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Carl Matthew Lampert
(M. S. thesis)

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by

Carl Matthew Lampert

Master of Science
Thesis
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DESIGN OF A SOLAR TEST COLLECTOR FOR EVALUATION OF SELECTIVE ABSORBERS

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ABSTRACT

A solar test collector was designed for the testing of thermally absorbing coatings under controlled conditions. The design consists of a collector fed by a controlled temperature fluid within the range of 25-90°C (77-194°F). This temperature is maintained by a custom electronic controller. A small variable flow pump circulates water through three collector pipes at selected flow rates. Strip heaters coupled with a differential temperature controller compensate for edge losses associated with small collectors. Detailed design and operation data are presented.

Spectral reflectance measurements are shown for many candidate black chrome/metal selective surfaces and are compared to a non-selective black painted absorber. The effects of black chrome layer thickness and substrate roughness are discussed. Of these surfaces four representative absorbers are analyzed in detail by test collector measurements. Efficiencies as high as 77% and 75% ($\Delta T = 0$) were obtained respectively for 1.0 $\mu$m black chrome on copper and nickel plated steel.
The highest \((a_l/e_l, 20^\circ C)\) ratio measurements were 20.3 and 18.5 for 0.7 \(\mu m\) black chrome on nickel plated polished steel and 1.0 \(\mu m\) black chrome on copper. The lowest loss coefficients were about 3.8 W/m\(^{\circ C}\) for all black chrome/metal surfaces with the highest being 8.4 W/m\(^{\circ C}\) for the black paint/metal sample. A collector model is presented which predicts these calculated loss coefficients within good agreement.
I. INTRODUCTION

A. Background

All sectors of society, both public and private, have become aware of a worldwide energy crisis. Currently, the world's energy is derived primarily from fossil fuel which is limited in supply for numerous reasons. We need to develop alternative long-term sources of energy to maintain and increase the standard of living for the whole world. There are many alternatives to a fossil fuel economy including the uses of solar energy (both thermal and electrical), wind power, geothermal, ocean thermal, and nuclear (including both fission and fusion). Some of these alternative sources of energy have serious drawbacks: wind and geothermal are limited to certain geographical locations; nuclear fission plants have serious ecological drawbacks such as safe and permanent radioactive waste disposal. Development of other nuclear schemes such as fusion and fast breeder fission reactors requires solution of many difficult problems.

One of the most reasonable and economical sources is solar energy—the energy which permits life to exist upon earth. Its usage appears to be the most promising alternative source of energy from the standpoint of abundance, availability, and non-polluting characteristics. The utilization of solar energy for the production of hot water, steam, and electricity is a viable way to lessen our fossil fuel dependence for both domestic and commercial needs. However, if we wish to reduce our dependence to a minimum, many types of alternate energies combined
with conservation and improved operating efficiencies for all energy using equipment must be employed to fill the tremendous need for energy, which no one source can satisfy.

The most immediate and practical application of solar energy with our current technology, appears to be that of heating air and fluids. Inevitably, solar energy will be used for large scale production of electricity, possibly by thermal means. To utilize solar energy for these purposes it must be collected first as heat and be transferred to a working fluid. To collect energy in a highly efficient and economical manner new energy absorbing materials for use in solar collectors have to be designed and evaluated. This need creates a challenge to the materials scientist to understand and design such absorbing surfaces.

B. Nature of the Problem

There are many economical prime candidates for collector coatings. These candidates fall into two categories: selective and non-selective types. Selectivity is produced by optical properties which vary greatly from one spectral region to another. A solar selective surface efficiently captures the sun's energy in the high intensity visible and near infrared spectral regions, while exhibiting poor infrared radiating properties. Accordingly, a selective surface will absorb and retain a high amount of energy from the sun while a non-selective surface will lose most of its absorbed energy by radiation. The theory of the selective absorbers will be discussed at length in Section IV.
Currently, the most promising inexpensive selective surfaces are black nickel, black zinc and black chrome. An excellent review is given by Mattox and Kominiak.\textsuperscript{1} The black nickel electroplated surface has been found to be unstable to thermal cycling, particularly due to the interdiffusion of oxygen and sulfur, which resulted in the degradation of optical properties.\textsuperscript{2,3} Also, it has been shown that this coating is subject to degradation in the presence of water vapor.\textsuperscript{4} The black zinc surface is produced by chloride or chromate conversion and only currently has it been investigated.\textsuperscript{5,6} The black chrome surface has been quite successful, but not until recently has it been tested or its properties evaluated. Black chrome surfaces can be prepared from a variety of acetic acid, acid chloride and acid hydroxide electroplating baths. The most popular ones are "Chromonyx",\textsuperscript{7} by Harshaw Chemical Company and "Econo-Chrome BK",\textsuperscript{8} produced by Dupont Chemical Company. Both coatings are resistant to moisture and appear to be environmentally and operationally stable. The Harshaw coating has somewhat better optical properties than that of the Dupont coating.\textsuperscript{9} Also, more is known about the Chromonyx coating as it has been studied in detail by several investigators.\textsuperscript{10-16}

A need existed to build a solar test collector to test different varieties of black chrome surfaces under realistic, repeatable, controlled and well recorded conditions. Another goal was to create many different types of black chrome absorbers while varying such characteristics as surface roughness and substrate type and quality. In this way, optical values of these coatings can be correlated to test collector data.
The design and results of such described surfaces will be presented in the following sections.
II. SOLAR TEST COLLECTOR

A. Concept of Design

The solar test collector was designed so that certain collector parameters could be held constant or controlled and yet different coatings could be tested without the use of extremely elaborate or costly equipment. This design allows different types of selective and non-selective surfaces to be tested and evaluated in terms of collection efficiency under various operating temperatures and flow rates. Results for various Chromonyx coatings will be presented later and compared with those for a black painted surface.

The main components of the collector consist of a body and cover, which houses three absorber pipes; a controlled temperature water bath; and a variable-flow pump.

The collector body is designed to permit easy removal of collector pipes. The body can be set any desired tilt angle with respect to the sun, to suit the season of the year. The collector pipes consist of a metallic material (e.g., copper or steel) coated with a selective or non-selective surface. Of the three parallel pipes, the center pipe is the critically controlled and monitored one. The purpose of the two outside pipes is to restrict the amount of heat lost from the sides of the central pipe. Furthermore, controlled temperature heating strips are placed under the two outside pipes to reduce overall edge losses. In this fashion, a small collector can simulate large collector surroundings along the central pipe. This simulation is achieved by a differential temperature controller which maintains constant
temperatures at all pipe outlets by turning on strip heaters when required. Across the central pipe both inlet and outlet temperatures are recorded with better than one degree accuracy (depending upon calibration).

The collector is fed by a controlled temperature bath which supplies a fluid at a set, adjustable temperature in the range 25 - 90°C (77-194°F). This temperature is maintained by a custom electronic controller. A small variable-flow pump circulates water through three collector pipes according to a specified but adjustable flow rate. The fluid from the collector is passed into a cooling bath and is recirculated to the controlled temperature water bath. Simultaneous measurements are made of solar radiation, ambient temperature, wind direction and velocity. The flow chart for the collector, showing the significant features described, is depicted in Fig. 2.1. Photographs of complete test apparatus are shown in Figs. 2.2, 2.3, and 2.4.

B. Collector Body Design

1. Collector Housing

The collector body consists of a wooden housing filled with shaped and molded insulation in which all collector test pipes are mounted along with valve systems and flowmeter. The collector is covered by a removable vapor proof double-glass cover.

A wooden housing was chosen instead of a metal one because of ease of fabrication, weight and workability of the material, particularly for on-site modifications. The body is constructed so that it supports
Fig. 2.1. Solar Test Collector Flow Chart
Fig. 2.2. Solar Test Collector, Side View.
a mechanically weak polyurethane foam insulation. The insulation is Upjohn type Trymer\textsuperscript{19} CPR 9545 isocyanurate rigid cellular (93\% closed cell content) plastic foam. This foam has the ability to withstand 149°C (300°F) continuously.\textsuperscript{20} Other material characteristics (at room temperature) include a density of 28.8-36.8 kg/m\textsuperscript{2} (1.8-2.3 lbs/ft\textsuperscript{2}) with an insulating K-factor of 0.0216 W/m°C (0.15 BTU/ft\textsuperscript{2}hr °F/in.) and water absorption of 0.0033 kg/m\textsuperscript{2} (0.04 lbs/ft\textsuperscript{2}).\textsuperscript{21} The completed housing is finished by two coats of durable enamel paint. Dow Corning silicone RTV adhesive sealant is used as a caulking material where needed.

