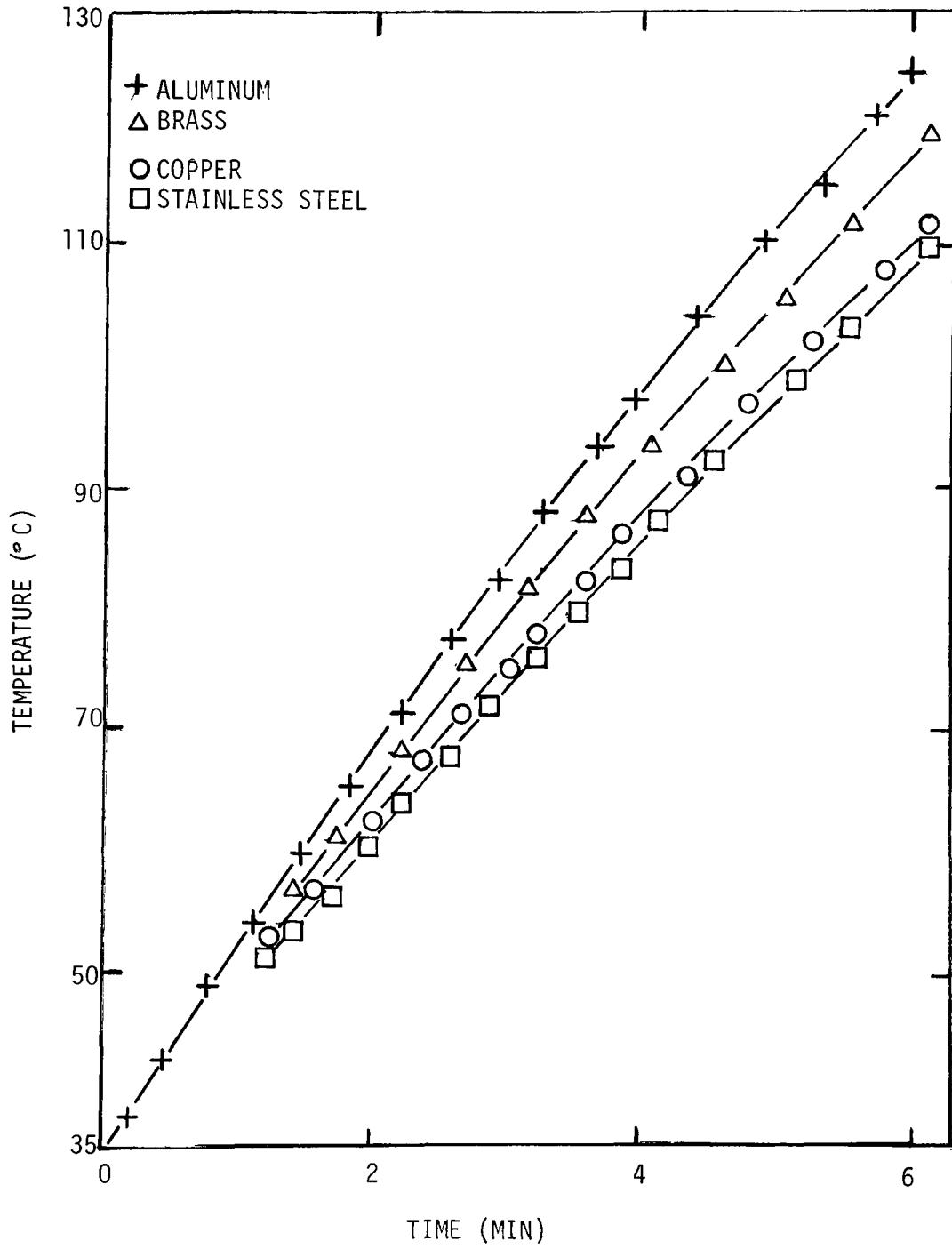


Figure A-5: Temperature increase vs. time for different metals coated with cobalt oxide.

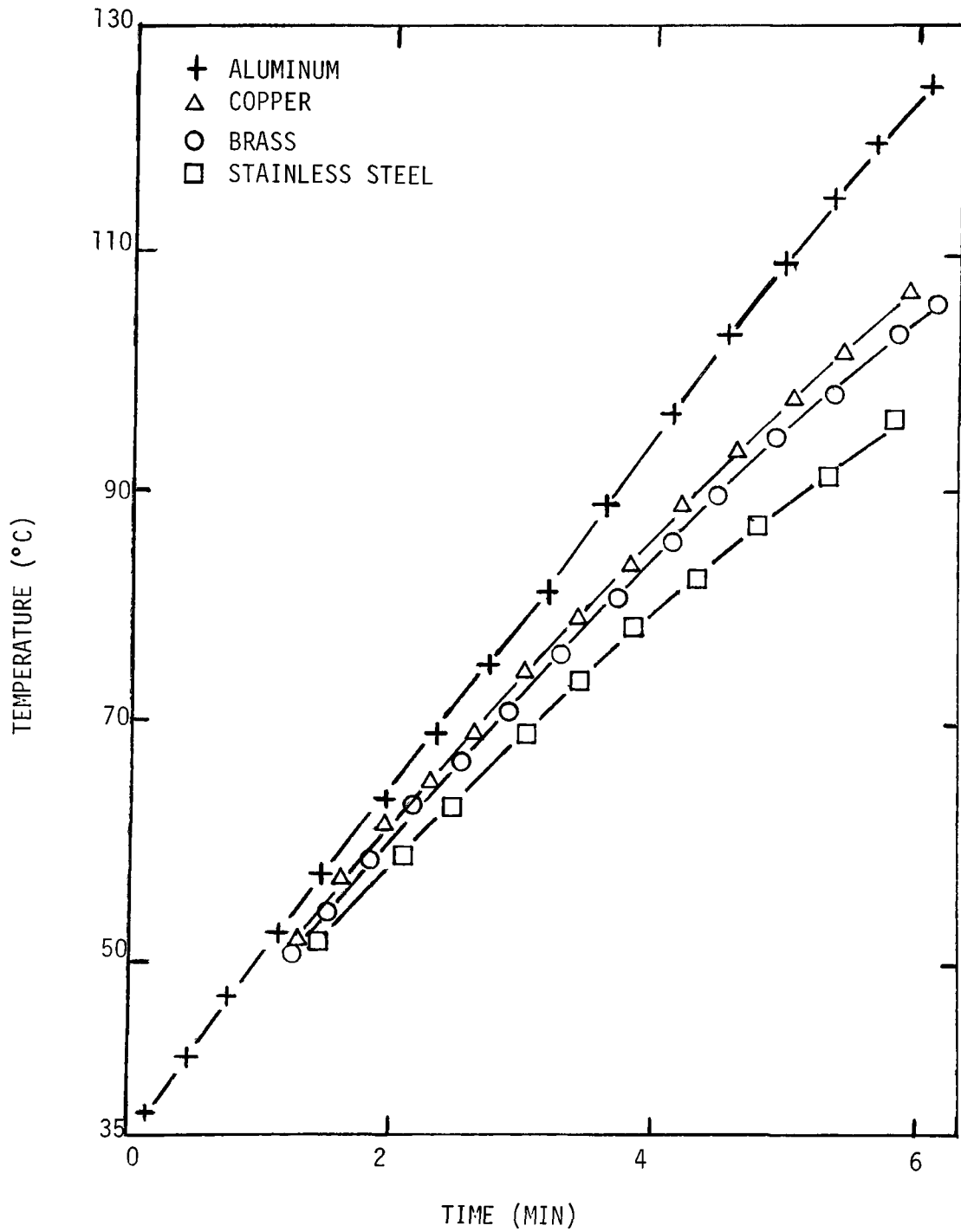


Figure A-6: Temperature increase vs. time for different metals coated with chromium oxide.

