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ON A DIGITAL PYRANOMETER MONITORING NETWORK FOR UTILITY COMPANIES*

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A Pyranometer having a black ball thermal detector, a differential temperature correction circuit, and a digital magnetic tape output has been designed and built. An electricity power demand factor cassette recorder is used to correlate time, sunlight, electrical load, and temperature; and the results are machine readable. The data will aid a utility company in future projections of the effect of using solar energy for heating and cooling on electricity and gas demands. Instrument design, the monitoring network data handling, and interpretation of the information are discussed.

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Introduction

Utility companies rely on meteorological data to predict short term future sales of gas and electricity. Immediate, near term and long range future purchases of fuel and sales of energy are affected by weather patterns. If (or, as) solar energy systems for heating and cooling buildings are installed, the seasonal, daily and hourly load patterns will be significantly altered in various regions of the United States. The sensitivity of fuel purchases to extreme weather variations can be expected to dramatically increase if many similarly sized solar heating and cooling systems are installed within one distribution district.

In order to predict the possible effects of wide-spread collection of solar energy on the distribution of electrical energy for air-conditioning, and gas for space heating and hot water, one needs detailed measurements of the solar fuel income as a function of time for each district being served. The mixture of solar energy that can be used to satisfy base, intermediate, or peak demands will greatly affect the future capital needs and building of utilities, particularly those in sunny climates with high growth rates.

To satisfy the need for an integrated solar fuel monitoring network, a low cost pyranometer is necessary but not sufficient. The response time, accuracy, lifetime, calibration, precision and form of the output determine the technical performance of the monitor; however the total cost of collecting and correlating the information will determine its commercial success. The cost of collecting solar fuel data versus the cost of not collecting it will differ for each utility as the calendar advances.

To prepare for the possible introduction of solar heating and cooling systems in California, the Lawrence Berkeley Laboratory (LBL) of the University of California and the Pacific Gas and Electric (P.G.&E.) Company are developing a solar fuel monitoring network. Both on-line real time measurements of solar insolation and recorded data will be collected. A relatively sparse matrix of on-line, medium accuracy, primary instruments is to be augmented by a denser array of off-line, lower accuracy, reference instruments.

Monitoring Network

Figure 1 outlines the P.G.&E. service area, which includes mountains, valleys, deserts, and coastal meteorological regions. Weather recording station locations have been chosen as to provide the most representative site for the surrounding service area. Ambient air temperature is recorded at all sites, while wind velocity and humidity are recorded at Oakland, Sacramento, and Fresno. Solar insolation will be recorded at selected sites using commercial electronic pyranometers.

The U.S. Weather Bureau records solar insolation at several sites in California and percentage of possible sunshine at seven sites in California (Eureka, Fresno, Los Angeles, Red Bluff, Sacramento, San Diego and San Francisco).

(1) The number of these sites is too small to allow a utility to correlate energy demands with growth and sunlight on a regional basis.

(2) The form of the data (mostly on paper) does not allow an economic means to study daily variations although gross monthly averages can eventually be compared to various broad load study results.

(3) Detailed hour-by-hour peak demand studies require accurate local data. The occasionally available hour-by-hour weather tapes are somewhat cumbersome for this particular purpose. Also the general lack of solar data inhibits the use of weather tapes. The uncertainty of calibration which now surrounds solar insolation measurements further degrades the usefulness of the data.

(4) A transient demand or surge analysis requires minute-by-minute data with accurate time correlation between energy demand and available solar fuel. Simulation studies involving solar assisted residences can then be attempted using previous residential load study data for gas and electricity for various climatic regions.

Figures 2 and 3 illustrate the mean monthly temperature contours for January and July respectively (Ref. 1). Note that in the summer the mean temperature in Berkeley does not indicate a need for air conditioning while in Concord 30 miles away it is required. The mean temperature at Inyokern, 116°F, should not be used for design purposes since the peak temperatures by definition exceed that value 50% of the time, in the direct sun.

For the winter months, precipitation data needs to be correlated to the availability of solar energy. A detailed knowledge of the expected numbers of sequential cloudy days (and the opacity of the clouds) will affect the size of thermal storage and collector area to be recommended for various locations. The eventual cost of solar collection components and the cost of peak, intermediate, and base load energy are expected to become major factors influencing the introduction of solar energy in California.

By considering the amount of energy used for heating and cooling, and the growth rate by building type (residential, multi-family, commercial, industrial) one can begin to formulate likely scenarios for the impact of using solar energy. Particular attention to sales of air conditioners and heat pumps needs to be correlated to peak energy demands.

Other Pyranometers

A wide variety of pyranometers have been designed and built using various principles of operation. The most commonly used variety contains Thermopiles and costs from about $500. to $1000. each; less expensive silicon solar cell varieties begin at about $100. Wig-Wag (Ref. 4) and other mechanical radiation meters have also been built. Each of these instruments also requires a means for recording the data.