2. **Cover System**

The wooden collector cover, consisting of two rectangular glass windows surrounded by a wooden frame and glazed with RTV sealant, provides a secure vapor proof protective covering for the collector pipes. The purpose of the collector cover is to reduce the amount of heat loss from the pipes due to thermal convection. Also, the cover is important for suppression of radiation emitted by the absorber surface. With a selective absorber this amount of radiation is small but not zero because of its finite emittance. The glass windows serve as a barrier for the infrared energy emitted by the absorber, thus acting to trap locally this thermal energy. This effect is due to the optical properties of the glass. The collector cover glass is ASG low iron window glass\textsuperscript{22} (0.24 cm thick). These particular glass plates exhibit an ultraviolet transmission edge at about 0.3 microns with average transmission of 92\% to the cutoff wavelength at about 3 microns in the infrared.\textsuperscript{23} At wavelengths less than 0.3 microns and greater than 3 microns this glass absorbs energy.
Low iron glass is used, because common window glass contains iron oxide impurities which reduce transmission in the infrared and ultraviolet spectral regions.

Incorporated into the collector cover system is a vapor barrier created by a flexible closed cell polyurethane high density spline. Where the cover passes over the three collector pipes a molded gasket attached to a removable wooden plate serves as a seal between the cover and body. The interconnection between the collector and cover can be viewed in Fig. 2.5, which shows a cross sectional view of the entire collector body.

3. Piping System

The piping which feeds and discharges fluid to the three collector pipes is made of solid brass, insulated by polyurethane flexible foam. Fiberglass wool serves as an insulating medium between the flexible polyurethane foam and the rigid foam of the collector body. Strip heaters are placed between the foam insulation and bottom surfaces of the outer collector. These strip heaters are attached to strips of asbestos cloth by RTV silicone adhesive and then fastened to the polyurethane foam by Carboline Neoprene adhesive. The neoprene adhesive is also used to cover the exposed surfaces of the foam insulation to retard abrasion and weathering. The strip heaters are waterproof Briskeat type BS-41 which operate at 115 VAC and 192 Watts. These heaters are cycled on and off independently by a differential temperature controller discussed in Subsection E. The placement of the two strip heaters can be viewed in Fig. 2.5.
Fig. 2.5 Test Collector Body, Cross Section View.

- 3/32" low iron glass
- Resistance heating tape
- Polyurethane foam
- 3/4" plywood
- 3/4" fir
- 8 1/2"
- 15"
- 5"
The collector pipes may be any type material as long as they are approximately 3.8-4.2 cm (1.5-1.66 in.) outside diameter and 1.37 m (4.5 ft) long. The comparison of identical coatings on different substrate (pipe) materials is complicated by differences of thermal conductivity. Examples of different types of pipe materials are mild steel, copper, galvanized steel and aluminum. Also, a flat plate conforming to size specifications and inlet/outlet clearances could be tested in a similar manner as individual pipes. The position of the collector pipes can be seen in Figs. 2.5 and 2.6.

4. Flowmeters

The flowmeter system is designed to permit balanced and regulated flow of fluid through the three collector pipes. The fluid flow through the outer collector pipe is regulated by two matched needle valves. The flow in the center test pipe is monitored and controlled by a low-flow flowmeter/needle valve combination. This flowmeter is a Brooks Model 1515 custom made for 0-49 L/hr, (0-13 g/hr) of water. The accuracy of this type of flowmeter is important due to its bearing upon the final calculation of collector efficiency. The absolute accuracy of the flowmeter is ± 10% (up to 100°C) which could be improved. Due to this limitation the calculated absolute efficiency can vary by at least ± 10%. The reproducible accuracy is ± 0.5% (up to 100°C) of the instantaneous reading. This means that relative measurements of uncertainty of efficiency between different test pipe types will not depend heavily upon the relative accuracy of the flow rate.
Fig. 2.6 Test Collector Body, Top view with cover removed.

- 0-13 GPH insulated flow meter
- Wooden case
- 1.5" - 1.633" OD pipes
- Guard pipe
- Test pipe
- Guard pipe
- Rigid polyurethane foam isocyanurate, rated 300°F
- Thermocouples
- Back pressure valve
- Inlet
- 4'
- 7'
- Outlet
- Drain

XBL-7611-4472
The mass flow rate \( (m) \) is calculated by the use of the following empirical equation for water.\(^{25}\)

\[
\dot{m} \text{ (kg/sec)} = n \left[ .016876808 \exp \left( -.005139049 T \right) \right]
\]

where

\[
n = \text{volumetric flow rate (L/min)}.
\]

The above calculation accounts for changes in fluid density with temperature, a small but significant factor; also, it includes various conversions of units.

5. Collector Pipe Coupling

The mating of a 0.95 cm (0.375 in. i.d.) rigid brass pipe manifold with three threadless 3.8 cm (1.5 in.) o.d. collector pipes initially presented a perplexing problem. This connection design also had to incorporate a thermocouple probe and was to be leakproof, compact, and easy to assemble on site.

The final design of the connector consists of a threaded brass tube which passes through the length of a rubber tapered plug. A nut, washer, and O-ring assembly holds the internal end tight while a union fitting, washer and O-ring assembly provides the outer coupling. A thermocouple probe can be inserted by use of a large hollow needle drawn through the rubber plug. When the needle is withdrawn, the rubber contracts around the thermocouple creating a watertight seal. The thermocouple probe is a Cal-Alloy\(^{28}\) brand copper-constantan ungrounded junction with a stainless steel 0.154 cm (0.060 in.) diameter sheath. Sealing of the collector pipes is achieved by tightening the union fitting
against the rubber plug causing outward expansion of the plug by axial compression. A cross-sectional view of this connector plug and thermocouple is shown in Fig. 2.7. Also, note that the collector pipes are slightly beveled inside to remove burrs.

C. Test Collector Tilting Stand

To orient the collector a stand is needed which has the ability to tilt the collector so it will be perpendicular to the sun's rays at solar noon. The stand is designed for an overall range of 12°-62° tilt angle (with respect to horizontal plane) adjustable in 1° increments. The collector stand is designed for 37.8 degrees north latitude (Berkeley area) where the optimum tilt varies from 12°-62°. The higher angle corresponds to the winter months. For the low angles a smaller set of support platens are used in the collector stand to obtain a greater angular selectivity. The collector tilting stand may be viewed in Figs. 2.2, 2.3, 2.4 supporting the test collector.

The collector tilt angle, among other angles may be calculated by the following relationship:\(^29\)

\[
\cos A = \sin D \sin F \cos B - \sin D \cos F \sin B \cos E \\
+ \cos D \cos F \cos B \\
+ \cos D \sin F \sin B \cos E \cos C \\
+ \cos D \sin B \sin E \sin C
\]

and\(^30\)

\[
D = 23.45 \sin \left(\frac{(284 \pm N)\frac{360}{365}}{365}\right)
\]
Fig. 2.7
Collector Pipe, Connector Plug and Thermocouple, Cross Section View.

3/8" - 1 1/2" Brass pipe nipple

Insulated thermocouple leads

3/8" fitting

Thermocouple probe

No. 7-8 Rubber stopper

7/8-20 nut

Collector pipe

Stainless steel shield

3/8"

1 1/4"

No. 7-8 Rubber stopper

7/8-20 nut

XBL-7611-4469
where

\[ A = \text{Angle between direct beam radiation and normal to the collector plane;} \]
\[ B = \text{Collector tilt angle (slope with horizontal plane);} \]
\[ C = \text{Hour angle (zero to noon, positive in morning, negative in afternoon);} \]
\[ D = \text{Solar declination;} \]
\[ E = \text{Surface Azimuth, direction of collector tilt (South, zero; East, positive; West, negative);} \]
\[ F = \text{Latitude (North, positive; South, negative);} \]
\[ N = \text{Day number (1-366).} \]

D. **Pumping, Heating and Storage Supplies**

1. **Pumping System Design**

   For pumping of collector fluid a Flotec brand electric self priming pump, Model R2Bl-1100 v. is used. It is equipped with a variable displacement cone which can be adjusted at an angle in such a way that the flow through the pump varies. The adjustment of cone angle is simple and can be done while the pump is in operation. In conjunction with a feedback piping system a large range of pumping flow rates can be achieved, 0-22 L/min (0-49 gal/min) in excess of the test pipe flowmeter range. A Blue White Industries, Model F-400, primary flowmeter is used to monitor the total fluid flow into the collector body. The flowmeter has a range from 0-227 L/hr (0-60 gal/hr). The initial flows in all three collector pipes are set by use of the primary
flowmeter in combination with feedback valve and cone adjustments. The flows can be balanced amongst the three pipes by needle valves in conjunction with the central pipe flowmeter. The arrangement of flowmeter and feedback system is represented in Fig. 2.1.

2. Heater and Storage System Design

An electric water heater serves both as a source for supplying temperature controlled water and storage tank for hot water. The water heater is a Sears, Roebuck and Co. fast recovery model No. 183.32123. This water heater has a 20 gallon capacity with a 1650 Watt, 120 VAC heating element. The stock thermostat has been bypassed and heating is controlled by a 20 ampere mercury relay which is actuated by a solid state temperature controller. An auxiliary storage tank is used to buffer and to cool down hot collector effluent. This 18 gallon tank can be disconnected from the system by two manual control valves. The auxiliary tank is necessary for cooling when the collector's effluent temperature ranges from 65° to 99°C (150°F-210°F), typical of low flow rates. The tank arrangement can be viewed best in Fig. 2.2. The auxiliary tank has been omitted from the flow chart shown in Fig. 2.1 for simplicity.