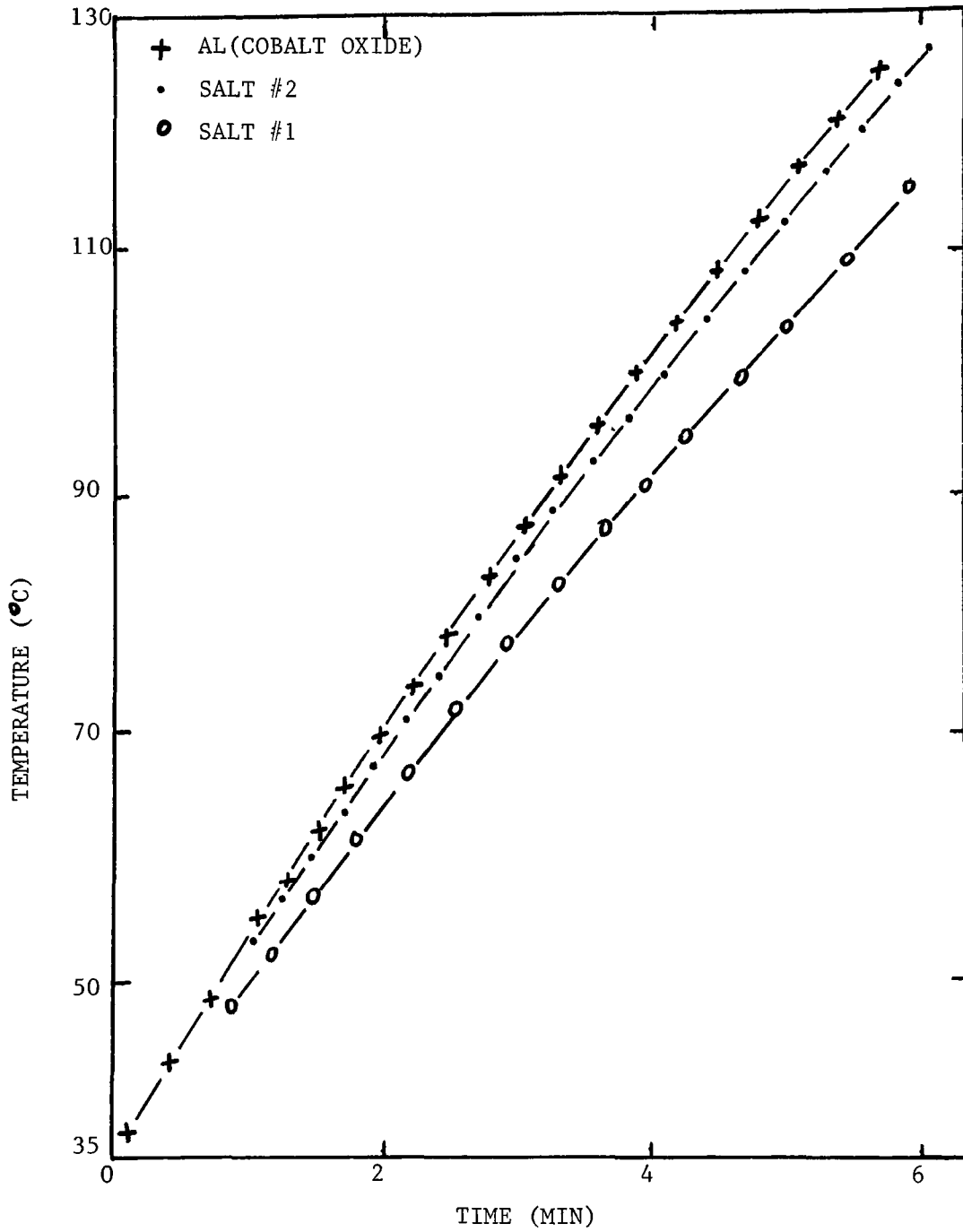


Figure A-7: Comparison of cobalt oxide and salt coatings.

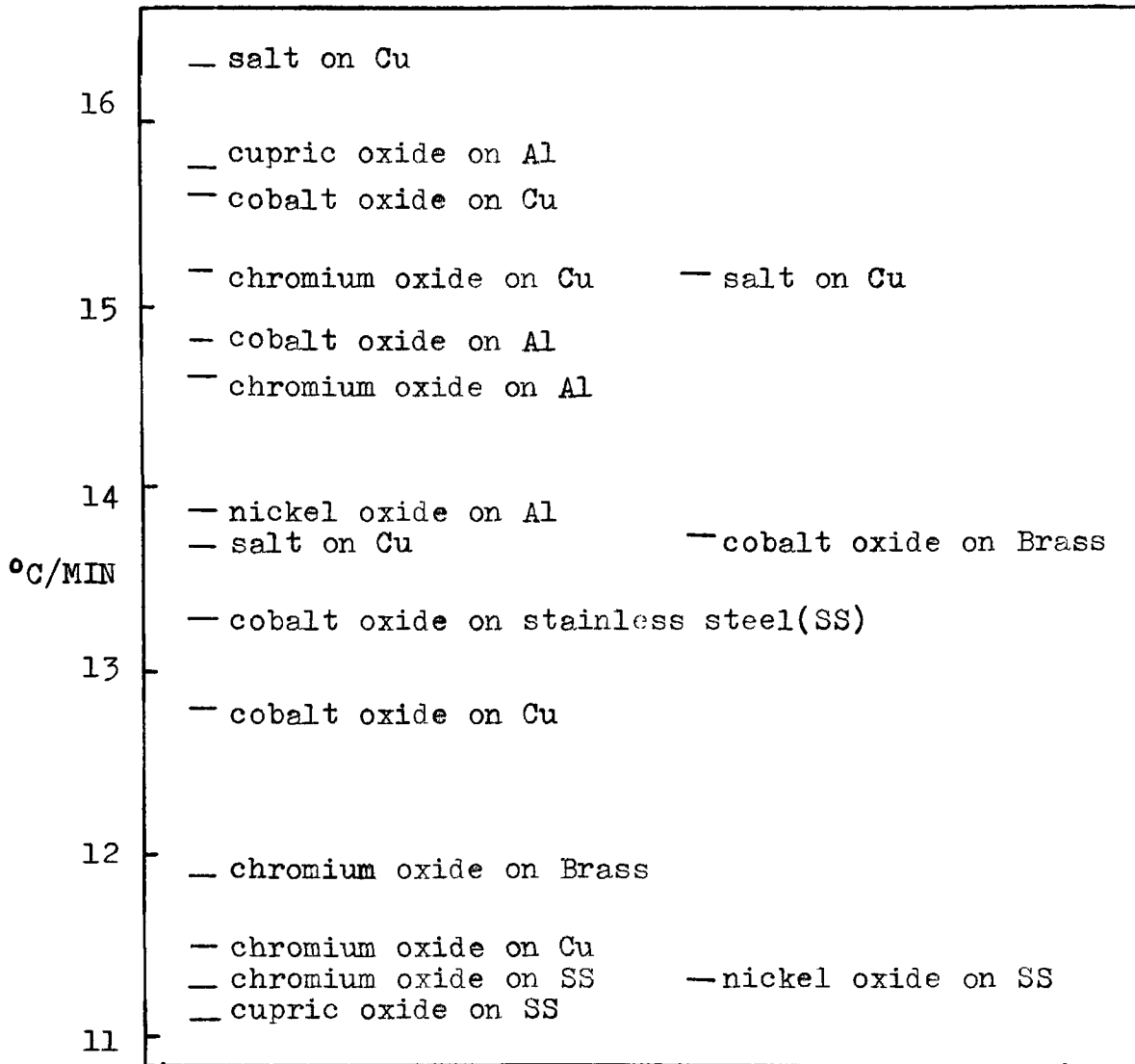


Figure A-7a: Temperature rise of different coatings (°C/MIN).

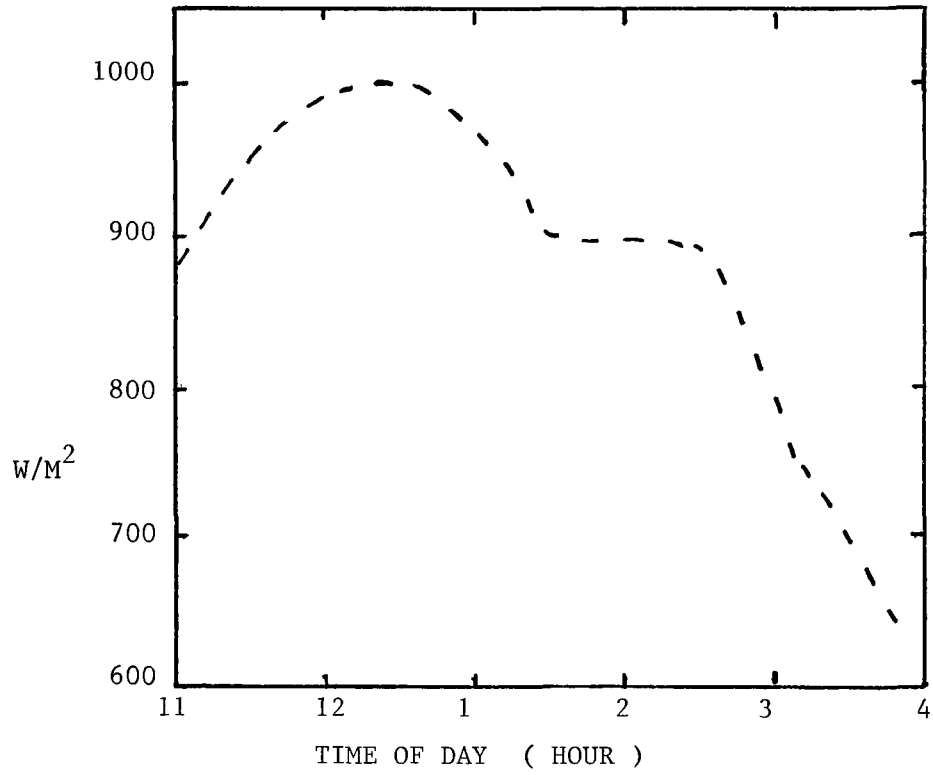


Figure A-8: Solar radiation vs. time of day.