Our goal is to provide an inexpensive instrument to measure solar insolation so that a large number of sites may be studied. It is also desirable to minimize the data recording, reduction, and interpretation phase of this information collection project. A mechanism for weekly data reduction that can easily be converted to on-line data collection was also desired. The minimum cost objective was balanced against the data quality and quantity objective, and it was decided to develop a new method for monitoring solar insolation.

The Thermopile approach was not selected for widespread introduction due to its high cost. The eventual need for several hundred instruments prohibits the use of a basically expensive detector. However, comparisons to this type of instrument will continue to be made in order to correlate results with historical data and to seek out trends.

A mechanical detector was not used due to expected maintenance and slightly higher interface costs. Mechanical detectors should be re-considered and are promising candidates when properly protected from wind and vibration.

Solid state detectors were not used in the initial design, since a direct measurement of the thermal heating effect of a black surface was desired for the solar heating and cooling of buildings. The following semiconductors are possible candidates for future developments of this instrument: silicon, cadmium sulfide, cadmium selenide, gallium arsenide, gallium phosphide and various ternary crystals. All other detectors are not now in sufficient production to allow the very low cost required for this application.

The difficulties with using a semiconductor are:

(1) The spectral sensitivity may limit the basic measurement to variations in the color of the sky, rather than to the energy transmitted over the entire spectrum. Absorption and reflection of solar radiation by water molecules and various pollutants will spectrally bias the measurement and need corrections. A spectrally flat detector from 200 to 1,200 nm can be assembled from a combination of blue-sensitized silicon, cadmium sulfide and gallium arsenide, but is expensive and hence unavailable for this application.

(2) The temperature dependence of semiconductor sunlight detectors requires a temperature compensation circuit or a means for measuring temperature and a computational correction algorithm.

(3) The cosine dependence of sunlight transmitted through a protective glass envelope onto a horizontal surface is affected by the properties of the horizontal surface. Non-linearities occur at the Brewster's angle. Polarization is usually not a problem, although if filters are used to smooth out the spectral sensitivity, polarization and focusing effects must be eliminated.

(4) Variations in sensitivity require strict calibration of accuracy and precision. Differences in manufacturing processes between companies and quality control variations from batch to batch result in detectors having various sensitivities.

(5) Lifetime and degradation of surface effect semiconductors should be documented. Bulk and junction devices are probably not as vulnerable to degradation, except the photons need to pass through a dirty outer protective cover and be absorbed or converted in the detector material.

In spite of the above difficulties, the rapid time response of semiconductor cells and their low cost provide a strong incentive to include one in a "percent of possible sunshine" instrument and for cloud counter applications. The combination of the thermal detector described here and a blue-sensitized silicon detector will improve the time response and hence the versatility of this instrument.

Electronic Pyranometer

Figure 4 is a cross-sectional diagram of the pyranometer. The detector is an aluminum globe with a black surface.

A sphere placed anywhere on the earth will always have the same cross-sectional area projection intercepting sunlight, both at the poles and at the equator. A flat plate is quite different due to variations in reflection from the surface as a function of declination. For a silicon detector, the cosine effect at low sun angles (or high latitudes) requires a large correction.

The black surface presents a uniform spectral absorptivity and emissivity. Since the black ball electronic pyranometer is basically a differential temperature detector, heat losses will affect its operation. A flat black paint can provide a reasonable surface. However, other instruments using a black surface have appeared to change color over long periods of time (10 years). Older instruments which now appear to be green need to be recalibrated. To avoid this effect, the process of change must be understood. At this time I am unaware of an explanation for the change in color of older detectors. It may be due to ultraviolet light degrading the pigment or perhaps a mildew effect. Until this is resolved, a flat black dull anodization (aluminum oxide) layer can be applied to the surface. If mildew is a problem, a hermetic seal, dessicant inert gas and a mildicide can be used.

The size and material of the sphere will determine its thermal mass and hence its time response. One centimeter and two centimeter radius solid spheres have been tested. The one centimeter solid sphere has a rather long time constant (about 6 minutes) which is useful to simulate the time constants of solar collectors. However, accurate data on short duration clouding can not be obtained using solid spheres. A black ball detector using a hollow sphere should have a faster time response. A theoretical analysis of the thermal balance including conduction,

convection, and radiation effects needs to be performed in order to fully understanding the meaning of the measurement.

Comparisons to other commercial pyranometers should also be performed to check the calibration of this new instrument.

Figure 5 is a circuit diagram of one version of this device. It contains two temperature transducers, an amplifier, a voltage controlled oscillator, frequency indicator, and an interface relay. A power supply, switches, mounting hardware and connectors complete the electronics package. Figure 6 is a photograph of a prototype version of this device.