E. Collector Electronic Controller

1. Controller Design Constraints

The control system was designed to perform three basic functions. First, it must be able to regulate accurately the fluid inlet temperature
to the collector, while being able to allow for an adjustable range of
temperatures, chosen by the operator (up to 100°C). Also, the system
must be able to sense different pipe outlet temperatures and cycle on
strip heaters to the outer pipes when their temperatures are lower than
the central pipe. The final function is that the system must provide
linear output signals, which indicate the various collector temperatures,
in such a way that they may be fed easily into a recording device. Also,
the controller must be resistant to the consequences of a difficult
operating environment. A chief problem is power line transients bypassing
the power supply and falsely triggering the control instrumentation.
Since the controller circuitry senses microvolt changes at its input
stages, noise or spikes on the order of volts originating from the power
line can easily find their way into the signal circuitry, causing false
readings. The circuitry was designed to handle such random interrup­
tions. But if spike voltage groups occur over long durations then the
heater temperature control is of little use and the feed water tempera­
ture could conceivably rise slightly. This line voltage effect rarely
occurs and would have very little effect over many hours of testing.
Another way random noise could be introduced into the control circuitry
is by the operation of pumps and motors. Since the entire test collector
and control electronics is situated on the roof of a research laboratory
where there are many blowers, it is very important to design circuits
with this in mind.

Another consideration is to restrict the range of the operating
temperatures of the entire electronic assembly. If there is a
large variation in temperature, electronic circuitry calibration will
be unstable and incorrect readings could be the result.

Fortunately, very little heat is self-generated when using solid state circuitry. The major problem is the magnitude change of the ambient temperature of the rooftop environment. This problem can be solved partially by proper shielding and the physical placement of the control circuits. All of these effects must be taken into account before a final design is adequate. The nature of the operating environment indicated that the controller had to be prototyped with noisy line voltage and under a range of ambient temperatures.

2. **Controller System**

The controller makes decisions and operates various heaters to compensate for outer collector pipe losses, and to regulate inlet water temperature.

The strip heater control system obtains its signals from the collector pipe outlet thermocouples. The outer pipe signals are compared to that of the central test pipe. Depending upon the difference in signals the heaters will turn on or off independently.

Another circuit controls the water heater element. In this case the thermocouple signal is obtained at the inlet of the central pipe. This signal is compared to a set, adjustable voltage, calibrated in degrees. When the inlet temperature is lower than the set temperature, the water heater will operate. When the inlet temperature appears the same or greater (probably it will never greater than the set temperature) the heater will be off. The complete control diagram is depicted in Fig. 2.8.
Fig. 2.8. Electronic Control Diagram.
Shown in Fig. 2.8 are also many significant technical details. The inputs of the four channels pass through two amplifier stages. The first stage is for basic filtering and smoothing with an amplification gain of 100; the second stage contains a low pass filter and further amplification of 25. The second amplifier also acts as a summing amplifier for the temperature compensation and offset signals. The overall gain of both stages is 2500 with an output of 100 millivolts per degree celsius. Another operational amplifier is used to filter and boost the reference junction voltage from the temperature compensation unit. Temperature compensation is achieved by use of a diode signal (exhibiting a linear temperature dependence with voltage) which is calibrated and amplified to simulate an ice point reference (0°C), with respect to ambient temperature. Also necessary to such a design is to have the input thermocouples referenced initially to the ambient temperature. This requirement is satisfied by bonding four Omega brand [0.051 cm (.020 in.) diameter] fine wire thermocouples to the diode body. The unit was then encapsulated in a thermally conductive silicone adhesive. The actual circuit schematic for this compensation unit along with the complete controller schematic is shown in Figs. 2.9 and 2.10. A key to electronic devices used in the schematics is shown in Fig. 2.11.

In the circuit schematics shown in Figs. 2.9 and 2.10 note that for each channel four input resistors plus a 56 microfarad capacitor act as an input filter with a very low pole at 0.14 Hertz. The 0.01 microfarad capacitor on IC1, IC2, IC3, and IC4 is used for internal
Fig. 2.9. Water Bath Controller, Temperature Compensation, and Chart Recorder Input Circuit Schematics.
Fig. 2.10. Strip Heater Controller Circuit Schematic.
Fig. 2.11. Electronic Component Details.
frequency compensation for the operational amplifiers. This value gives unity gain at 3.6 kilohertz and 36 Hertz at the -3db point with a closed loop gain at 40db. For IC5, IC6, IC7 and IC8 the 1 microfarad capacitor and feedback resistors act like low pass filters with a pole at 1.59 Hertz. The 36 picofarad capacitor (on IC5-IC8) is used for frequency compensation and unity gain stability. On the outputs of IC9a and IC9b the diodes D1 and D3 are used to stop current flow through the unijunction oscillator (Q1, Q2, and Q3) when the signal becomes negative. Also, for these two operational amplifiers, the feedback resistor has been chosen for 20 millivolts of hysteresis at 15 volts or 16 millivolts at 12 volts, where the supply voltage can be ±15 volts or ±12 volts, (battery).

Final testing and calibration of this controller was done extensively under different ambient temperatures up to 60°C (140°F) with a laboratory water bath accurate to ±0.1°C. The final accuracy of the temperature controller for each channel is about ±0.5°C. The overall accuracy from thermocouple probe to chart recorder is about ±1°C. A photograph of the controller is shown in Fig. 2.12. A calibration procedure is shown in Appendix A for the controller, which will be of interest to users of the test collector.

3. Chart Recorder

A Leeds and Northrup two channel chart recorder is used to record test pipe inlet temperatures and exit temperatures. A simple voltage divider circuit (shown in Fig. 2.9) was constructed so the input of the recorder would accept the controller output signals. A four
Fig. 2.12. Electronic Controller.
channel recorder could also be used to monitor all the signals if desired.

F. Solar Energy and Weather Measurements

Incident solar radiation is measured and recorded every fifteen seconds by use of a pyranometer mounted on the test collector body. An Eppley brand hemispherical black and white pyronometer (type 8-48) is used for this application. It measures the sum of diffuse and direct beam radiation. The signal from the pyranometer is fed into a Leeds and Northrup point plotting chart recorder. A simple voltage divider is used to match the input voltage range to the chart scale. The chart data has to be multiplied by a factor 184.3317972 W/m² to give a meaningful solar insolation value. The absolute accuracy of the pyranometer is about ± 2.5% to ± 3.6%.

Wind velocity and direction were measured on a nearby building where the instruments are housed. Accurate readings are available due to the fact that there are no large objects to interfere with the wind patterns. Wind velocity and direction were monitored so that in some instances the test collector results could be related to wind convection losses.

Ambient temperature was measured continuously (with ± 1°C accuracy) next to the collector site.
III. EXPERIMENTAL COLLECTOR RESULTS

A. Test Conditions

The test collector results were obtained under clear sky conditions with wind velocity below 1.50 m/s (3.4 mile/hr) from the northwest or west. Also, these results were obtained with solar radiation typically between approximately 600 to 1000 W/m² (95.1 - 317 BTU/ft²-hr.) and with steady flow rates (for water) within the range of 2.45 - 49.2 L/hr (0.675 - 13 gal/hr). Typical inlet temperatures of 30, 35, 40, 45, 50, and 60°C (86, 95, 104, 113, 122, and 140°F) were used for the tests. The glass cover plates were cleaned as required.

B. Theory

Test results were calculated according to the National Bureau of Standards (NBS) proposed standards for testing solar collectors. Collectors are evaluated by relating the integrated instantaneous efficiency to the ratio of net temperature change above ambient and incident solar radiation. Efficiency is defined as the ratio of useful energy collected and the solar energy intercepted by the collector. Instantaneous efficiency can be represented by the following equation:

\[ \eta = \frac{Q/A}{I} \]  

(3.10)

and Q/A can be represented by the following expression.
\[
\frac{Q}{A} = I(ta)_e - U_L(T_p - T_a) \tag{3.11}
\]

where

\( Q \) = useful energy collected (W);
\( A \) = cross sectional area intercepted (m\(^2\));
\( I \) = solar radiation per unit time per unit area (W/m\(^2\));
\( (ta)_e \) = the effective transmission absorption factor for the collector;
\( U_L \) = the heat transfer loss coefficient for the entire collector (W/m\(^2\)°C);
\( T_p \) = average absorber temperature (°C);
\( T_a \) = ambient temperature (°C).

It is convenient to use a constant parameter \((F')\) to compensate for the use of the average fluid temperature \((\bar{T}_f)\) instead of the temperature \((T_p)\). The constant \(F'\) is usually close to unity. In terms of \(T_f\), equation (3.11) may be represented by the following:

\[
\frac{Q}{A} = F'[I(ta)_e - U_L(T_f - T_a)] \quad \text{and} \quad \bar{T}_f = (T_{fi} + T_{fe})/2 \tag{3.12}
\]

and

\( T_{fi} \) = inlet fluid temperature (°C);
\( T_{fe} \) = exit fluid temperature (°C).