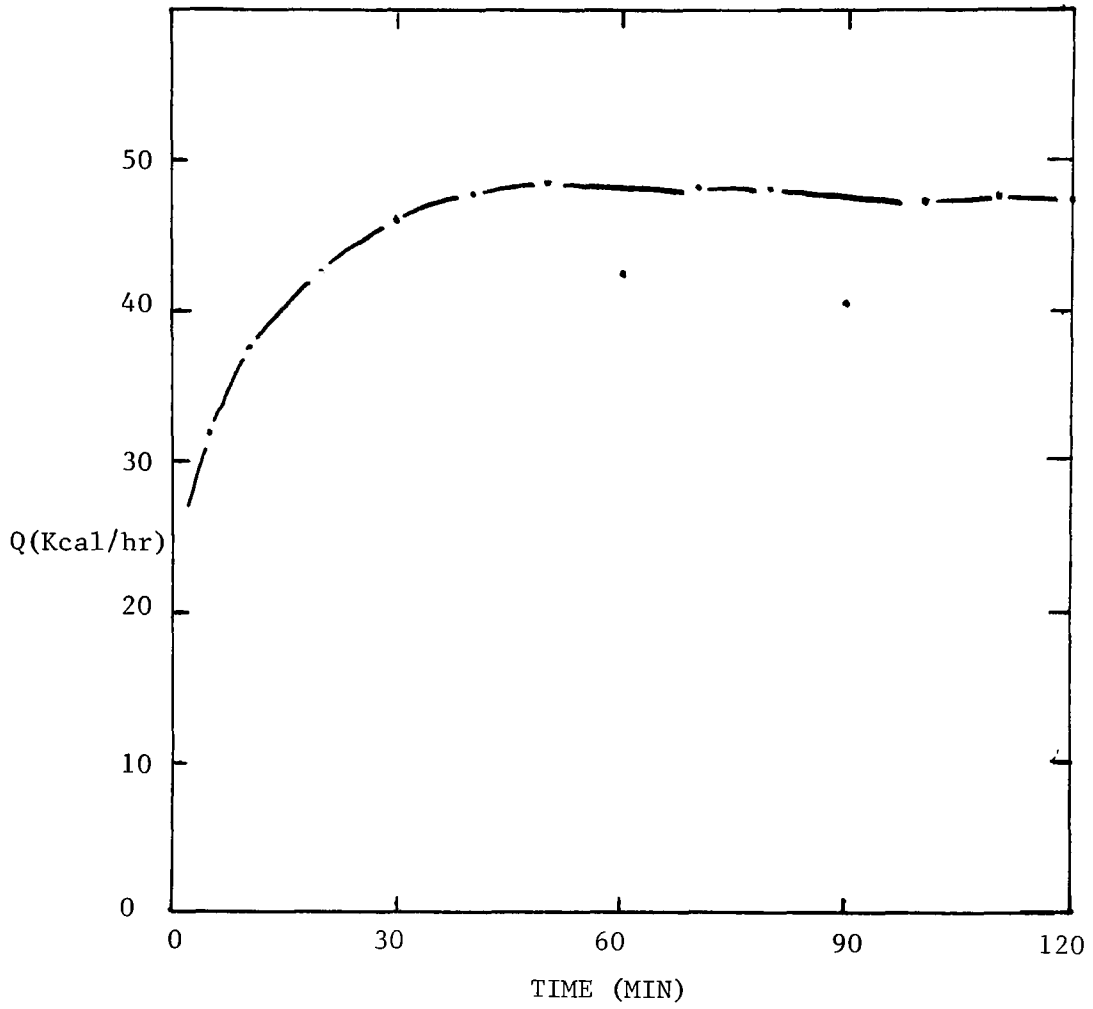


Figure A-9: Heat gain vs time at a flow rate of 0.94 litres/hr. and an ambient temperature of 26.5°C.

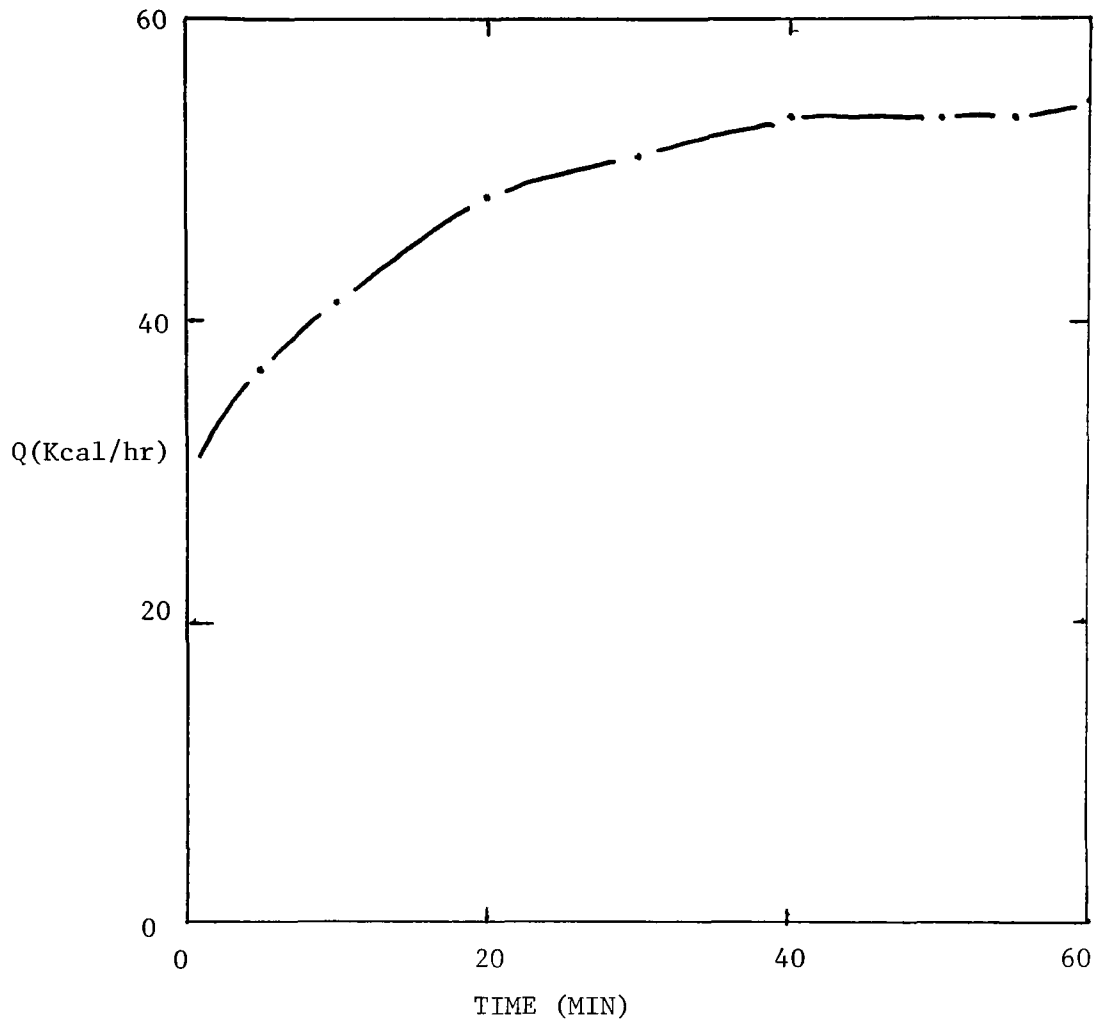


Figure A-10: Heat gain vs. time at a flow rate of 1.611 litres/hr. and an ambient temperature of 26.5 C.

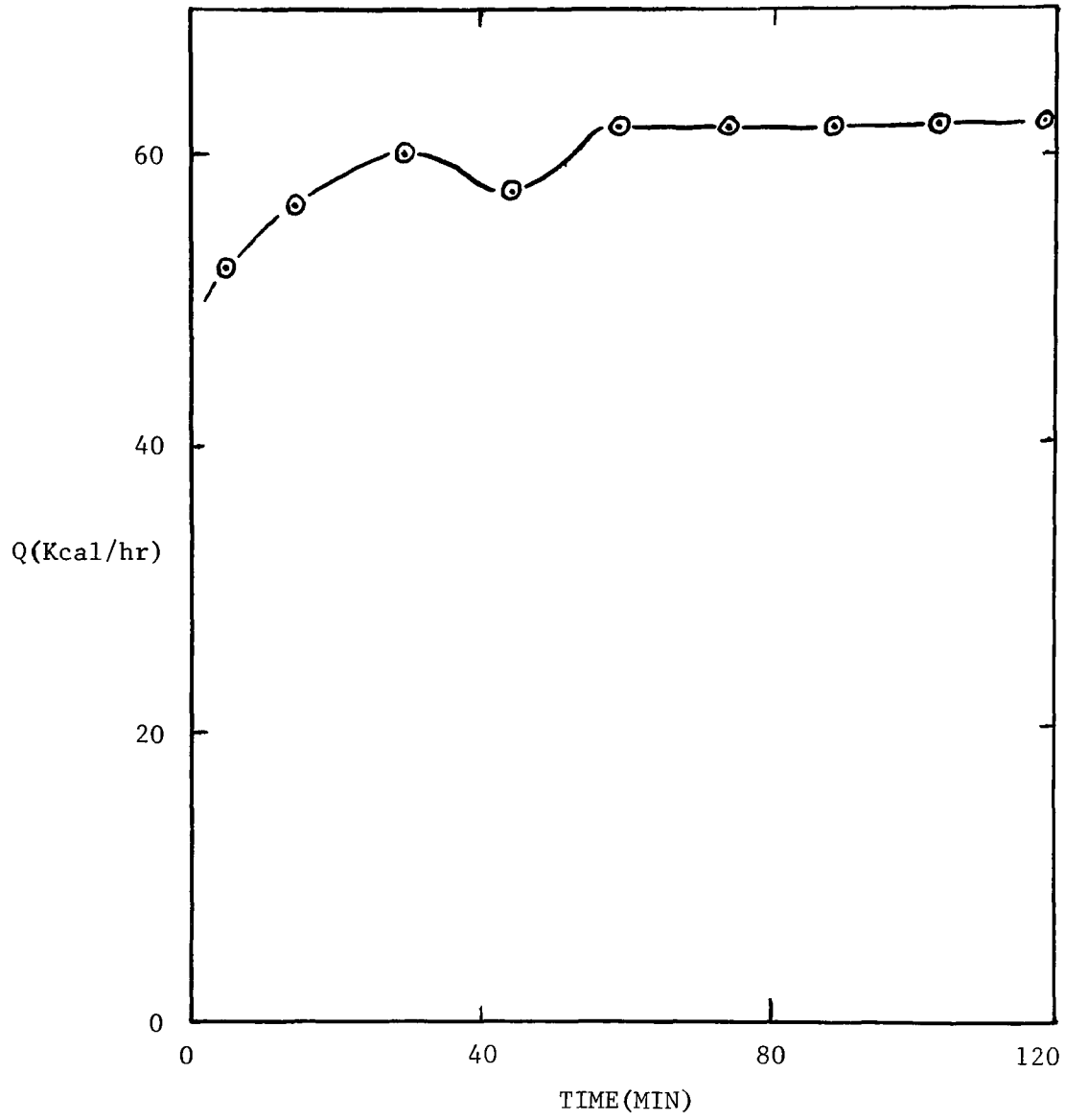


Figure A-11: Heat gain vs. time at a flow rate of 2.724 litres/hr and an ambient temperature of 23.5°C