A sun or black ball temperature is measured and converted to a voltage linearly proportional to temperature using National 5600 AH sensors. The bias and calibration resistors adjust the signal such that the conversion ratio is 10 mV per degree centigrade.

The difference between the temperature of the black ball and the reference temperature (in the box) is amplified. As the ambient temperature changes during the night, the differential between the exposed black ball temperature and the reference temperature should be zero. During sunny daylight hours, the black ball heats up and the differential temperature rises. Measured temperature differentials for insulated black surface detectors can be expected to approach 100°C which will produce a one volt signal. This is a signal increase by a factor of 100 over commercial detectors which typically produce about 10 mV in full noon sun. Hence the signal to noise ratio is improved, as well as the absolute voltage output.

After the temperature differential signal is amplified, it drives a voltage controlled oscillator. The oscillator has been tuned to a maximum frequency of one Hertz to match the maximum frequency acceptable by the 28-day tape recorder. Frequency modulation of the solar insolation signal

is preferred to amplitude modulation for the usual reasons of noise immunity and spike suppression. One disadvantage of recording a signal proportional to frequency on a magnetic tape is that one must accurately control tape speed, or simultaneously record a clocked time track. The latter is performed using a synchronous clock motor, a gear reduction train, a pulse translator and a parallel recording track.

A higher frequency and digital dividing circuits were not used due to their higher cost. Some variations in the output signal will occur as the ambient temperature and wind speed change. The accuracy that can be obtained with this design is a function of temperature extremes in the enclosure. Electrical heaters and fans may be included to compensate for extreme temperature variations. Additional temperature compensation circuitry can also be added to correct for variations in output frequency proportional to temperature changes of the reference electronics itself. A detailed study of these effects and their elimination has not been performed due to funding limitations. In general, the components chosen are commercially available. Replacement circuits which have stability over wider temperature ranges are available for a higher price. For example the LM 301 operational amplifier costing about $0.65 ea/100 for 0 to 70°C can be replaced by LM 201's at $5.00 ea/100 for -25°C to +85°C or by LM 101's at $8.00 ea/100 for -55°C to +125°C operation.

Summary

The goal was to design an instrument which could record solar insolation on a digital magnetic tape. The total construction cost excluding the recorder was limited to $100. or less, based on 100 unit prices.

A Westinghouse digital magnetic tape-cassette recorder was chosen as the recording device. Its normal use is for recording billing or meteorological data. The Pacific Gas and Electric Company has provided the use of a number of these recorders allocated in various California climates. Furthermore they will be collecting the data tapes using their meter reader and weather forecasting personnel. They have also provided a data reduction service using their computers and a tape translation program.

P.G.&E. is unusual in that it provides both gas and electric service. It is unique in that it uses all the following energy sources: nuclear, fossil, hydro, and geothermal; hence it is natural to be exploring the use of solar energy. If a proposed 100 MWe solar photo-thermal plant is built at Inyokern, California, we will be able to add yet another alternative fuel source.

Intensive local use of solar energy for heating and cooling of buildings (SHCB) can drastically alter the demand for gas and electricity. If a new California community of single or multiple family dwellings adopts solar energy, then the daily and hourly demand will be quite different. The capital expenditure allowed for the distribution system may also be affected, as would sales of electric heating and window air-conditioners, and hence utility revenue. The widespread use of SHCB can reduce the need for capital to build new large generating plants, and alter rate structures.

In order to know how load patterns can be expected to develop, one needs to know how much and when solar fuel can be expected for each of the cities and climates served.

Acknowledgments

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Figure 1: Weather recording stations of Pacific Gas and Electric Co. Selected pyranometer sites are: University of California at Berkeley, Oakland, Sacramento, Fresno, Redding, and Santa Maria/Bakersfield.

Figure 2: Mean monthly minimum temperature isotherms for California in January (Ref. 1).

Figure 3: Mean monthly maximum temperature isotherms for California in July (Ref. 1).

Figure 4: Cross sectional diagram of an electronic pyranometer.

Figure 5: Prototype circuit diagram for an electronic pyranometer.

Figure 6: Photograph of an electronic pyranometer.