Fitting equation (3.12) into (3.10) the following is obtained:

\[
\eta = F'(ta)_e - \frac{F' U_L(T_f - T_a)}{I} \quad \text{and} \quad \Delta T = (\bar{T}_f - T_a) \tag{3.13}
\]
Equation (3.13) indicates that if efficiency is plotted with respect to $\Delta T/I$ a straight line will result, where the slope will be $F'U_L$ and y-intercept equal to $F'(t_a)e$. In reality the loss coefficient, $U_L$ and the effective transmission absorption product $(t_a)e$ are not constant and are both functions of collector temperature and ambient weather conditions. Also, $(t_a)e$ is a function of incident angle with respect to the collector. As a result, curves generated in such a manner will be somewhat general but comparable if fairly constant conditions exist. To separate these dependencies in terms of true functions an extremely accurate collector would have to be built, which is currently beyond the "state of the art". NBS quotes that the best collector accuracy is no better than $\pm 5\%$.\textsuperscript{39}

To determine the solar collector efficiency factor $(F')$ the effective transmittance absorption product $(t_a)e$ must be calculated. This product is defined by the following expression:$^{40}$

$$
(t_a)e = (t_a)_{\psi} + (1-t_a) \sum_{k=1}^{n} a_k t_{k-1}
$$

(3.14)

where $(t_a)_{\psi}$ = the collector cover transmittance absorption product, at some angle $(\psi)$ with respect to the collector surface normal;

$\quad t_a$ = the cover transmittance due to absorption;

$\quad t = $ the product $(t_k) \times (t_a)$;

$\quad t_r$ = the cover transmittance due to reflection;

$\quad a_k$ = the ratio of the overall loss coefficient to the loss coefficient from the k-th cover to the surroundings.
For a two cover test collector, equation (3.14) reduces to the following equation:

\[(ta)_e = (ta)_\psi + (1-t_a) (a_1 + a_2 t)\] (3.15)

where \(t\) is the average solar transmittance of a single cover \((t=0.92)\).

The constants \((a_1 \text{ and } a_2)\) depend mainly upon emittance of the absorber and slightly upon ambient weather conditions and absorber temperature.

For an absorber surface with known average infrared emittance \((e_1)\), (emittance is defined in Section IV), the constants \((a_1 \text{ and } a_2)\) can be approximated. Also, ambient weather conditions must be specified. For 5 m/sec. \(\phi\) wind at 100°C absorber temperature the following constants have been evaluated:

\[a_1 = 0.15, \quad a_2 = 0.62 \quad \text{for } e_1 = 0.95 \quad \text{(non-selective absorber)}\]
\[a_1 = 0.09, \quad a_2 = 0.40 \quad \text{for } e_1 = 0.10 \quad \text{(selective absorber)}\]

The transmittance absorption product \((ta)_0\) for near normal incidence (to the collector surface) is given by equation 3.16:

\[ (ta)_0 = \frac{a_1 t_0}{1-(1-a_0)d_0} \] (3.16)

where

\[t_0 = \text{near normal total transmittance of two glass covers; } (t_0=0.84)\]
\[a_1 = \text{near normal average absorptance of collector absorber;}\]
\[d_0 = \text{diffuse near normal reflectance for a two cover system } (d_0=0.15).\]

so for two covers equation (3.16) becomes:
The transmittance due to absorption \((t_a)\) is defined for near incident angles by the following expression:

\[
(ta)_0 = \frac{0.84 a_i}{0.85 + 0.15 a_i}
\]  \hspace{1cm} (3.17)

where

\[
k = \text{the extinction coefficient for the cover material, for low iron glass } k = 0.04/\text{cm};
\]

\[
l = \text{effective thickness of material } (l = 0.24 \text{ cm});
\]

\[
n = \text{number of cover plates } (n=2).
\]

evaluating equation (3.18),

\[
t_a = 0.98
\]

Also, \(t_a\) could be derived from \(t_r\) or \(t\) given the average index of refraction (in the solar spectrum) for glass. This method agrees with the above result. Now, with a value for \(t_a\), equation (3.15) may be equated in terms of the average absorber absorptance \(a_i\). Values for \(a_i\) will be determined by reflectance measurements presented in Section IV.

For a selective absorber (at near incident angles) equation (3.15) becomes:

\[
(ta)_e = \frac{0.84 a_i}{0.85 + 0.15 a_i} + 0.0086
\]  \hspace{1cm} (3.19)
And for a non-selective absorber it becomes:

\[(ta)_e = \frac{0.84a_i}{0.85 + 0.15a_i} + 0.015\]  

(3.20)

The correction for \((ta)_o\) in both cases is minor, with the selective absorber requiring the least correction. So, similar values for \((ta)_e\) would be obtained with slight variations from actual absorber emittance values, absorber temperature and wind velocity.

In Appendix B a model is presented for the collector; it also includes various parameters of the foregoing theory.

C. Calculation of Test Results

Another equivalent expression for instantaneous efficiency which is used for experimental data (a NBS proposed standard) is the following equation:

\[\eta = \frac{\dot{m} C_p \int_{S_1}^{S_2} (T_{fe} - T_{fi}) \, ds}{\int_{S_1}^{S_2} I \, ds} / A_a\]  

(3.21)

where \(S_1\) and \(S_2\) represent limits of a time interval such as 0, 15-30 minutes;

\[A_a = \text{the frontal area, receiving or aperture area (m}^2);\]

\[C_p = \text{the heat capacity of the fluid (J/kg °C);}\]

\[\dot{m} = \text{the mass flow rate (kg/sec).}\]

The quantities for heat capacity \((C_p)\) and mass flow rate \((\dot{m})\) have been omitted from the integration in the numerator since they remain
essentially constant.

All test pipes were evaluated by equation (3.21) using six minute intervals for integration over thirty minute periods. Due to the nature of the collector, the difference in inlet and outlet temperatures were fairly constant over these thirty minute periods. The solar insolation values varied slightly in a linear manner over the interval, either decreasing or increasing except for solar noon. In most cases, the overall insolation characteristics exhibited a classical Gaussian distribution.

The types of surfaces tested were three selective absorbers of the Chromonyx black chrome type and one non-selective absorber of a commercial black spray paint. The non-selective absorber is made by Cal Custom/Hawk Company and it contains 4.8% black iron oxide in a modified silicone resin and stable to 649°C (1200°F).44,45

The designations and specifications of the absorbers are as follows:

R1 - 1.0 micron of black chrome on 12.7 microns of NuSat
nickel on cold rolled mild steel.

R16 - 1.0 micron of black chrome on mild steel.

R9 - 1.0 micron of black chrome on copper.

HPl - a thick coating (several hundred microns) of heat proof black paint on galvanized steel.

Galvanized steel was used on the HPl pipe due to its corrosion resistance. The oxidation of steel interferes with adherence of the paint film.
In Figures 3.1 - 3.4 are shown the test collector results for the aforementioned samples. All lines are curve fit by a linear regression least squares approximation to represent the relationships of each of the curves; they are plotted in Fig. 3.5.

The equations, slopes and intercepts are shown in the following table for the various curves.

<table>
<thead>
<tr>
<th>Type</th>
<th>Figure Number</th>
<th>Equation</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>3.1</td>
<td>$\eta = -3.6x + 0.75$</td>
<td>$r^2 = 0.992$</td>
</tr>
<tr>
<td>R16</td>
<td>3.2</td>
<td>$\eta = -3.3x + 0.71$</td>
<td>$r^2 = 0.973$</td>
</tr>
<tr>
<td>R9</td>
<td>3.3</td>
<td>$\eta = -3.5x + 0.77$</td>
<td>$r^2 = 0.979$</td>
</tr>
<tr>
<td>HP1</td>
<td>3.4</td>
<td>$\eta = -6.8x + 0.66$</td>
<td>$r^2 = 0.971$</td>
</tr>
</tbody>
</table>

To determine the actual collector performance factor ($F'$) the value of $(\eta)_{e}$ has to be determined. The product $(\eta)_{e}$ will be determined in the following section along with the optical properties of various coatings.

The plating conditions for R1, R4 and R16 are as follows:

1. Cleaning by an electrolytic alkaline kelating cleaner, 88°C (190°F) at 76-86 mA/cm² (70-80 A/ft²).
Fig. 3.1. Efficiency Plot for Black Chrome on Nickel Plated Steel (R1).
Fig. 3.2. Efficiency Plot for Black Chrome on Steel (R16).
Fig. 3.3. Efficiency Plot for Black Chrome on Copper (R9).
Fig. 3.4. Efficiency Plot for Black Paint on Galvanized Steel (HP1).
Fig. 3.5. Comparative Efficiencies for Four Absorber Surfaces.
*2. Nickelplate (dull finish, NuSat process).

3. Black chrome (Chromonyx) plate, 216 mA/cm², (200 A/ft²), 24°C (75°F) for 2-3 ** minutes at 24 volts.

4. Water rinse, alcohol rinse and dry.

*Only for Sample R1.  **Depends on thickness desired.