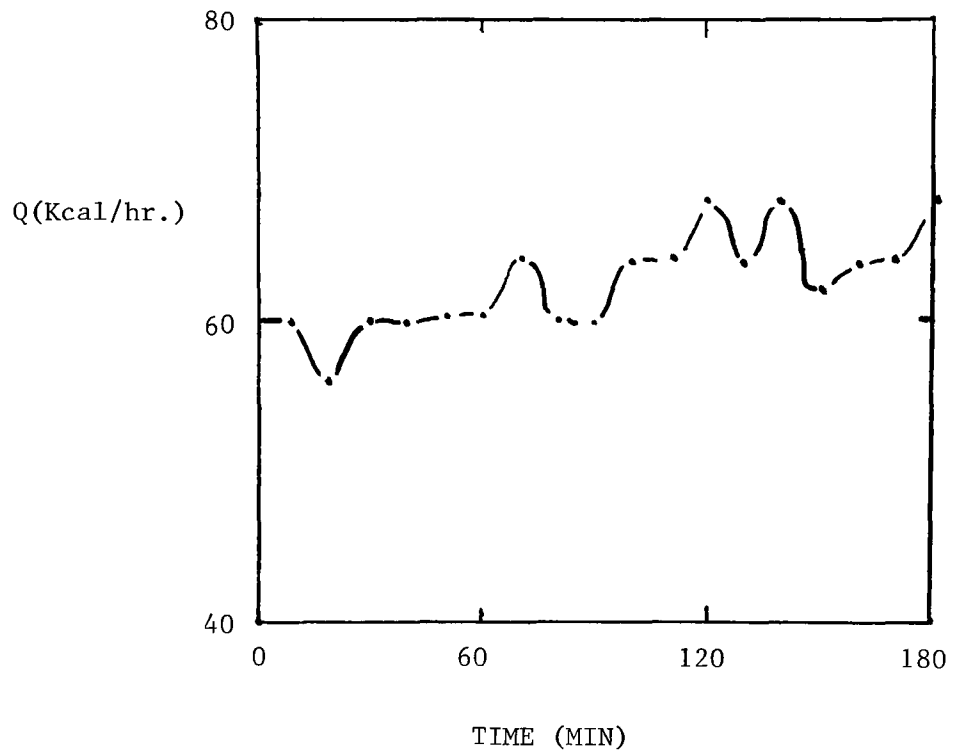


Figure A-12: Heat gain vs. time at a flow rate of 7.2 litres/hr. and an ambient temperature of 29°C.

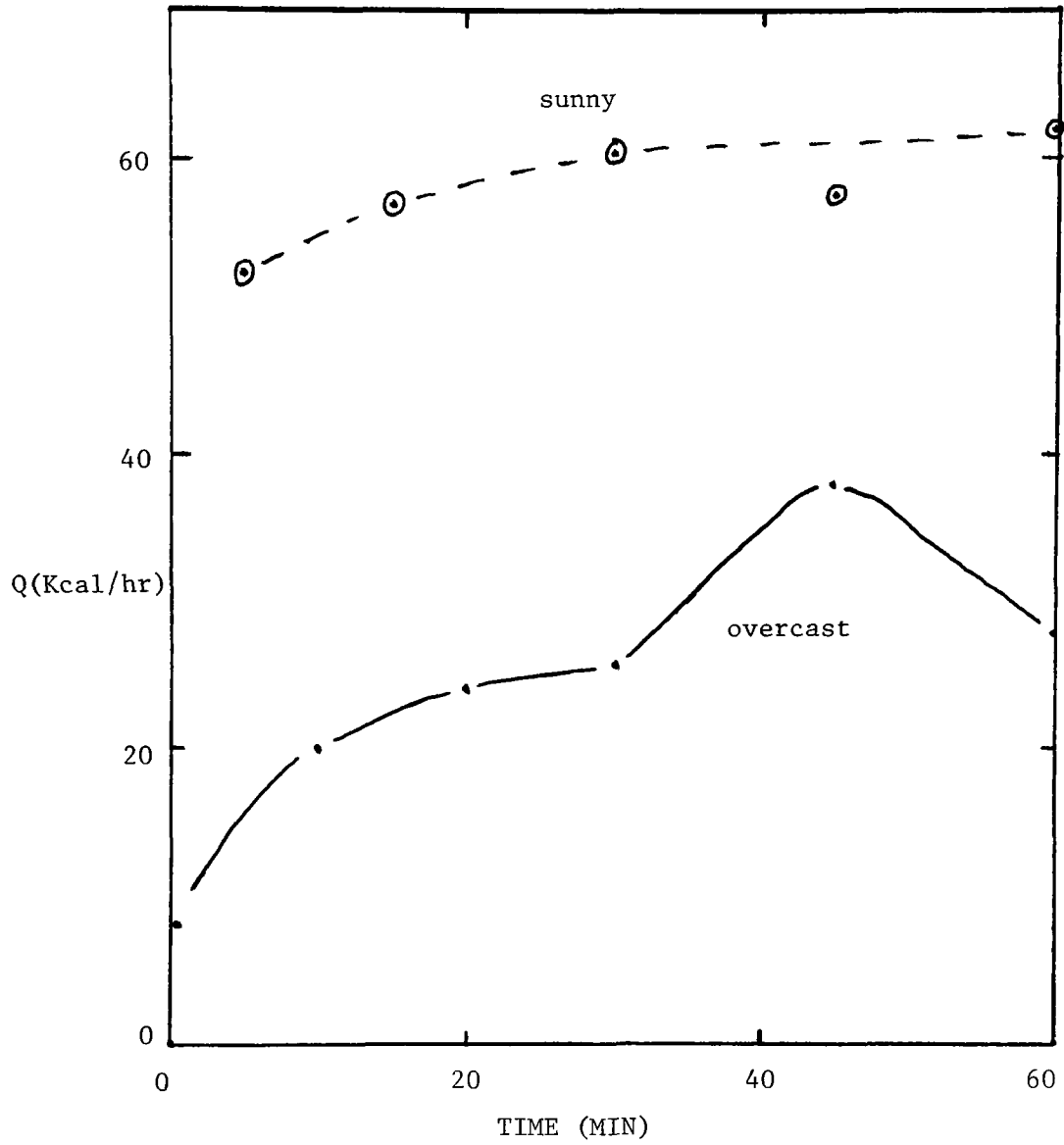


Figure A-13: The comparison of heat gains for sunny and overcast days.

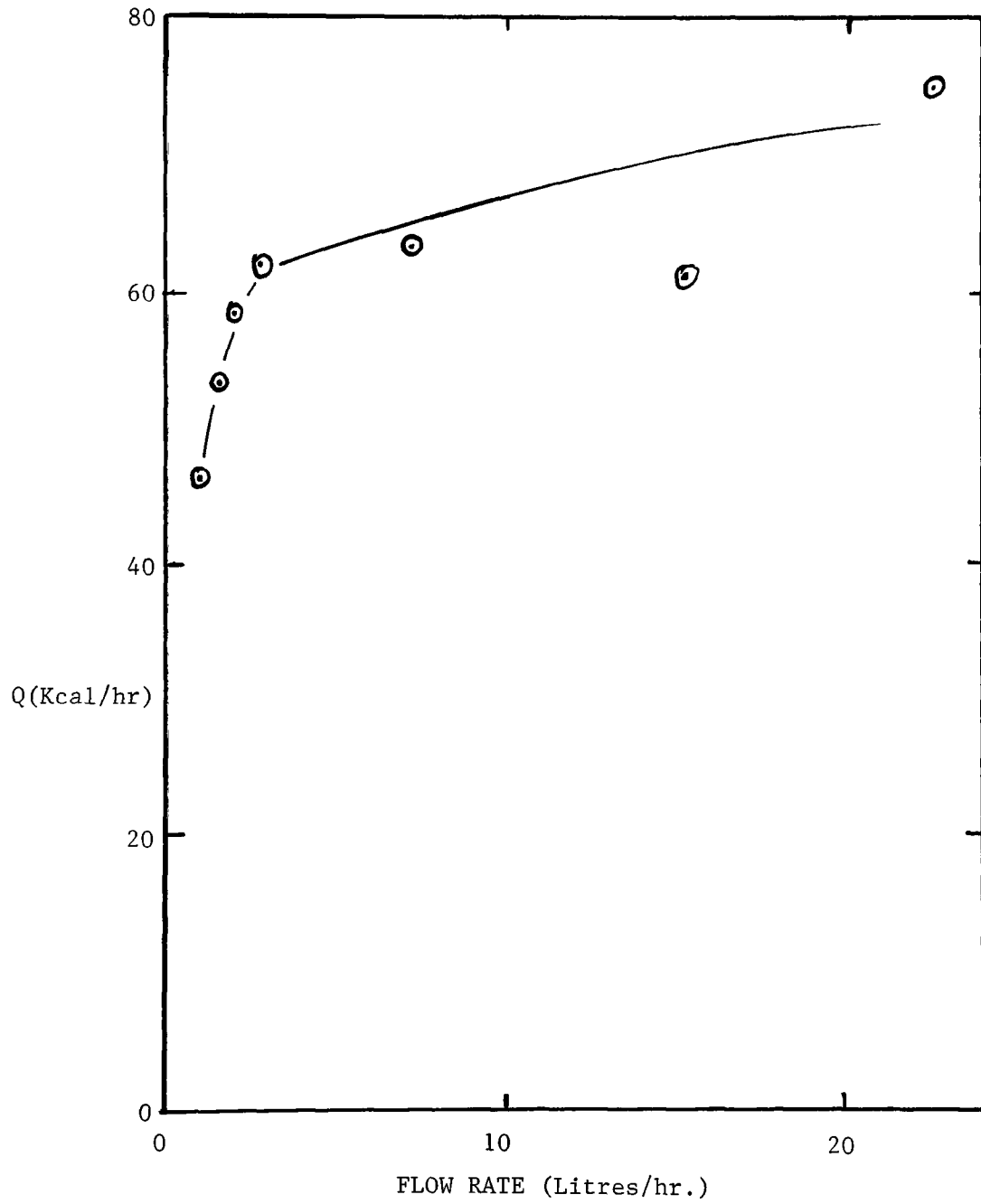


Figure A-14: The effect of flow rate on the heat gain.