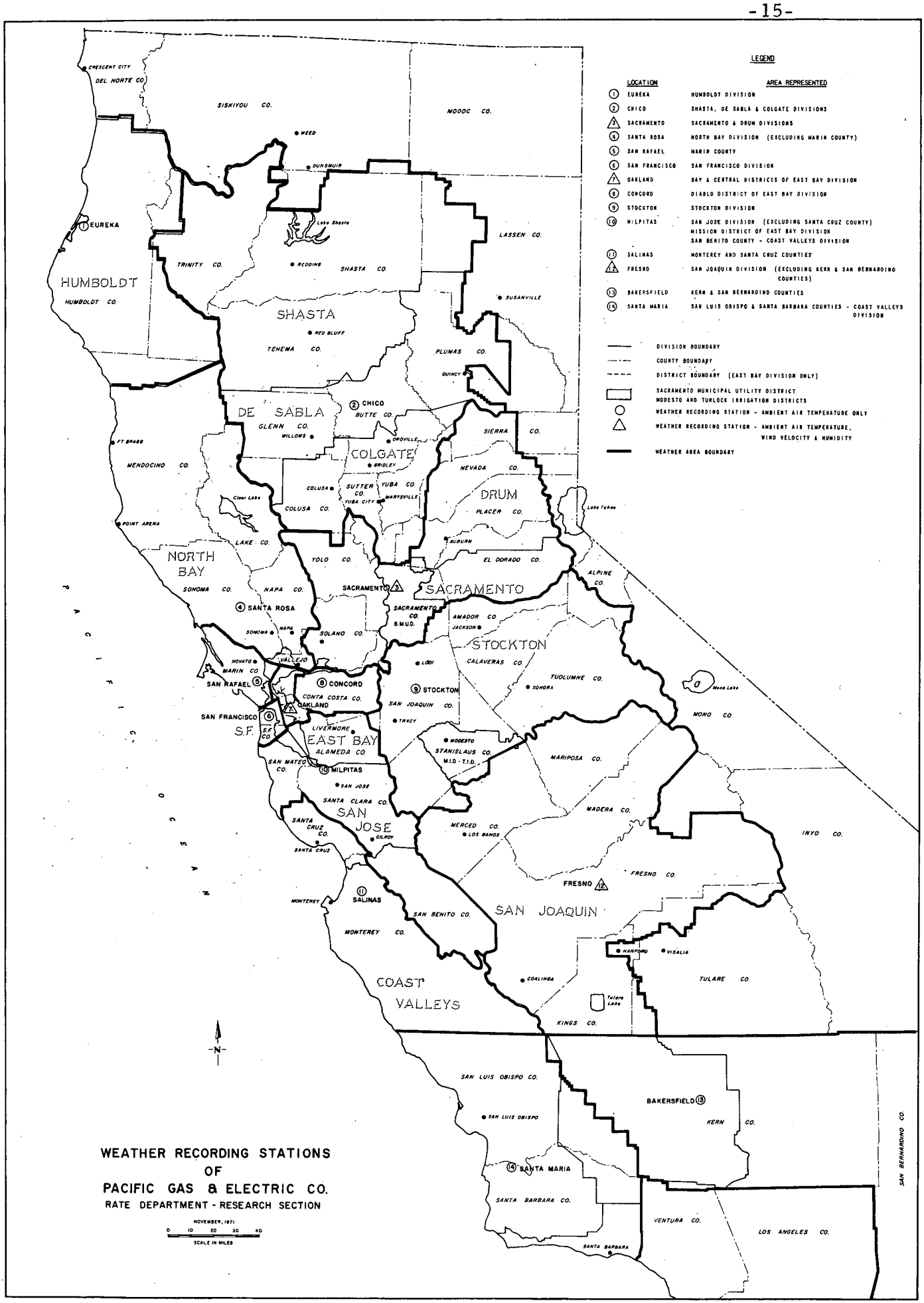


Figure 1.