D. Discussion of Results

The data presented in Figs. 3.1-3.5 is somewhat typical of data obtained by other investigators with flat plate selective and non-selective collectors. 47 In some cases the scatter in the data points is representative of a situation one might expect for experimental conditions which would vary slightly with time. A true but very difficult procedure would be to control all collector parameters, except for insolation and resultant temperature differences, in such a way so they are time invariant. This might be achieved by the use of a completely simulated (fixed environment) collector.

An overall view of the data reveals that for the selective black chrome surface the data points for efficiency are mainly between 50-70%. These values indicate, under near optimal conditions, the efficiency at which the collector usually operates. The non-selective paint has 40-60% efficiency under the same conditions. The efficiency on the y-intercept is not a realistic operating point because the collector is at the ambient temperature (\(\bar{T} = T_a\) or \(\Delta T=0\)). Frequently, this intercept value is mistakenly reported as optimum efficiency.

In reality, the curve fit for the data points is not linear except in the central region. Near the region of the y-intercept
the curve should flatten out and in the region of the x-intercept the curve should dip downward. These effects occur because the loss coefficient \( U_L \) is a function of temperature. At higher temperatures the loss coefficient increases and at lower temperatures it decreases. The slope ratio between black paint and black chrome is approximately 2, which indicates that black paint will not perform as efficiently as black chrome at a given temperature. Also, the difference in x-axis intercept shows that black chrome will function at higher temperatures than black paint.

The black chrome plated copper pipe exhibits the highest net efficiency. This effect is due partially to the difference in thermal conductivity between copper and steel. Of the pipes tested, the copper pipe has approximately 2.5 the thermal conductance of the steel pipe. Choosing copper rather than steel for pipe material would depend upon the relative cost of materials and collector fluid flow rates (absorber heat transfer rate).

The effect of nickel plating steel creates only a slight rise in both the loss coefficient and efficiency of the absorber (see Fig. 3.5). Although the efficiency is increased by nickel plating, it may be more cost effective to use black chrome directly on steel for collectors operating below 100°C.
IV. SELECTIVE ABSORBERS AND REFLECTANCE MEASUREMENTS

A. Theory

The distribution of solar energy in terms of wavelength or energy can be modeled as approximately a 5762°C blackbody,\(^4\) (analogous to a perfect emitter of energy). In Fig. 4.1 is presented the air mass 1 solar terrestrial spectrum\(^4\) with the spectrum of energy for surfaces operating as blackbody emitters at 100°C (212°F) and 300°C (598°F). The solar spectrum shown deviates from the ideal blackbody spectrum due to various atmospheric absorptions. Included in this figure are two typical characteristic reflectances for black chrome. The reflectance of black chrome represents a high absorption of solar energy in the visible and near infrared while exhibiting a poorly emitting surface in the infrared. In this manner most solar energy absorbed by the coating is retained. The reflectance property of black chrome is typical for most selective surfaces except for the position and shape of the transition region.

The property of absorptance \(a_\lambda(\mu,\phi)\) dictates the amount of energy absorbed by the surface. Absorptance is the fraction of incident energy at a given wavelength from the direction \((\mu,\phi)\) that is absorbed when it strikes the surface \((\mu\) is the cosine of the polar angle and \(\phi\) is the azimuthal angle). Emittance \(e_\lambda(\mu,\phi)\) is defined as the ratio of the emitted total energy intensity from a surface in the direction \((\mu,\phi)\) to the blackbody intensity, where both
Fig. 4.1. Wavelength Relationship between Black Chrome Spectral Reflectance, the Solar Spectrum and Black Body Spectra (100°C, 300°C).
the surface and blackbody are at the same temperature. Although true absorptance and emittance can be determined independently with effort, usually both values are derived from monochromatic angular hemispherical reflectance measurements, herein to be referred to as reflectance. An integrating spectral reflectometer is used to obtain reflectance measurements. This equipment utilizes the property of a material oriented at a particular angle to reflect a certain amount of monochromatic energy incident upon it. Reflectance is obtained by the ratio of the reflected energy intensity over a hemisphere (all angles of reflection) to the incident intensity. An integrating hemisphere is used because absorber surfaces exhibit a diffuse or Lambertian component in their reflectance which would be undetected otherwise. Both absorptance and emittance are related by the relationship \( a_\lambda(\mu,\phi) = e_\lambda(\mu,\phi) \) where \( \lambda \) is a particular wavelength and \( (\mu,\phi) \) specified direction. Absorptance and emittance are related to reflectance by the expression \( a_\lambda(\mu,\phi) = e_\lambda(\mu,\phi) = 1 - r_\lambda(\mu,\phi) \) where \( r_\lambda(\mu,\phi) \) is reflectivity at wavelength \( \lambda \) and position \( (\mu,\phi) \). In practice, absorptance and emittance are average values. Absorptance \( (a_i) \) is the average absorptance at each wavelength weighted according to the solar energy intensity distribution of wavelengths. Net emittance \( (e_i) \) is calculated by taking the average emittance at each wavelength weighted according to the blackbody intensity distribution (corresponding to the operating temperature of the absorber surface).

To absorb energy a particular material which exhibits any one or several of the following properties can be a selective absorber:
1. Dispersions of particles in a metal or dielectric matrix.
2. Semiconductor films overlaid on metals, the film having the proper absorption edge or band gap.
3. Interference thin films, dielectric and metal stacks.
4. Multiple absorption due to surface geometry.
5. Thin film quantum size effects.

The most common types of absorbers are probably types 2 and 3 because they have been studied in other fields of research—particularly in optics, electronics and heat transfer. The black chrome absorber falls between the type 1 and 2 categories, although a complete description is under current investigation. Black chrome is commonly electrodeposited on a reflective metal which influences the low infrared emittance properties. The deposit is probably a fine dispersion of chromium particles within a definite size range surrounded by an adherent and (possibly amorphous) chromium oxide such as Cr$_2$O$_3$. Specific details of the physics of the coating as well as materials science aspects of the coating are not well known. A preliminary model has been presented describing some of the observed characteristics of various types of black chrome, but presently a complete model has not been found which fits well with the experimental evidence. One major problem is characterizing the black chrome structure in such a way that all effective optical constants, necessary to verify a descriptive theory, can be determined.
B. Reflectance Measurements

All spectral reflectance measurements for the wavelength range 0.28 - 1.8 microns (visible and near infrared) were done on a Cary 14 spectrophotometer with a spherical diffuse reflector attachment. The measurements for the wavelength range 2.0 - 25 microns (infrared) were performed on a Gier-Dunkle Model HC300 heated cavity reflectometer with an SP 210 absolute directional integrating spherical attachment. Also, room temperature total emittance measurements were performed on a Gier-Dunkle model DB100 emissometer for reference use.

All reflectance measurements are near normal (20°) with respect to the incident monochromatic beam. The measurements are performed at room temperature, (approximately 20°C), including the heated cavity samples which are water cooled to about room temperature.

All black chrome samples, (R1-R17), were commercially electroplated according to the specifications listed in the previous section. For the substrate samples (S1-S4) only minor cleaning was performed before measurements were made.

In the following table are listed the various sample types tested:

1. Steel Substrates
   - R1 - 1.0 micron BC on 12.7 microns, Nickel on Steel
   - R2 - 0.9 micron BC on 12.7 microns, Nickel on Steel
   - R3 - 1.0 micron BC on 12.7 microns, Nickel on Sandblasted Steel (1)
   - R5 - 0.7 micron BC on 12.7 microns, Nickel on Polished Steel
   - R16 - 1.0 micron BC on Steel
   - R12 - 1.0 micron BC on Sandblasted Steel (2)
2. Copper Substrates
   R4 - 1.0 micron BC on 12.7 microns, Nickel on Copper
   R17 - 0.17 microns BC on 12.7 microns, Nickel on Copper
   R11 - 0.7 microns BC on 12.7 microns, Nickel on Sandblasted Copper (2)
   R9 - 1.0 microns BC on Copper
   R10 - 1.0 microns BC on Sandblasted Copper (1)

3. Misc. Substrates
   HPI - High temperature black paint--Cal Custom/Hawk Co.
   S1 - Untreated Copper, cold rolled
   S2 - Polished Steel
   S3 - 2.5 microns, Chrome on Steel
   S4 - 12.7 microns, Nickel on Copper

   Notation
   (1) Samples are sandblasted with 1mm (0.04 in.) dia., Sand
   (2) Samples are sandblasted with 10 micron (3.94 μ in.) dia., Sand
   BC stands for Black Chrome.

C. Discussion of Reflectance Measurements

1. Reflectance Plots and Photomicrographs

   In the figures to follow, reflectance measurements will be shown for several metallic substrates and for black paint and black chrome applied to copper and steel under various conditions. A comparison of black chrome thickness dependence versus reflectance and the effect of sandblasting substrates will be presented. Scanning electron micrographs depicting the surface and cross-sectional morphology of selected samples will be shown, also.
In Fig. 4.2 are reflectance values for black paint and various types of substrates. The faint lines for the substrates below 2 microns in wavelength are estimated from averaged data. The estimated data shows the reflectance trend in the visible region. Many of these substrates behave alike as do steel (S2), chrome (S3) and nickel (S4). Copper (S1) exhibits a very high reflectance up to its absorption band in the visible region—(this band accounts for copper’s orange color). The reflection property of copper is another reason to suspect that selective surfaces applied to copper will behave in a superior manner, more so than steel, as in the test collector results.