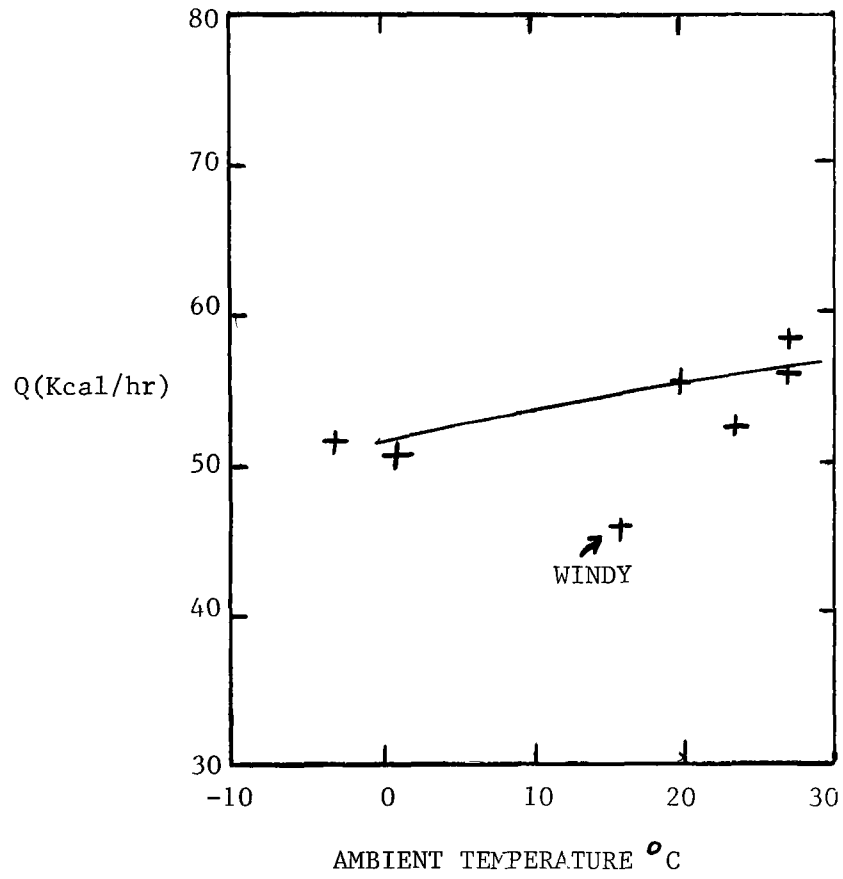


Figure A-15: The effects of wind and ambient temperature on the heat gain.

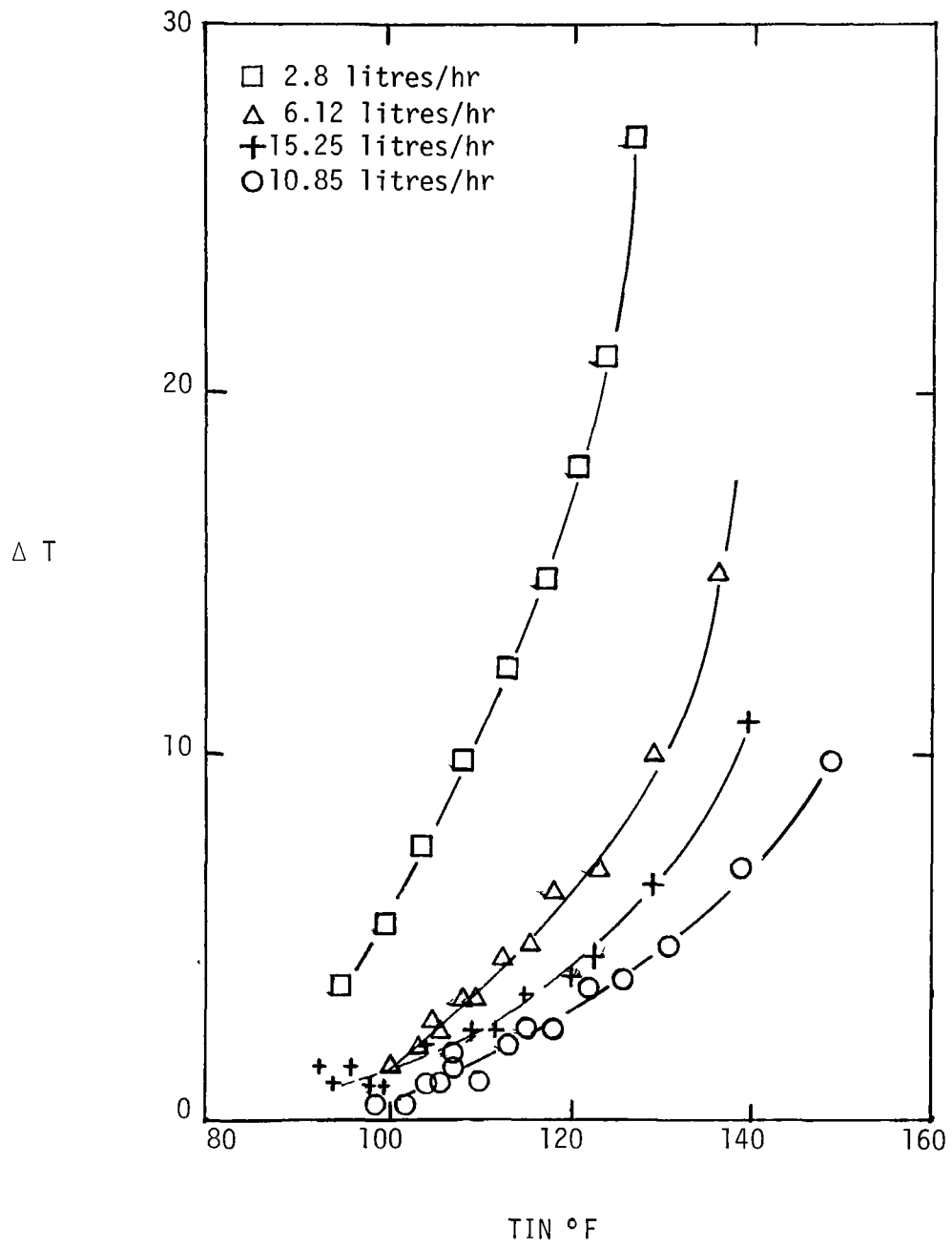


Figure A-16: Heat losses for different flow rates.

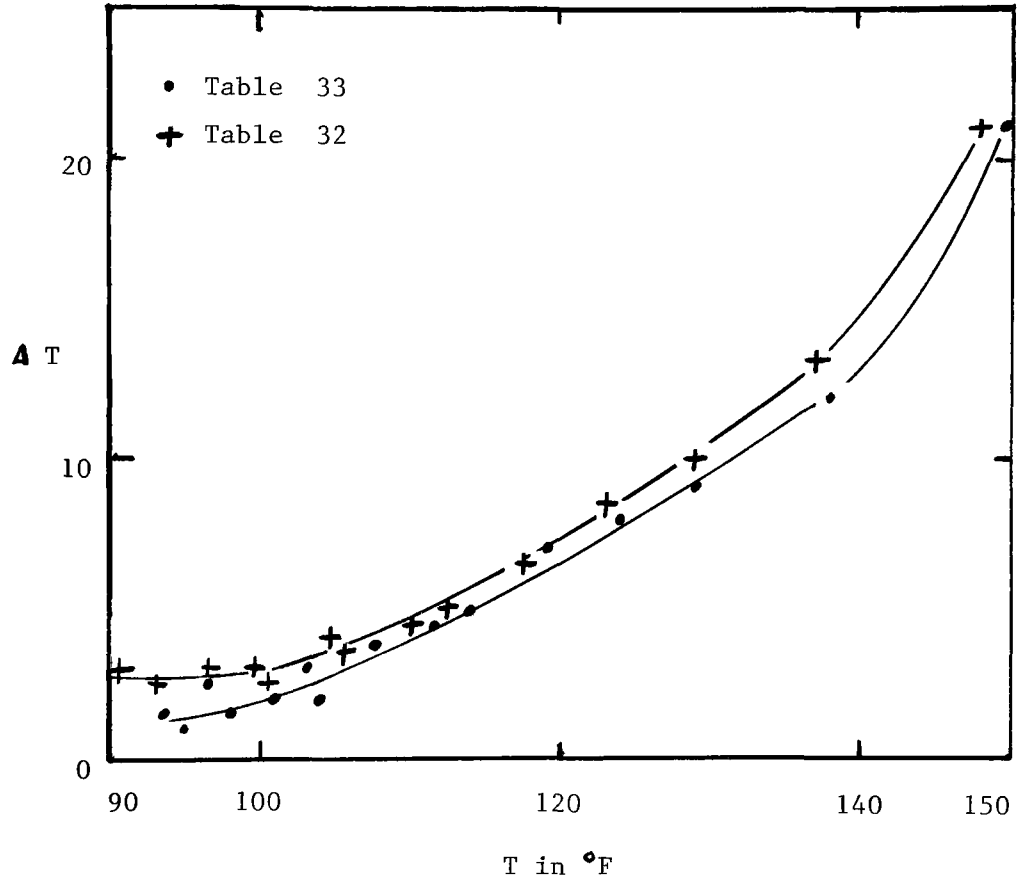


Figure A-17: Reproducibility of heat loss experiments.

APPENDIX - B

Table 1

Time of Day	Solar flux W/m ²
11:00	873
11:10	897
11:20	928
11:30	950
11:40	967
11:50	984
12:00	994
12:10	996
12:20	997
12:30	1001
12:40	994
12:50	982
1:00	967
1:10	950
1:20	933
1:30	899
2:00	899
2:30	899
2:40	873
2:50	819
3:00	797
3:10	751
3:20	729
3:30	695
3:40	661

Table 2

Date: 2/August/77

Flow Rate: 0.94 litres/hr

T ambient: 26° C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	102	98	4	2.09
5	159.5	98	61.5	32.1
10	170	98	72	37.6
20	180	98.5	81.5	42.6
30	187	99	88	46.0
40	191	100	91	47.5
50	196	103	93	48.6
60	182	101	87	42.3
70	199	109	90	47.0
80	204	114	90	47.0
90	188	110	78	40.7
100	204	113.5	90.5	47.3
108	207	116	91	47.5
120	212	121	91	47.5

Q avg. (excluding start up): 46.14 K cal/hr

Weather Conditions: Mostly sunny. Slight breeze
 5 min cloud cover at 50 min
 and at 90 min
 cloudy at 108 min

Table 3

Date: 28/July/77

Flow Rate: 0.94 litres/hr

T ambient: 27°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (OF)	Q (K cal/hr)
0	94	91	3	1.57
10	158	96	62	32.4
20	146	90	56	29.2
30	148	92	56	29.2
40	161	92	69	36.0
50	158	92	66	34.5
60	175	92.5	82.5	43.1
70	156	93	63	32.9
80	166	95	71	37.1
90	192	101	91	47.5
100	178	99	79	41.3
110	180	103	77	40.2
120	149	98	51	26.63

Q avg (excluding start up): 39.08 K cal/hr

Weather Conditions: Cloudy periods after 10 minutes.