XBL 751-106

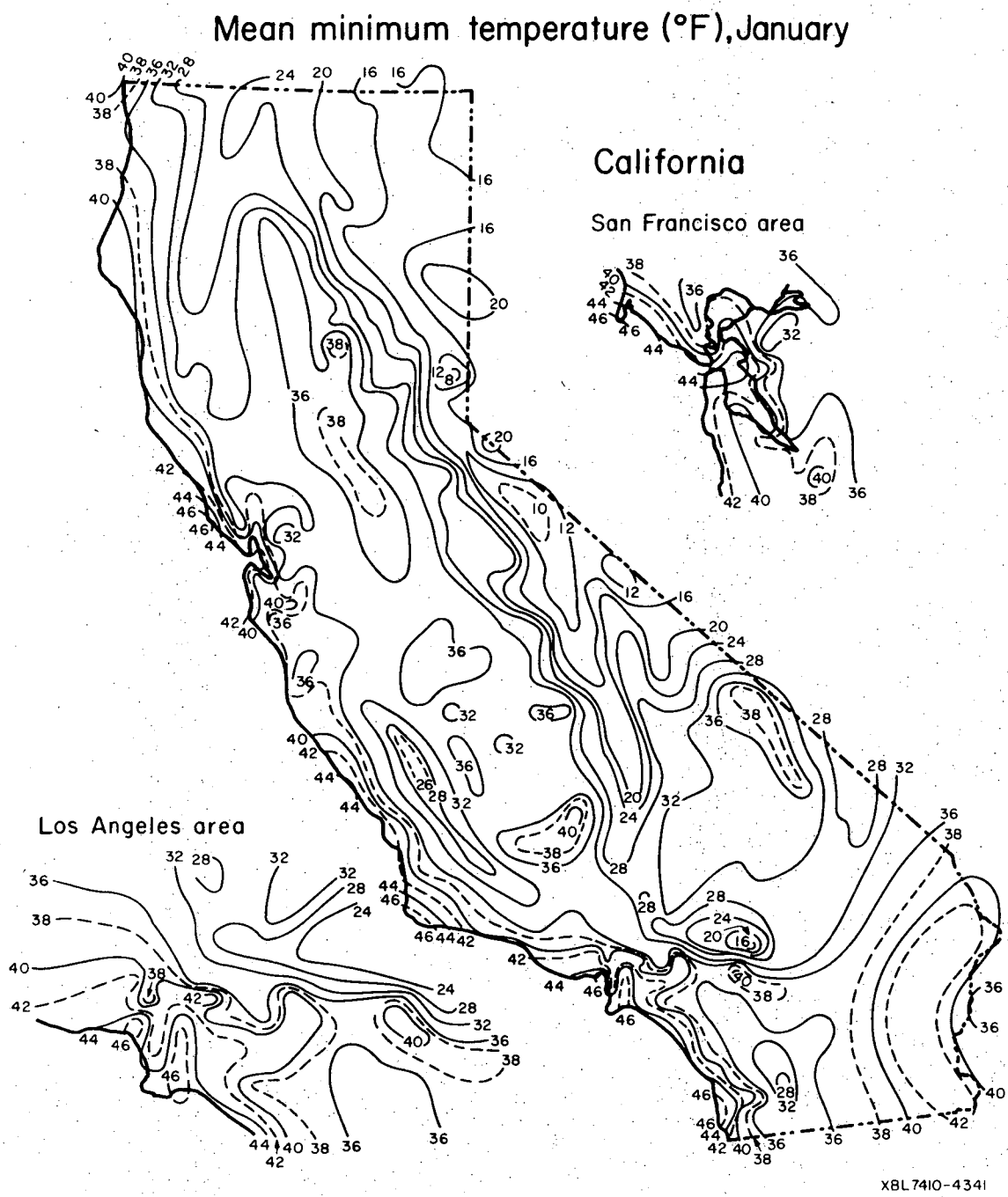

Mean minimum temperature (°F), January
California
San Francisco area
Los Angeles area
XBL 7410-4341

Figure 2.