Included in Fig. 4.2 is the reflectance for black paint (HP1) where it exhibits partial selectivity beyond 10 microns. It also exhibits an absorption around 19 microns. The surface morphology of black paint appears as a microrough particulate surface, generated by spray painting (see Fig. 4.3).

Reflectance measurements for steel samples are shown in Fig. 4.4 and 4.5. The interference phenomena seen in Fig. 4.4 between 0.6 - 1.4 microns in wavelength will be discussed later (under thickness effects). The samples all exhibit similar characteristics except for the sandblasted substrate (R12) which shows degraded infrared reflectance. The highest reflectance is shown by a 0.7 micron coating of black chrome on nickel plated polished steel (R5). In terms of solar selectivity the reflectance for black chrome on nickel plated steel (R1) was only slightly better than black chrome on steel (R16). This effect was also noted in the test collector results. As shown in Fig. 4.1, steel (S2),
Fig. 4.2. Spectral Reflectance for Black Paint (HP1) and Four Substrates; Copper (S1); Steel (S2); Chrome (S3); and Nickel (S4).
Black paint (high temperature) on galvanized steel (HP1) examined at 20kV, 45° tilt. a) 2000X; b) 4000X.

Fig. 4.3.
Fig. 4.4. Visible Region, Spectral Reflectance for Six Black Chrome Absorbers on Steel Substrates.
Fig. 4.5. Infrared Spectral Reflectance for Six Black Chrome Absorbers on Steel Substrates.
followed by nickel (S4), has higher reflectance for all wavelengths shown. In the visible and near infrared regions the high reflectance of steel must reduce effectively the net solar absorptance of the black chrome coating as shown in Fig. 4.4 (compare samples R1 and R16). In the infrared region the reflectance for steel and nickel are closer in magnitude than for the visible region. Comparing samples R1 and R2 in Fig. 4.5 the difference between two different substrates is small in terms of reflectance. The overall effect of a steel substrate over that of a nickel plated one is to reduce the solar selectivity in the visible range.

A typical surface morphology for black chrome nickel plated steel is shown in Fig. 4.6. The particulate but physically tough surface resembles a partially sintered powder. This surface morphology, exhibiting 0.05-0.30 micron particle size range, is characteristic of all black chrome surfaces investigated. In Fig. 4.6a, the dark "vein-like" structure separating dome-shaped regions of black chrome corresponds to the grain structure of the nickel layer below. The "veins" replicate the grain boundaries and irregularities of the nickel layer. An interesting effect was noted when attempting to electroplate black chrome on large polycrystalline zinc (ave. grain diameter of 5 mm). The black chrome deposit exhibited poor solar selectivity because the coating only plated preferred zinc grains. When either the large polycrystalline zinc was sandblasted, or small polycrystalline zinc (ave. grain diameter 5 μm) was used for plating, solar selectivity increased and the deposit appeared as depicted in Fig. 4.6. From this
Fine structure of Black Chrome on nickel-plated steel examined at 20kV.
(a) 2000x; (b) 20000x; (c) 42000x.

Fig. 4.6.
evidence one can conclude that black chrome plating and resulting selective properties are influenced by the substrate grain size and orientation. Work is being conducted presently by the author on this effect. A typical cross-section of black chrome on nickel-plated steel (etched in 5% nital) is shown in Fig. 4.7. Black chrome shows a high structural coherence along the nickel interface. Under the electron beam of the scanning electron microscope the black chrome layer appeared to "glow" or charge. This charging effect is typical of electrical insulating and some semiconducting materials.

Black chrome electroplated on copper, steel and nickel plated substrates all exhibit similar reflectance properties. For black chrome on copper, reflectance plots for the visible and infrared range are shown in Figs. 4.8 and 4.9., respectively. The copper samples show the same interference phenomena in the region of 0.4 - 1.6 microns as noted with steel samples.

For black chrome on copper (R9) the transition from low to high reflectance (1-4 μm) shows a sharper rise than for the nickel and steel substrates, in that order. This order is reversed for the initial wavelength at which the transition takes place. The initial transition for sample R9 is at a higher wavelength (1.8 microns) than all other samples tested. The sharp rise may be due to the fact that the copper substrate reflectance has an inherently higher value than for nickel and steel.

To view this relationship compare samples R1, R16 and R9 in Figs. 4.4, 4.5, 4.8 and 4.9. These transition effects clearly show an interaction between the black chrome layer and the substrate.
Cross section of *Black Chrome* on nickel-plated steel showing various layers at 20kV, 15° tilt, (a) 4000×; (b) top edge 10,500×.

*Fig. 4.7.*
Fig. 4.8. Visible Region Spectral Reflectance for Five Black Chrome Absorbers on Copper Substrates.
Fig. 4.9. Infrared Spectral Reflectance for Five Black Chrome Absorbers on Copper Substrates.
material; but it is very difficult to explain merely in terms of substrate reflectance (compare S1, S2 and S4 in Fig. 4.2). Such effects as surface roughness, grain size and orientation may also affect the transition region.

The copper samples that exhibit the best solar selectivity are 0.7 microns of black chrome on nickel plated copper (R11 and R17) and 1 micron of black chrome on copper. The effect of sandblasting upon reflectance (R17 and R10) will be discussed later.

The typical surface morphology for black chrome on copper (R9) is shown in Fig. 4.10. The major difference between the surface morphology for R9 and the nickel plated sample (R1) is the surface roughness. The copper sample exhibits a very smooth surface compared to the nickel sample. Figure 4.11 shows the details of the black chrome cross-section on copper.

The effect of black chrome thickness is pictured in Figs. 4.12 and 4.13. In general, the thicker the black chrome layer the later the transition takes place; and the interference region moves accordingly; also, the interference peak intensity is larger for the copper samples than steel. Samples with 0.7 microns of black chrome show the steepest transition slope, (Fig. 4.13). Thicker layers of black chrome show less solar selectivity. In confirmation of these findings, other investigators have found the optimum black chrome thickness to be about 0.5 - 1.0 microns.51

The interference phenomena noted before can be seen clearly in Fig. 4.12. This effect is characterized by a rise followed by a fall
Black Chrome on Copper (untreated, R9) at 20kV. a) 2000X; b) 10,000X.

Fig. 4.10.
Cross-section of Black Chrome on Copper (untreated, R9) at 20kV, 15° tilt. a) 10,000X; b) 20,000X.

Fig. 4.11.
Fig. 4.12. Visible Region Spectral Reflectance for Five Thicknesses of Black Chrome on Nickel Plated Substrates.
Fig. 4.13. Spectral Reflectance for Five Thicknesses of Black Chrome on Nickel Plated Substrates.
in reflectance, in the shape of a sine wave. The intermediate point between the up and down cycle will be used for reference. For samples with 0.7 microns of black chrome this reference point is about 0.8 microns in wavelength. Similarly, for 0.9 and 1.0 microns thickness, the reference points are about 0.9 and 1.1 microns, respectively. The interference effect is clearly due to the effective thickness of the coating. The coating thickness becomes highly disturbing to wavelengths of the same size as the coating (a well known result).

The last three figures deal with the effect of substrate sandblasting on the surface morphology and reflectance of black chrome. In Fig. 4.14 are three micrographs representing the effect increasing substrate roughness has upon the morphology of black chrome. Note that the microscopic particle structure remains the same regardless of sandblasting. The overall effect of sandblasting is to degrade the infrared reflectance, (see Figs. 4.15 and 4.16). For sandblasting, either 10 microns or 1 mm dia. sand was used. Samples R3 and R10 were blasted with 1 mm sand and R11 and R12 were microblasted with 10 micron sand. Both R3 and R11 have nickel layers. The effect of plating nickel over the surface lessened the influence of sandblasting, probably by filling up damaged areas with nickel. Only in one case was the visible reflectance improved (R10) but at the expense of degraded infrared reflectance.

2. Calculation of Test Collector Parameters

By integration of \((1-r_\lambda)\) where \(r_\lambda\) is spectral reflectance, over the solar spectrum the integrated absorptance \(a_i\) is obtained. Also,
Black Chrome on various types of nickel-plated steel substrates viewed at 20kV, 60° tilt. (a) polished steel, 400x; (b) untreated steel, 400x; (c) sandblasted steel, 400x.

Fig. 4.14.
Fig. 4.15. Visible Region Spectral Reflectance for Sandblasted Substrates.
Fig. 4.16. Infrared Region Spectral Reflectance for Sandblasted Substrates.
by integration of \((1-r_{\lambda})\) over the 100°C blackbody spectrum the integrated emittance \((e_i)\) is obtained. The higher the ratio of these values \((a_i/e_i)\) the greater the selectivity. In practice a ratio of 10 is very good for a selective absorber and a ratio of 1 for non-selective absorbers.