Windy

Table 4

Date: 9/August/77

Flow Rate: 1.611 litres/hr

T ambient: 26.5°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (OF)	Q (k cal/hr)
Run #1				
0	89	89	0	0
5	134	93	41	36.70
10	140	94	46	41.2
20	147	93	54	48.3
30	152	95	57	51.0
40	160	100	60	53.7
50	164	104	60	53.7
55	165	105	60	53.7
60	169	107.5	61.5	55.0
Run #2				
0	89	89	0	0
5	143	92.5	50.5	45.2
10	154	97.5	56.5	50.6
20	161.5	100.5	61.5	54.6
30	169	110	59.0	52.8
40	170	112	58.0	51.9
50	178	118.5	59.5	53.3
60	184.5	125.5	59.0	52.8
70	185	127	58.0	51.9

Continued

Table 4 Continued

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
80	188	130	58.0	51.9
90	188	130	58.0	51.9
100	188	131.5	56.5	50.6
110	193	138	55.0	49.2
120	198	141	57.0	51.0
130	196	139	57.0	51.0

Q avg (excluding start up): Run #1: 53.42 K cal/hr

Run #2: 51.66 K cal/hr

Weather conditions:

Sunny. Some Haze in Run #2

After 60 min

Table 5

Date: 3/March/77

Flow Rate: 2.069

T ambient: -3°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
5	100	55.5	44.5	41.2
7	103	56	47	54.0
10	103	58	45	51.7
15	105	61	44	50.6
20	108.5	63	45.5	52.3
25	112	68.5	43.5	50.0
30	113	70	43	49.4
40	123	75.5	47.5	54.6
50	129.5	85	44.5	51.2
55	132	87	45	51.7
60	131	89	42	48.3
70	133	97.5	35.5	40.8
80	138	105	33	37.9
85	142	104	38	43.7
90	145	105	40	46.0
100	147.5	110	37.5	43.1
110	150	117.5	32.5	37.4
116	158.5	122	36.5	42.0
140	160	122	38.0	43.7

Q avg. (excludes start up): 51.53 K cal/hr)

Weather Conditions: Slight Breeze. Cloudy from 60 to 75 min

Table 6

Date: 25/March/77

Flow Rate: 2.069 litres/hr

T ambient: 1°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q K cal/hr)
0	67	49	18	20.7
7	104	60	44	50.6
12	110	66	44	50.6
18	113	70	43	49.4
30	125	80	45	51.7
36	128	84	44	50.6
42	131	87	44	50.6
50	137	95	42	48.3
60	142.5	98	44.5	51.2
72	148	107	41	47.1
88	155	116	39	44.8
100	161.5	121.5	40	46.0
105	163.5	124	39.5	45.4
110	166	126	40	46.0
120	170	132	38	43.7
125	175	136	39	44.8
135	177.5	139.5	38	43.7
141	181	140.5	40.5	46.6
148	190	150	40	46.0
160	196	157	39	44.8

Continued

Table 6 Continued

Time (min)	Tout (° F)	Tin (° F)	ΔT (° F)	Q (K cal/hr)
167	198	159.5	38.5	44.3
170	199	160	39	44.8
180	203	161	42	48.3

Q avg. (excluding start up): 50.48 K cal/hr

Weather Conditions: Sunny. Slight fogging of lenses
after 60 min. Three fogged lenses
after 120 min.

Table 7

Date: 3/May/77

Flow Rate: 2.069 litres/hr

T ambient: 16°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	70	65	5	5.75
3	103	69	34	39.1
7	107	70	37	42.5
12	109	71	38	43.7
16	112	74	38	43.7
20	116.5	78.5	38	43.7
25	120	80.5	39.5	45.4
30	124	86	38	43.7
35	128.5	92	36.5	42.0
40	132.5	94	38.5	44.3
50	140	102	38	43.7
60	150	111	39	44.8
70	157	117	40	46.0
80	161	122	39	44.8
90	169	128	41	47.1
100	174	133	41	47.1
110	178.5	140	38.5	44.3
120	193	152	41	47.1
130	199	154.5	44.5	51.2
140	204	163	41	47.1
147	207	165	42	48.3

Table 7 Continued

Q avg (excluding start up): 45.66 K cal/hr

Weather Conditions: Slight breeze, Sunny.

Table 8

Date: 29/May/77

Flow Rate: 2.069 litres/hr

T ambient: 20°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	73	69	4.0	4.6
10	81	73.5	4.5	8.62
20	131	85	46	52.9
30	140	93	47	54.0
40	149	102	47	54.0
50	153	102	51	58.6

Q avg. (excluding start up): 55.53 K cal/hr

Weather conditions: Strong breeze, Sunny

Table 9

Date: 13/May/77

Flow Rate: 2.069 litres/hr

T ambient: 23.5°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
5	107.5	68	39.5	45.4
10	102	69	33.0	37.9
20	121	71	50	57.5
30	131.5	85	46.5	53.5
40	140	94	46	52.9
50	149	104	45	51.7
60	154	111	43	49.4
75	164	120	44	50.6
90	174	130	44	50.6
100	182	137.5	44.5	51.2
110	186	141.5	44.5	51.2
120	196	149.5	46.5	53.5
130	198	152	46	52.5
142	207	155	52	59.8

Q avg. (excluding start up): 52.48 Kcal/hr

Weather conditions: Light breeze, slight haze

Table 10

Date: 16/May/77

Flow Rate: 2.069 litres/hr

T ambient: 27°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	76	65	11	12.6
10	118	71.5	46.5	53.5
20	122.5	77	45.5	52.3
30	132	80.5	51.5	59.2
40	139	85	54	62.1
50	142	91	51	58.6
60	146	94.5	51.5	59.2
70	147.5	100	47.5	54.6
80	152	103.5	48.5	55.8
90	153	108	45	51.7
100	161	112	49	56.3
110	165	117	48	55.2
120	167	120	47	54.0

Q avg. (excluding start up): 56.67 Kcal/hr

Weather Conditions: Windy, Sunny

Table 11

Date: 26/May/77

Flow Rate: 2.069 litres/hr

T ambient: 27°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	78	70	8	9.2
10	128	70	58	66.7
20	136	72	64	73.6
30	148	76	72	82.8
40	135	80	55	63.2
50	141	88	53	60.9
60	146	97	49	56.3
70	157	104	50	57.5
80	158	110	58	55.2
90	163	113.5	49.5	56.9
100	163	116.5	46.3	53.2
110	170	121.5	48.5	55.8
120	172	126	46	52.9
130	174	128	46	52.9
140	176	132	44	50.6

Q avg. (excluding start up): 58.33 K cal/hr

Weather conditions:

Sunny, light breeze

Cloud from 30 to 40 min

Slight haze 90 to 110 min

Table 12

Date: July/77

Flow Rate: 2.724 litre/hr

T ambient: 23.5°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	77	77	0	0
5	119	84.5	34.5	52.2
15	125	87.5	37.5	56.8
30	134	94	40	60.5
45	138	100	38	57.5
60	149	108	41	62.1
75	156	115	41	62.1
90	161	120	41	62.1
105	164	123	41	62.1
120	168	127	41	62.1
135	173	133	40	60.5
150	176	135	41	62.1

Q avg. (excluding start up): 61.23 K cal/hr

Weather conditions: Windy, cloudy

Table 13

Date: 11/July/77

Flow rate: 2.724 litre/hr

T ambient: 26°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	89	77	5	7.57
10	100	87	13	19.7
20	107	91	16	24.2
30	113	96	17	25.7
45	130	105	25	37.8
60	126	108	18	25.2

Q avg. (excluding start up): 28.73 K cal/hr

Weather conditions: Overcast

Table 14

Date: 15/June/77

Flow Rate: 2.724 litre/hr

T ambient: 26.3°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	87	83	4	6.05
5	124	88	36	54.5
15	133	92	41	62.1
30	143	101	42	63.6
45	153	112	41	62.1
60	161	120	41	62.1
75	167	126.5	40.5	61.3
90	174	134	40.0	60.5

Q avg. (excluding start up): 61.92 K cal/hr

Weather conditions: Sunny

Table 15

Date: 13/June/77

Flow Rate: 2.724 litres/hr

T ambient: 27.5°C

or 81.5 F

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	96	90	6	9.08
5	126	92	34	51.5
15	134	96.5	37.5	56.8
25	142	103.5	38.5	58.3
45	149	113	36	54.5
60	158	120	38	57.5
75	165	125.5	39.5	59.8
90	173	134.5	38.5	58.3
105	177	138	39	59.0
120	184	147	37	56
135	186	150	36	54.5
150	193.5	154	39.5	59.8
160	193	156	37	56

Q avg. (excluding start up): 57.37 K cal/hr

Weather conditions: Slight haze after 20 min

Table 16

Date: 14/July/77

Flow Rate: 2.724 litre/hr

T ambient: 27.5°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	90	89	1	1.51
10	129	95	34	51.5
20	136	101	35	53
30	143	102	41	62.1
45	152	116	36	54.5
60	159	122	37	56.6
75	166	129	37	56
90	174	136	38	57.5
105	181	143	38	57.5
120	186	147	39	59
135	191	151	40	60.5
150	193	156	37	56
165	195	161	34	51.5
180	197	159	38	57.5
195	198	163	35	53
210	198	163	35	53