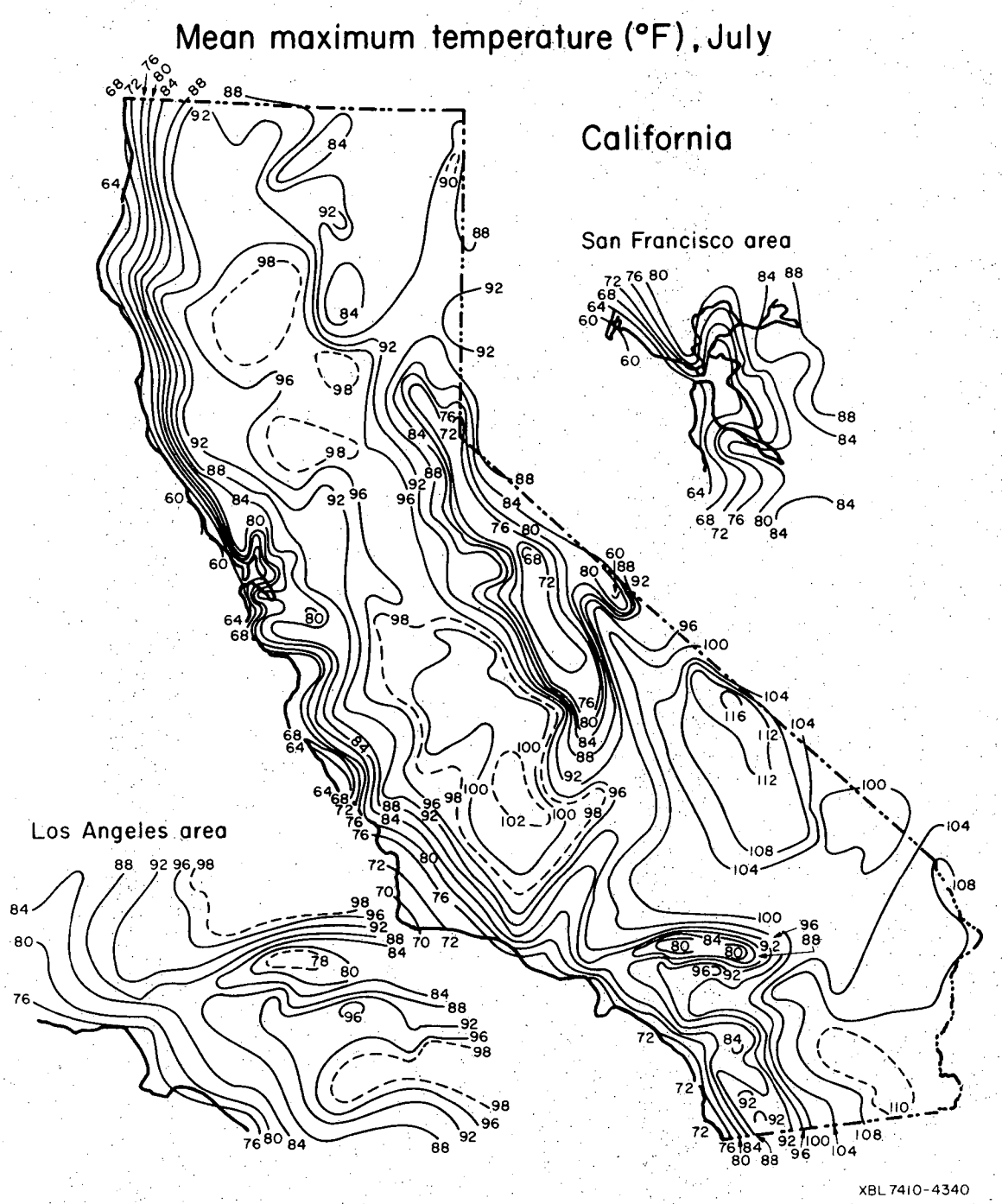
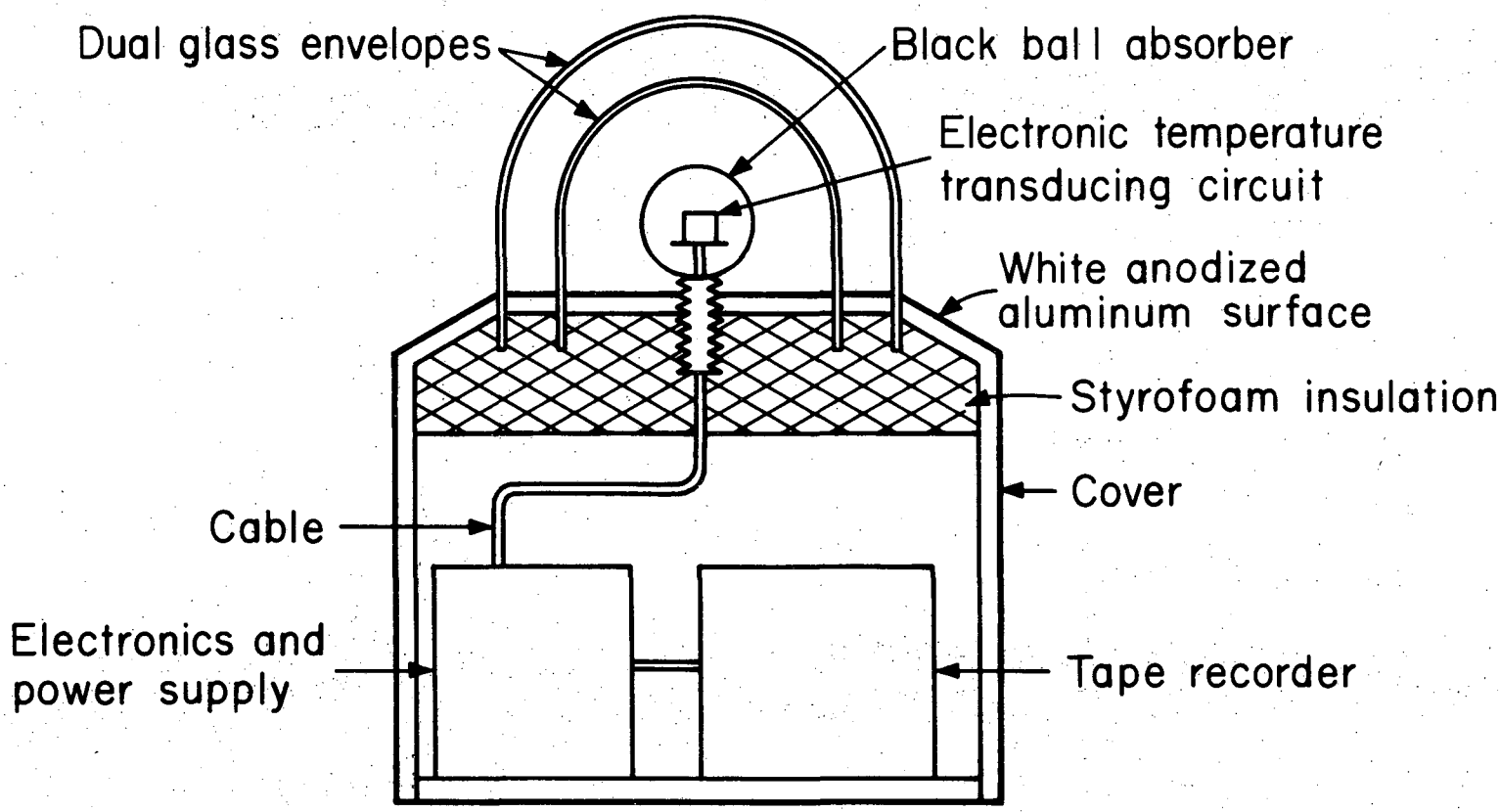