The results are shown in the following table for 20°C measurements (test collector samples are marked *).

<table>
<thead>
<tr>
<th></th>
<th>R1*</th>
<th>R2</th>
<th>R3</th>
<th>R5</th>
<th>R16*</th>
<th>R12</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_i)</td>
<td>0.958</td>
<td>0.951</td>
<td>0.956</td>
<td>0.932</td>
<td>0.92</td>
<td>0.948</td>
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<tr>
<td>(e_i)</td>
<td>0.070</td>
<td>0.065</td>
<td>0.118</td>
<td>0.046</td>
<td>0.070</td>
<td>0.244</td>
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<tr>
<td>(a_i/e_i)</td>
<td>13.7</td>
<td>14.6</td>
<td>8.10</td>
<td>20.3</td>
<td>13.1</td>
<td>3.9</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>R4</th>
<th>R17</th>
<th>R11</th>
<th>R9*</th>
<th>R10</th>
<th>HP1*</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_i)</td>
<td>0.957</td>
<td>0.916</td>
<td>0.916</td>
<td>0.942</td>
<td>0.929</td>
<td>0.95</td>
</tr>
<tr>
<td>(e_i)</td>
<td>0.078</td>
<td>0.050</td>
<td>0.059</td>
<td>0.051</td>
<td>0.266</td>
<td>0.832</td>
</tr>
<tr>
<td>(a_i/e_i)</td>
<td>12.3</td>
<td>18.3</td>
<td>15.5</td>
<td>18.5</td>
<td>3.5</td>
<td>1.14</td>
</tr>
</tbody>
</table>

By using data from Mattox et al.\(^{52}\) we can estimate the integrated emittance at 100°C rather than at 20°C. The equation which describes the change in emittance with temperature (for black chrome on Ni plated substrates) is as follows:

\[
e = 0.000405T + 0.06175 \quad \text{where } T \text{ is in } ^\circ\text{C}
\]

By modifying the equation the following is generated as an approximation only.
From these results one can calculate (by using equations 3.19 and 3.20) the effective transmission absorption product \((ta)_e\) for the test collector. Also, the collector performance coefficient \((F')\) and the loss coefficient \((U_L)\) may be obtained. These results are summarized in the following table.

<table>
<thead>
<tr>
<th></th>
<th>R1*</th>
<th>R2</th>
<th>R3</th>
<th>R5</th>
<th>R4</th>
<th>R17</th>
<th>R11</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e_i(100^\circ\text{C}))</td>
<td>0.096</td>
<td>0.089</td>
<td>0.162</td>
<td>0.063</td>
<td>0.107</td>
<td>0.069</td>
<td>0.081</td>
</tr>
<tr>
<td>(a_i/e_i(100^\circ\text{C}))</td>
<td>10.0</td>
<td>10.7</td>
<td>5.9</td>
<td>14.8</td>
<td>8.9</td>
<td>13.3</td>
<td>11.3</td>
</tr>
</tbody>
</table>

In Appendix B is a calculation of \(U_L\) from a mathematical model. The model values are comparable.
V. CONCLUSIONS AND RECOMMENDATIONS

A solar test collector has been designed and constructed which was used to measure the efficiency of four collector surfaces--three selective black chrome and one non-selective black paint. This collector was compensated for edge losses and measures differential pipe temperatures with $\pm 1^\circ C$ accuracy. The absolute uncertainty of the collector measurements of efficiency are about $\pm 10\%$ (for example a value of 60% efficiency could vary from 54-66%), while it has a few percent uncertainty in reproducibility and is limited by the accuracy of the mass flow rate measurement. The collector typically operates at low flow rates (0-49 L/hr) up to temperatures of 100°C at atmospheric pressure. The collector is designed so collector pipes may be removed with ease and it has the ability to regulate the fluid inlet temperatures within $\pm 1^\circ C$ accuracy. The inlet temperatures are adjustable (25-90°C) and are maintained by an electronic controller. The collector includes a manual tilting stand for orientation to the sun. A heat transfer model has been presented (Appendix B) which models this collector's performance. Calculated and experimental values are in good agreement.

The four surfaces tested (R1, R9, R16 and HPl) are representative of a range of possible combinations. The loss coefficients for these four surfaces show that black paint has about a factor of two times greater loss than for the black chrome samples. The loss coefficient for the black chrome samples was about the same--3.8 W/m$^2$ °C for all
three. Black chrome on copper was the most efficient of the surfaces tested; probably, this is due to reflectance and high thermal conductivity of copper. Black chrome on nickel-plated steel and steel substrates had comparable properties. The effect of nickel plating steel accounted for only a 0.04 rise in efficiency for the absorber. Nickel plating may not be cost effective in light of this result. For the low flow rates at which this collector operated, the effect of the high thermal conductivity of copper is not as great as it could be in promoting high heat transfer rates. If a factor of 2-6% efficiency is sacrificed for lower cost, steel pipes could be used. Black paint for use as a collector surface has lower efficiencies particularly at higher temperatures compared to the selective surfaces. The y-axis intercept efficiencies for black chrome (at t=0) are 0.77 for the copper sample, 0.75 for nickel plated steel, 0.71 for steel and to 0.66 for black paint. Typically, the operating efficiencies are at least 0.05 - 0.10 lower than the intercept values.

Spectral reflectance measurements are used to obtain optical parameters such as solar absorptance and infrared emittance. The best solar selectivity characteristics were exhibited by 0.7 microns of black chrome on nickel plated polished steel (a_i/e_i = 20.3) and by 1.0 micron of black chrome on copper (a_i/e_i = 18.5) -- the copper sample tested by the test collector. Almost all combinations showed good selectivity. The effect of the nickel layer was marginal in promoting higher selectivity for the steel samples and it degraded selectivity on the copper samples. In light of this result it may be
best to copperplate steel instead of nickel plating. The effect of sand blasting increased the solar absorptance slightly while affecting the infrared emittance adversely. Sandblasting or micro-blasting is not recommended. The increase in black chrome thickness shifts the transition region further into the infrared wavelengths; these coatings also exhibited lessened selectivity. Optimum thickness of black chrome is about 1.0 - 0.7 microns. The surface morphology revealed by scanning electron microscopy shows that for all the surfaces studied the coating appears to be a mass of adherent particles within the size range 0.1 micron to 0.3 microns.

Recommendations for research are many. An important study would be to relate different types of black chromes used by various investigators in terms of chemistry and microstructure. Another study could be to relate the interaction of the substrate properties to those of the black chrome selectivity properties. This effect of black chrome on chrome and copper-plated steel might be interesting, also.

The overall direction of the work presented thus far is towards the characterization and improvement of the black chrome microstructure. Once the microstructure and chemistry are known, the same selective surface effects might also be created for a paint or a sintered powder coating. The key point here is to make a very inexpensive equivalent surface to that of electroplated black chrome. This coating would have to be cost competitive with black paints for the residential solar collector market. However, for the production of process steam,
black chrome surfaces must be studied at high operating temperatures. It is very important to understand the degradation mechanism of this surface. Presently, black chrome exhibits degradation of solar selectivity at 300°C. Therefore, the study of the change in microstructure and composition at different temperatures is of paramount importance. Such knowledge and understanding could lead to both low cost selective absorbers and stable high temperature absorbers.
ACKNOWLEDGMENTS

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APPENDIX A. CALIBRATION PROCEDURE FOR THE SOLAR TEST COLLECTOR TEMPERATURE CONTROLLER

The controller may be operated from a solid state ± 15 volt power supply or depending upon the requirement, a ± 12 volt battery supply may also be used. In each case the controller must be calibrated for accuracy or to compensate for change in supply voltage. For reference, the physical controller and header layout are shown respectively in Figs. A.1 and A.2. Also, it may be helpful to refer to figures in 2.9 and 2.10, in Section II.

A. Initial Adjustments

1. Set the compensation potentiometers (comp 1-4) to 0.54 of full resistance scale for ± 15 volt operation (for ± 12 v. operation set to 0.50).

2. Adjust gain potentiometers (Gain 1-4) to 4000 Ohms and set offset potentiometers (Offset 1-4) to 0.50 full resistance scale.

3. The compensation potentiometer on header (H9) should be adjusted to give 0.0 volts at pin 2 and 3 of header (H9) when unit is at room temperature.

B. Offset and Gain Adjustments

1. To calibrate offset and gain use ice 0.0°C and a hot water bath (50.0°C) with input copper-constantan thermocouple (50.0°C = 2.035 mV).
2. For each channel (1-4) adjust the respective gain control to obtain a 5 volt change of output, measured at testpoint (TP 1-4), for a 50°C temperature variation (for ± 12 supply adjust to 4 volts).

3. For each channel adjust offset for -5 volts output with input thermocouple at 0.0°C (for ± 12 volt operation set to -4 volts).