Q avg. (excluding start up): 56.47 K cal/hr

Weather conditions: Haze in sky

Table 17

Date: 28/June/77

Flow Rate: 2.724 litre/hr

T ambient: 30°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	103	95	1	12.11
5	134	92	42	63.6
15	145	94	51	77.2
30	152	96.5	55.5	84
45	157	101.5	55.5	87
60	156	110	46	69.6
75	160	117	43	65.1
90	162	120	42	63.6
105	164	125	39	59
120	164	130	34	51.5
135	160	130	30	45.4
150	161	131	30	45.4
165	164	131	33	49.9
180	164	134	30	45.4

Q avg. (excluding start up): 66.10 K cal/hr (irregular)

Weather conditions: Sunny with cloudy periods for first 100 min

Cloudy after first 100 min

Table 18

Date: 18/July/77

Flow Rate: 7.2 litres/hr

T. ambient: 29°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	91	93	0.2	---
10	117	102	15	60
20	126	112	14	56
30	134	119	15	60
40	143	128	15	60
50	149	134	15	60
60	154	139	15	60
70	159	143	16	64
80	163	148	15	60
90	166	151	15	60
100	167	151	16	64
110	170.5	154.5	16	64
120	174	157	17	68
130	180	164	16	64
140	179	162	17	68
150	182	166.5	15.5	62
160	184	168	16	64
165	188	172	16	64
170	184	168	16	64
180	187	170	17	68

Q avg. (excluding start up): 63.19 K cal/hr

Weather conditions: Windy after 120 min, sunny

Table 19

Date: 5/Oct./77

Flow Rate: 15.25 litres/hr

T ambient: 18°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	90	76	14	118.6
5	93	80	13	110.1
10	97	84	13	110.1
15	100	87.5	12.5	105.9
20	102	89.5	12.5	105.9
25	104	94	10	84.7
30	101	94	7	59.3
35	97	92	5	42.4
40	94	90.5	3.5	29.7
45	92	88	4	33.9
50	91	89	2	16.9
55	90	87	3	25.4
60	90	87	3	25.4
65	91.5	87.5	4	33.9
70	89	86.5	2.5	21.2

Cooling

75	91.5	86.5	5.0	42.4
80	97	88.5	8.5	72.0
85	94	88.5	5.5	76.6
90	93.5	88.5	5	42.4
95	95	89.5	5.5	46.6

continued

Table 19 Continued

Time (min)	Tout (F)	Tin (F)	T (F)	Q (K cal/hr)
100	100	91	9	76.3
105	98	93	5	42.4
110	96.5	92.5	4	33.9

Q avg. (excluding start up) : Irregular

Weather Condition: Overcast after 25 min.

Table 20

Date: 19/July/77

Flow Rate: 15.256 litres/hr.

T ambient: 36.5°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	83	81	2	16.9
10	111	104	7	59.1
20	119	112.5	6.5	54.9
30	127	120	7	59.1
40	132.5	126	6.5	54.9
50	139	132	7	59.1
60	141	134	7	59.1
70	147	139	8	67.6
80	152	145	7	59.1
90	156	149	7	59.1
100	160	152	8	67.6
110	159	152	7	59.1
120	161	154	7	59.1
123	159	152	7	59.1
130	164	157	7	59.1
140	163	156	7	59.1
150	166	158.5	7.5	63.3
160	168	161	7	59.1
170	167	160	7	59.1
180	171	164	7	59.1

Q avg. (excluding start up): 60.10 (windy), Low Windy, sunny

Weather Conditions: Very windy after 100 min

Table 21

Date: 27/July/77

Flow Rate: 22.5

T ambient: 27°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	74	79	0	0
10	105.5	100	5.5	68.8
20	116	110.5	5.5	68.8
30	124	118	6	75
40	129.5	123.5	6	75
50	136	130	6	75
60	140	134.5	5.5	68.8
70	142.5	137	5.5	68.8
90	149	142	7	87.5
100	153.5	147.5	6	75
120	158	154	4	50
130	144	142.5	1.5	18.75

Q avg. (excluding start up): 75.02 K cal/hr.

Weather Conditions: Sunny, Windy after 50 min

Cloudy after 90 min

Table 22

Date: 22/July/77

Flow Rate: 22.5 litres/hr

T ambient: 28°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	89	89	0	0
10	105	102	3	37.5
20	119.5	115	4.5	56.3
30	123	117.5	5.5	68.8
40	126	120.5	5.5	68.8
50	130	124.5	5.5	68.8
60	130	126	4	50
70	141	135.5	5.5	68.8
80	147	141.5	5.5	68.8
90	149.5	142	7.5	93.8
100	158	151	7	87.5
110	154.5	149.5	5	62.5
120	164	157.5	6.5	81.3
130	170.5	164	6.5	81.3
140	170	164	6	75
150	172.5	168	4.5	56.3
160	166	161.5	4.5	56.3
170	176	170	6	75
180	179.5	173	6.5	81.3

Q avg. (excluding start up): 71.52 K cal/hr

Weather Conditions: Sunny with cloudy periods

Table 23

Date: 20/July/77

Flow Rate: 22.5 litres/hr

T ambient: 33°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	Q (K cal/hr)
0	92	92.5	0.5	---
10	110	107	3	37.5
20	119.5	116	3.5	43.8
30	125	121	4	50
40	127	123.5	3.5	43.8
50	133.5	128.5	5	62.5
60	136.5	132	4.5	56.3
70	139.5	134.5	5	62.5
80	142	137	5	62.5
90	147	142	5	62.5
100	146	140	6	75
110	143	139	4	50

Q avg. (excluding start up): 58.34 (K cal/hr)

Weather Conditions: Windy with some haze

Table 24

Flow Rate litres/hr	T ambient °C	Q avg. K cal/hr.
0.94	26	46.14*
0.94	27	39.08
1.611	26.5	53.42*
1.611	26.5	51.66
2.069	-3°C	51.53+
2.069	1°C	50.48
2.069	16°C	45.66
2.069	20	55.53
2.069	23.5	52.48
2.069	27	56.67
2.069	27	58.33*
2.724	23.5°C	61.23*
2.724	26.0°C	28.73
2.724	26.3	61.92*
2.724	27.5	57.37
2.724	27.5	56.47
2.724	30	transient
7.2	29°C	63.19*
15.25	18°C	overcast & transient
7.2	29°C	63.19*
15.25	18°C	overcast & transient

continued

Table 24 Continued

Flow Rate litres/hr	T ambient °C	Q avg. K cal/hr.
15.25	36.5°C	60.10 windy
22.5	27°C	75.02*
22.5	28°C	71.52
22.5	33°C	58.34

+ poor insulation on hoses

* clear sunny days with very low wind velocity

Table 25

5th October 77 Outside

Flow Rate: 15.24 litres/hr

T ambient: 18°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	Δ (LMTD)/min
0	96.5	92.5	-4	30.06	0.398
5	94	91	-3	28.07	0.194
10	92	91	-1	27.10	0.302
15	91	89	-2	25.59	0.100
20	90.5	88.5	-2	25.09	0.050
25	90	88.5	-1.5	24.84	0.448
30	87.5	86.5	-1	22.60	0.348
35	86	84.5	-1.5	20.84	0.052
40	86	84	-2	20.58	0.096
45	85	84	-1	20.10	0.100
50	85	83	-2	19.60	0.152
55	85	83	-1.5	18.84	-0.064
60	84	83	-1	19.16	

Table 26

Flow Rate: 2.2 litres/hr.

T ambient: 26°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	Δ (LMTD)/min
0	100	130.5	30.5	34.21	-0.468
5	103.5	130.5	27	36.55	0.174
10	105	126	21	35.68	0.414
15	104	122.5	18.5	33.61	0.342
20	104	118.5	14.5	31.90	0.45
25	102	116	14	29.65	0.42
30	101	112.5	11.5	27.55	0.246
35	100	111	11	26.32	0.38
40	99	108	9	24.42	0.29
45	98	106	8	22.97	0.136
50	98	104.5	6.5	22.29	0.448
55	96	102	6	20.05	0.146
60	95.5	101	5.5	19.32	0.146
65	95	100	5	18.59	0.146
70	94.5	99	4.5	17.86	0.148
75	94	98	4	17.12	0.146
80	93.5	97	3.5	16.39	0.148
85	93	96	3	15.65	0.146
90	92.5	95	2.5	14.92	0
95	92.5	95	2.5	14.92	0.248
100	91.5	93.5	2	13.68	0.102
105	91	93	2	13.17	0

Table 26 continued

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	Δ (LMTD)/min
110	91	93	2	13.17	0.15
115	90.5	92	1.5	12.42	0.05
120	90	92	2	12.17	

Table 27

Flow Rate: 2.8 litres/hr

T ambient: 23°C

Time	Tout	Tin	ΔT	LMTD	Δ (LMTD)/min
0	98	129	31	28.02	-0.15
5	101	126	25	38.77	1.44
10	96	116	20	31.55	-0.202
15	99	115	16	32.96	0.218
20	99	112.5	13.5	31.87	0.334
25	98	110	12	30.20	0.492
30	96	107	11	27.74	0.292
35	95	105	10	26.28	0.334
40	94	102.5	8.5	24.61	0.292
45	93	100.5	7.5	23.15	0.192
50	92.5	99	6.5	22.19	0.238
55	92	97	5	21	0.2
60	91	96	5	20	0.047
70	91	95	4	19.53	0.255
80	88	93	5	16.98	0.093
90	88	91	3	16.05	0.147
100	87	89	2	14.58	0.127
110	85.5	88	2.5	13.31	0.122
120	85	86	1	12.09	