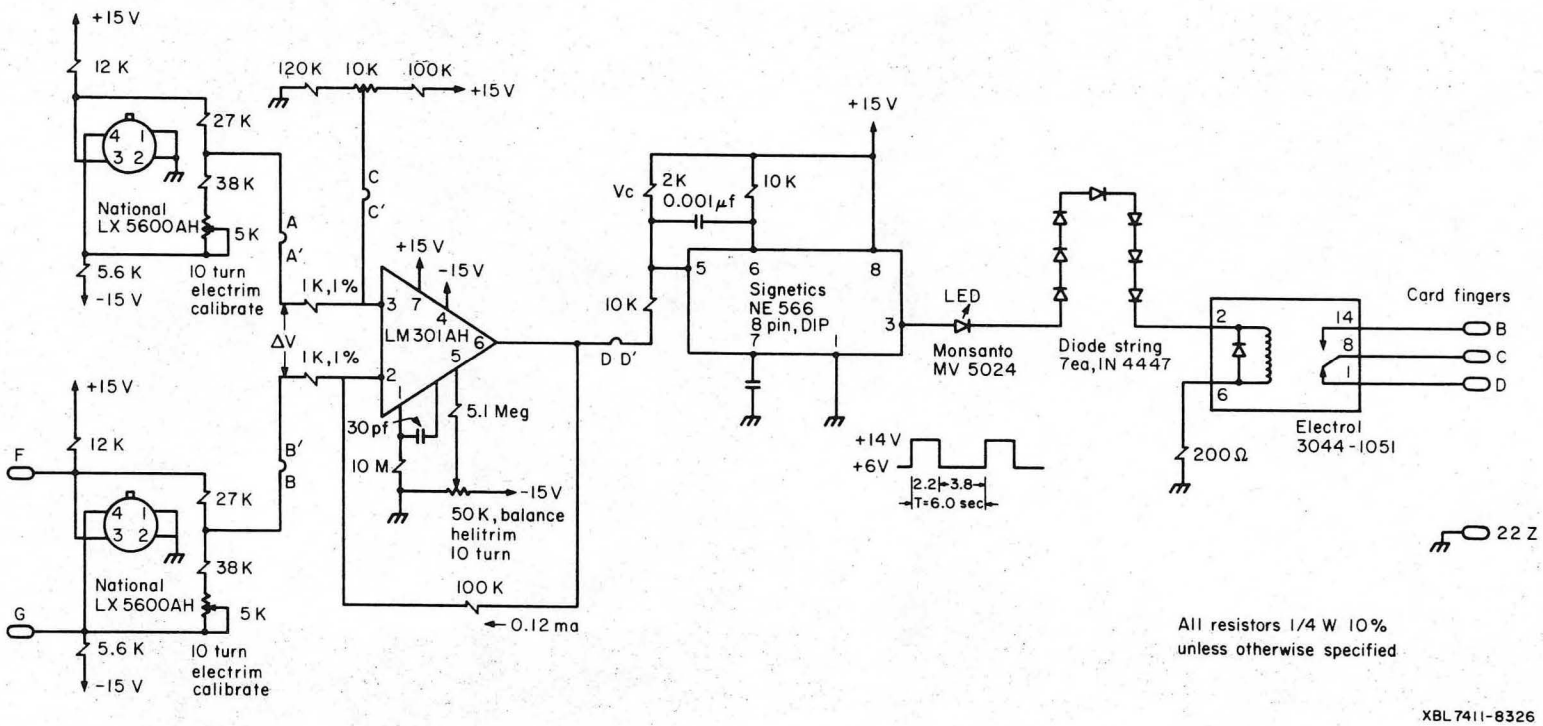