C. Reference Junction Temperature Compensation Adjustment

For each channel adjust the cold junction compensation potentiometer (Comp. 1-4) with the input thermocouple at a temperature of 0.0°C. The potentiometer should be adjusted so there is no change in the output reading when circuit assembly is both placed in an oven at 40°C (or less than 75°C) and alternately allowed to stabilize at room temperature. This adjustment may change the circuit offset so steps B-3 and C-1 should be repeated until a stable output is achieved.

D. Chart Recorder Adjustment

The voltage divider for the chart recorder should be set for a convenient scale factor with respect to the chart grid.

The temperature controller is now adjusted for 100 millivolts per °C (or 80 millivolts per °C for the ± 12 volt supply). At 50°C the output is set for 0.0 volts. The water bath temperature adjustment potentiometer in channel 4 is calibrated in degrees celcius (°C).
Fig. A.1. Component Layout for Electronic Controller.
Fig. A.2. Header Layout for Electronic Controller.

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APPENDIX B. HEAT TRANSFER MODEL FOR THE SOLAR TEST COLLECTOR

When analyzing a collector's performance and thermal loss characteristics, it is important to model the collector. A model such as the one to follow can be very helpful in evaluating a particular collector characteristic. The following development is a modified Duffie & Beckman model. Two versions of the same model will be presented, first a complete model and finally a simplified version.

A. Rigorous Model

![Diagram of heat transfer model for solar test collector]
where:

\[ I = \text{total incident radiation (direct and diffuse components)} \]
converted into the plane of the collector, W/m² (BTU/hr ft²).

\[ r = \text{reflection loss of collector cover, the loss is about 8% per glass plate.} \]

\[ R_n = \text{thermal resistance elements in m² °C/W (hr ft² °F/BTU) where} \]
\[ n = 1, 2, 3, 4, 5. \]

\[ Q = \text{heat available for the heating of fluid.} \]

\[ T_x = \text{temperature at locality } x, °C (°F). \]

The modeling of the resistive components can be expressed as:

\[ R_1 = 0 \text{ for low temperature collectors and for the test collector.} \]

\[ R_2 = \frac{L}{K} \text{ where} \]
\[ L = \text{thickness of insulation, } L=0.19 \text{m (0.625 ft);} \]
\[ K = \text{thermal conductivity of insulation } K=0.017 \text{ W/m°C} \]
\[ (0.01 \text{ BTU/hr ft °F}). \]

\[ R_2 = 11.2 \text{ °Cm²/W (62.5 hr ft² °F/BTU).} \]

\[ R_6 = 0, \text{ edge loss effect (in small collectors, this can be a significant term). In this case, it may be neglected due to strip heater simulation of large collector.} \]

\[ R_3 = (h_{p-c2}+h_{r2})^{-1} \text{ pipe to cover heat transfer where} \]
\[ h_{p-c2} = \text{convective heat transfer coefficient pipe to cover 2}; \]
\[ h_{r2} = \text{radiative heat transfer coefficient pipe to cover 2}. \]

\[ R_4 = (h_{c2-c1}+h_{r1})^{-1} \text{ cover to cover heat transfer where} \]
\[ h_{c2-c1} = \text{convective heat transfer coefficient cover 2 to cover 1}; \]
\[ h_{r1} = \text{radiative heat transfer doefficient cover 2 to cover 1}. \]
\[ R_5 = (h_w + h_{r4})^{-1} \]  
where

- \( h_w \) = wind convection coefficient;
- \( h_{r4} \) = radiative heat transfer coefficient cover to sky.

Now to evaluate the heat transfer coefficients:

For radiative heat transfer:

\[ h_{r2} = \frac{\sigma(T_p - T_{c2})(T_p^2 - T_{c2}^2)}{\left( \frac{1}{e_p} + \frac{1}{e_{c2}} - 1 \right)} \]

\[ h_{r1} = \frac{\sigma(T_{c2} - T_{c1})(T_{c2}^2 - T_{c1}^2)}{\left( \frac{1}{e_{c1}} + \frac{1}{e_{c2}} - 1 \right)} \]

\[ h_{r4} = e_{c1} \sigma(T_{c1}^2 + T_s^2)(T_{c1} + T_s) \left( \frac{T_{c1} - T_s}{T_{c1} - T_a} \right) \]

where \( \sigma \) Stephan-Boltzmann constant

\[ \sigma = 5.669 \times 10^{-8} \text{ watts m}^{-2} \text{ °K}^{-4} \]

- \( e_x \) = Total emittance (often called the emissivity) of element \( x \);
- \( e_x \) is a function of temperature.

- \( T_x \) = Temperature of element \( x \) (p=pipe, c=cover, a=ambient, s=sky)

For convective heat transfer

\[ h_{p-c2} = \frac{N K_a}{L_{p-c2}} \]

\[ h_{c2-c1} = \frac{N K_a}{L_{c2-c1}} \]
where

\[ N = \text{Nusselt number (pure conduction resistance/pure convection resistance)} \]

\[ L_{x-x1} = \text{spacing between element } x \text{ and } x_1, \quad L_{p-c2} = 0.0254\text{m}(0.083\text{ft}) \]

\[ a = \text{thermal conductivity of air, } 0.026 \text{ W/m°C, 20°C (0.0046 BTU/hr.ft}^2{\circ°F}) \]

Using Tabor’s approximation for a 45° tilt

\[ h_{p-c2} = \left( \frac{1.14(T_p-T_{c2})^{0.310}}{L_{p-c2}} \right) (1-0.0018(T-10)) \]

\[ h_{c2-c1} = \left( \frac{1.14(T_{c2}-T_{c1})^{0.310}}{L_{c2-c1}} \right) (1-0.0018(T-10)) \]

where

\[ T = \text{the average air temperature between the two elements in question.} \]

The wind convection coefficient can be expressed as \( h_w = 5.7 + 3.8V \)

where

\[ V = \text{velocity of air in M/sec.} \]

Now the total collector loss coefficient \( (U_L) \) can be evaluated in terms of the temperatures \( T_s, T_p, T_a, T_{c1}, T_{c2} \) and by emittances \( e_{c1}, e_{c2}, e_p \)

where

\[ U_L = \frac{1}{R_1+R_2+R_3+R_4+R_5+R_6} \]
which reduces to:

\[ U_L = \frac{1}{R_2 + R_3 + R_4 + R_5} \]

**B. Simplified Model**

For an approximation, the model can be simplified as follows:

\[ U_L = U_t + U_b \]

\[ U_L = \frac{1}{R_2 + R_3 + R_4 + R_5} \]

where:

- \( S \) = energy actually reaching the collector pipes;
- \( U_t \) = top loss coefficient;
- \( U_b \) = bottom loss coefficient = \( \frac{1}{R_2} \);
- \( U_b = \frac{K}{L} = 0.0893 \, W/°Cm^2 \);

\[ U_t = \frac{1}{R_3 + R_4 + R_5} = \left( \frac{1}{h_{p-c_2} + h_{c_2-c_1} + h_{c_1-w}} + \frac{1}{h_{w-c_4}} \right) \]

\( U_t \) is estimated after Klein\(^2\) (1973) modified for two covers at 45° tilt angle.
\[ U_t = \left( \frac{2}{(344/T_p) \left[ (T_p - T_a)/(2+f) \right]^{0.31} + \frac{1}{5.7 + 3.8V}} \right)^{-1} \]

\[ + \left( \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{(0.085 + 0.915 \, \epsilon_p)^{-1} + [(3+f-2e_g)/e_g]} \right) \]

for two cover plates \( f = (1.116 - 0.04464h_w + 5.58 \times 10^{-4}h_w^2) \) where

where \( h_w = (5.7 + 3.8V) \) as before.

The experimental loss coefficient \( U_L \) exp., for samples R1, R4, R16 and HPI, can be compared to a calculated \( U_t \) using spectral reflectance data.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R16</th>
<th>R9</th>
<th>HPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_i ) (100°C)</td>
<td>0.096</td>
<td>0.096</td>
<td>0.070</td>
<td>0.83</td>
</tr>
<tr>
<td>( U_L ) exp.</td>
<td>3.93</td>
<td>3.68</td>
<td>3.67</td>
<td>8.44 W/m²/°C</td>
</tr>
</tbody>
</table>

Solve equation for \( f \) where \( V = 1.5 \) M/sec.

\( h_w = 11.4, \quad f = 0.680 \)

Solve for \( U_L \) where \( U_L = U_t + U_b \) and \( e_g = .88, T_p = 100°C \)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R16</th>
<th>R9</th>
<th>HPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_L ) exp.</td>
<td>3.93</td>
<td>3.68</td>
<td>3.67</td>
<td>8.44 W/m²/°C</td>
</tr>
<tr>
<td>( U_L ) model</td>
<td>3.58</td>
<td>3.58</td>
<td>3.67</td>
<td>7.29 W/m²/°C</td>
</tr>
</tbody>
</table>
The experimental values compared to the model show excellent agreement except for black paint HPl. The true, emittance for HPl may deviate from the value used (according to spectral reflectance measurements) and account for the difference in \( U_L \text{ exp.} \) and \( U_L \text{ model} \).

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REFERENCES


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