Table 28

Flow Rate: 2.8 litres/hr

T ambient: 24°C

Time	T _{out}	T _{in}	ΔT	LMTD	Δ (LMTD)/min
0	99	124	25	34.82	-0.368
5	100	127	27	36.66	-0.132
10	103	124	21	37.32	0.254
15	103	121	18	36.05	0.460
20	102	117	15	33.75	0.524
25	100.5	113	12.5	31.13	0.290
30	99.5	111	11.5	39.68	0.436
35	98	108	10	27.50	0.292
40	97	106	9	26.04	0.236
45	96.5	104	7.5	24.86	0.438
50	95	101	6	22.67	0.146
55	94.5	100	5.5	21.94	0.248
60	93.5	98.5	5	20.70	0.394
65	92	96	4	18.73	0.048
70	92	95.5	3.5	18.49	0.154
75	91	95	4	17.72	0.246
80	90	93.5	3.5	16.49	0.048
85	90	93	3	16.25	0.200
90	89	92	3	15.25	0.047
100	89	91	2	14.78	0.100
105	88.5	90.5	2	14.28	0.550
110	86	87.5	1.5	11.53	

Table 29

Flow Rate: 5.46 litres/hr

T ambient: 23°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	$\Delta(LMTD/min)$
0	117	143	26	55.59	0.814
5	116	135	19	51.52	1.054
10	113	127	14	46.25	0.786
15	110	122	12	42.32	0.624
20	108.5	117	8.5	39.20	0.750
25	105	113	8	35.45	0.596
30	102.5	109.5	7	32.47	0.494
35	100.5	106.5	6	30.00	0.456
40	98	104.5	6.5	27.72	0.234
45	98	102	4	26.55	0.344
50	97	99.5	2.5	24.83	0.452
55	94.5	97.5	3	22.57	0.302
60	93	96	3	21.06	0.174
70	91.5	94	2.5	19.32	0.302
80	90	90	0	16.30*	0.070
90	89	89	0	15.60*	0.125
100	87.5	88	0.5	14.35	0.175
110	86	86	0	12.60*	0.20
120	84	84	0	10.60*	

*Temp difference between system and ambient

Table 30

Flow Rate: 6.12 litres/hr

T ambient: 27.7°C

Time (min)	Tout °F	Tin °F	ΔT °F	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	121	136	15	46.24	0.860
5	119	129	10	41.94	0.882
10	116	123	7	37.53	0.850
15	112	118.3	6.3	33.28	0.442
20	110.5	115.5	5	31.07	0.548
25	108	112.5	4.5	28.33	0.396
30	106.5	110	3.5	26.35	0.300
35	105	108.5	3.5	24.85	0.296
40	104	106.5	2.5	23.37	0.354
45	102	105	3	21.60	0.296
50	101	103	2	20.12	0.300
55	99.5	101.5	2	18.62	0.248
60	98.5	100	1.5	17.38	0.500
65	98	99.5	1.5	16.88	0.200
70	97	98.5	1.5	15.88	0.150
75	96.5	97.5	1	15.13	0.200
80	95.5	96.5	1	14.13	0.200
85	94.5	95.5	1	13.13	0.102
90	94	95	1	12.62	0
95	94	95	1	12.62	0.198
100	93	94	1	11.63	0
105	93	94	1	11.63	

Table 31

Flow Rate: 8.75 litres/hr

T ambient: 23°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	129	147	18	64.18	1.75
5	124	134	10	55.45	1.286
10	119	126	7	49.02	0.898
15	115	121	6	44.53	0.506
20	112	119	7	42.00	0.840
25	109	113.5	4.5	37.80	0.696
30	106	109.5	3.5	34.32	0.600
35	103	106.5	3.5	31.32	0.498
40	101	103.5	2.5	38.83	0.448
45	99	101	2	26.59	0.200
50	98	100	2	25.59	0.35
55	96.5	98	1.5	23.84	0.2
60	95.5	97	1.5	22.84	0.174
70	94	95	1	21.10	0.200
80	92	93	1	19.10	0.150
90	91	91	0	17.6*	

* Temp difference between system and ambient

Table 32

Flow Rate: 8.82 litres/hr

T ambient: 23°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	127	148	21	63.52	1.226
5	125	137	12	57.39	1.392
10	119	129	10	50.43	1.042
15	114.5	123	8.5	45.22	0.892
20	111	117.5	6.5	40.76	0.844
25	107.5	112.5	5	36.54	0.448
30	105.5	110	4.5	34.30	0.746
35	102.5	105.5	3.5	30.57	0.404
40	100	104	4	28.55	0.444
45	98.5	101	2.5	46.33	0.452
50	96	99	3	24.07	0.400
55	94	97	3	22.07	0.354
60	92	95.5	3.5	20.30	0.024
70	92	95	3	20.06	0.124
80	91	93.5	2.5	18.82	0.277
90	88	91	3	16.05	

Table 33

Flow Rate: 8.82 litres/hr

T ambient: 23°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	130	151	21	66.55	1.632
5	126	138	12	58.39	1.484
10	120	129	9	50.97	0.896
15	116	124	8	46.49	0.898
20	112	119	7	42.00	0.792
25	109	114	5	38.04	0.448
30	107	111.5	4.5	35.80	0.748
35	103.5	107.5	4	32.06	0.494
40	102	104	2	29.59	0.304
45	100	103	3	28.07	0.296
50	99	101	2	26.59	0.550
55	96.5	98	1.5	23.84	0.402
60	94	96.5	2.5	21.83	0.073
70	94	95	1	21.10	0.176
80	92	93.5	1.5	19.34	

Table 34

Flow Rate: 10.895 litres/hr

T. ambient: 28°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	Δ(LMTD)/min
0	138	148	10	60.46	1.688
5	131	138	7	52.02	1.194
10	126	131	5	46.05	0.896
15	122	126	4	41.57	0.802
20	118	122	4	37.56	0.546
25	116	118.5	2.5	34.83	0.600
30	113	115.5	2.5	31.83	0.348
35	111.5	113.5	2	30.09	0.598
40	109	110	1	27.10	0.652
45	105.5	107	1.5	23.84	0.048
50	105.5	106.5	1	23.60	0.102
55	105	106	1	23.09	0.300
60	103.5	104.5	1	21.59	0.198
65	103	103	0	20.6	0.25
70	101.5	102	0.5	19.35	0.352
75	99.5	100.5	1	17.59	0.074
85	99	99.5	0.5	16.85	0.25
90	98	98	0	15.60*	

*Temp diff between system and ambient

Table 35

Flow Rate: 12.00 litres/hr

T ambient: 24 C

Time (min)	Tout (F)	Tin (F)	ΔT (F)	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	135	150	15	67.02	1.872
5	128	138	10	57.66	1.688
10	121	128	7	49.22	0.950
15	116.5	123	6.5	44.47	0.844
20	113	118	5	40.25	0.698
25	110	114	4	36.76	0.696
30	107	110	3	33.28	0.552
35	104	107.5	3.5	30.52	0.498
40	102	104.5	2.5	28.03	0.400
45	100	102.5	2.5	26.03	0.348
50	98.5	100.5	2	24.29	0.350
55	97	98.5	1.5	22.54	0.200
60	96	97.5	1.5	21.54	0.200
65	95	96.5	1.5	20.54	0.352
70	93	95	2	18.78	0.148
80	92	93	1	17.30	0.176
90	90	91.5	1.5	15.54	0.100
100	89	90.5	1.5	14.54	

Table 36

Flow Rate: 14.9 litres/hr

T ambient: 26°C

Time	Tout	Tin	ΔT	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	146	156	10	72.08	1.986
5	138	144	6	62.15	1.602
10	130	136	6	54.14	0.994
15	126	130	4	49.17	0.950
20	121.5	125	3.5	44.42	1.614
25	118.5	122	3.5	36.35	-0.368
30	116	118	2	38.19	0.400
35	114	116	2	36.19	0.600
40	111	113	2	33.19	0.349
50	108	109	1	29.70	0.400
55	106	107	1	27.70	0.252
60	104.5	106	1.5	26.44	0.248
65	103.5	104.5	1	25.20	0.200
70	102.5	103.5	1	24.20	0.300
75	101	102	1	22.70	0.200
80	100	101	1	21.70	0.200
85	99	100	1	20.70	0.150
90	98.5	99	0.5	19.95	0.150
95	98	98	0	19.20*	0.15
100	97	97.5	0.5	18.45	0.100
105	96.5	97	0.5	17.95	

*Temp diff between system and ambient

Table 37

Flow Rate: 15.25 litres/hr

T ambient: 24°C

Time	Tout	Tin	ΔT	LMTD	$\Delta(\text{LMTD})/\text{min}$
0	142	158	16	74.51	3.076
5	129	140	11	59.13	1.730
10	122.5	129	6.5	50.48	0.994
15	118.5	123	4.5	45.51	0.548
20	116	120	4	42.77	0.950
25	111.5	115	3.5	38.02	0.598
30	109	111.5	2.5	35.03	0.500
35	106.5	109	2.5	32.53	0.500
40	104	106.5	2.5	30.03	0.448
45	102	104	2	27.79	0.400
50	100	102	2	25.79	0.398
55	98.5	99.5	1	23.80	0.302
60	97	98	1	22.29	0.225
70	94.5	96	1.5	20.04	0.175
80	93	94	1	18.29	0.175
90	91	92.5	1.5	16.54	

Table 38

Flow Rate: 15.25 litres/hr

T ambient: 24°C

Time (min)	Tout (°F)	Tin (°F)	ΔT (°F)	LMTD	Δ(LMTD)/min
0	138	152	14	69.57	2.172
5	130	138	8	58.71	1.498
10	123	130	4	51.22	1.246
15	117.5	123	5.5	44.99	1.148
20	112	117	5	39.25	0.594
25	110	113	3	36.28	0.600
30	107	110	3	33.28	0.550
35	104.5	107	2.5	30.53	0.452
40	102	105	3	28.27	0.496
45	100	102	2	25.79	0.350
50	98.5	100	1.5	24.04	0.302
55	96.5	99	2.5	22.53	0.350
60	95	97	2.0	20.78	0.149
70	94	95	1.0	19.29	0.200
80	92	93	1.0	17.29	0.200
90	90	91	1.0	15.29	0.151
100	88	90	2.0	13.78	0.074
110	87.5	89	1.5	13.04	