Mean maximum temperature (°F), July
California
San Francisco area
Los Angeles area
XBL 7410-4340

Figure 3.



XBL 7411-8325

Figure 4.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12 K
27 K
38 K
5 K
National
LX 5600AH
5.6 K
-15 V
10 turn
electrim
calibrate
120 K
10 K
100 K
+15 V
C
C'
A
A'
1 K, 1%
ΔV
B'
B
+15 V
-15 V
LM 301AH
30 pf
10 M
5.1 Meg
50 K, balance
helitrim
10 turn
-15 V
100 K
0.12 ma
F
G
Vc
2 K
0.001 μf
10 K
D D'
Signetics
NE 566
8 pin, DIP
LED
Monsanto
MV 5024
+14 V
+6V
2.2
3.8
T=6.0 sec
Diode string
7ea, IN 4447
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Card fingers
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All resistors 1/4 W 10%
unless otherwise specified
XBL 7411-8326

Figure 5.

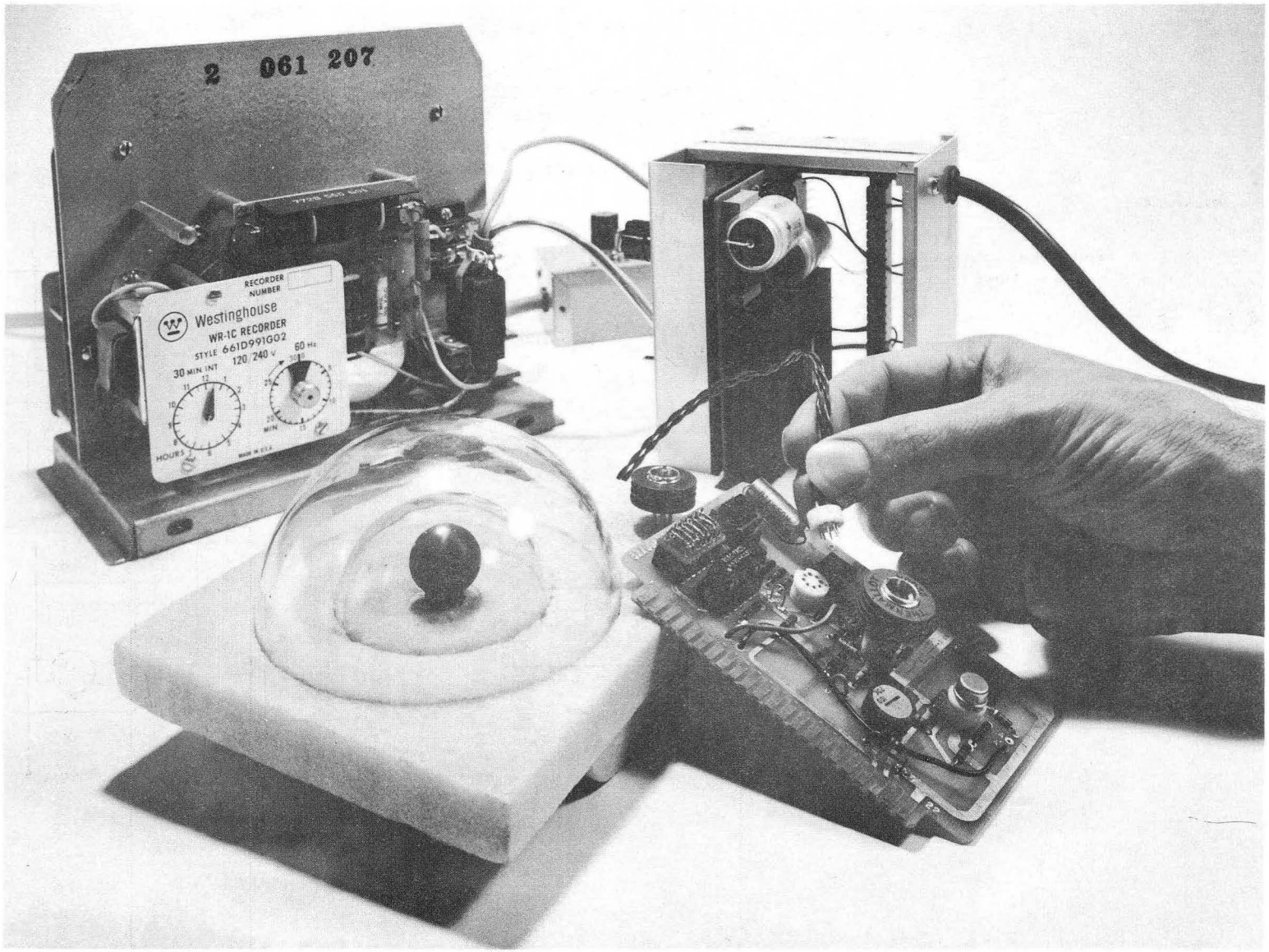

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Figure 6.

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