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**16. ABSTRACT**

An electrically powered conductive polymer overlay material, used to generate heat on a bridge deck, was developed and evaluated by the California Department of Transportation, Division of New Technology, Materials and Research. The concept was evaluated in the laboratory and a field test patch was installed on a bridge in the Sierra-Nevada Mountains to provide field performance data. The test patch consisted of a 10 foot by 10-foot conductive polymer overlay approximately 1-inch thick placed on a shoulder portion of the bridge deck. An AC voltage source was applied to produce heat by resistance. Thermocouples placed inside and outside the heating overlay recorded bridge deck temperatures. Over a fifteen day period, the average nighttime temperature in the overlay was elevated 10.9°F above the adjacent deck. This temperature elevation was achieved at a power consumption rate of 8.34 Watts per square foot, resulting in a power requirement of 0.77 W/ft<sup>2</sup>F.

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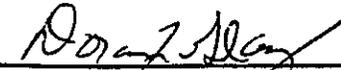
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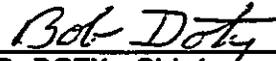
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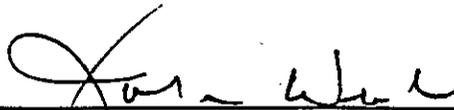
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FOR ICE CONTROL**

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Caltrans Study # F91TL01-05

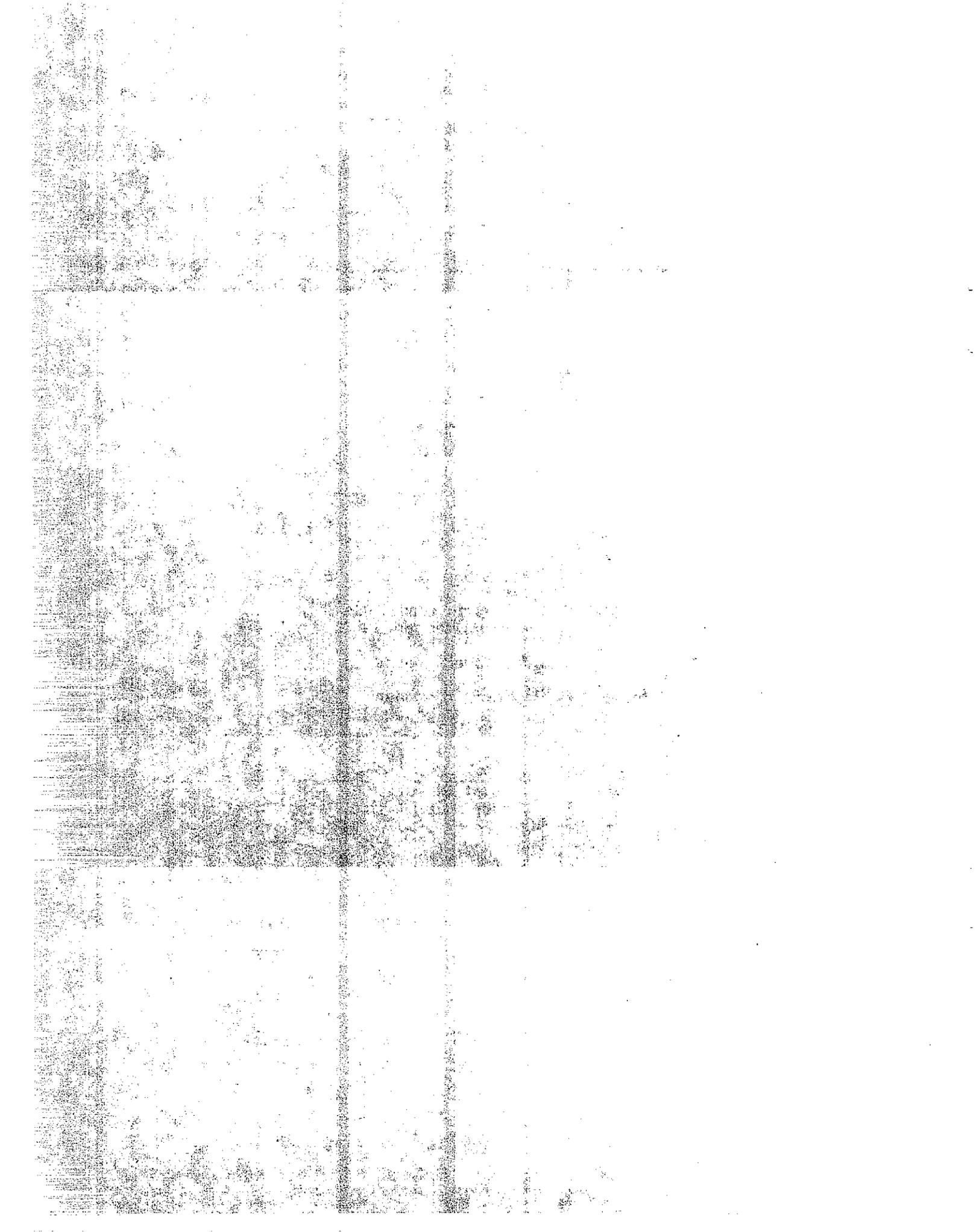
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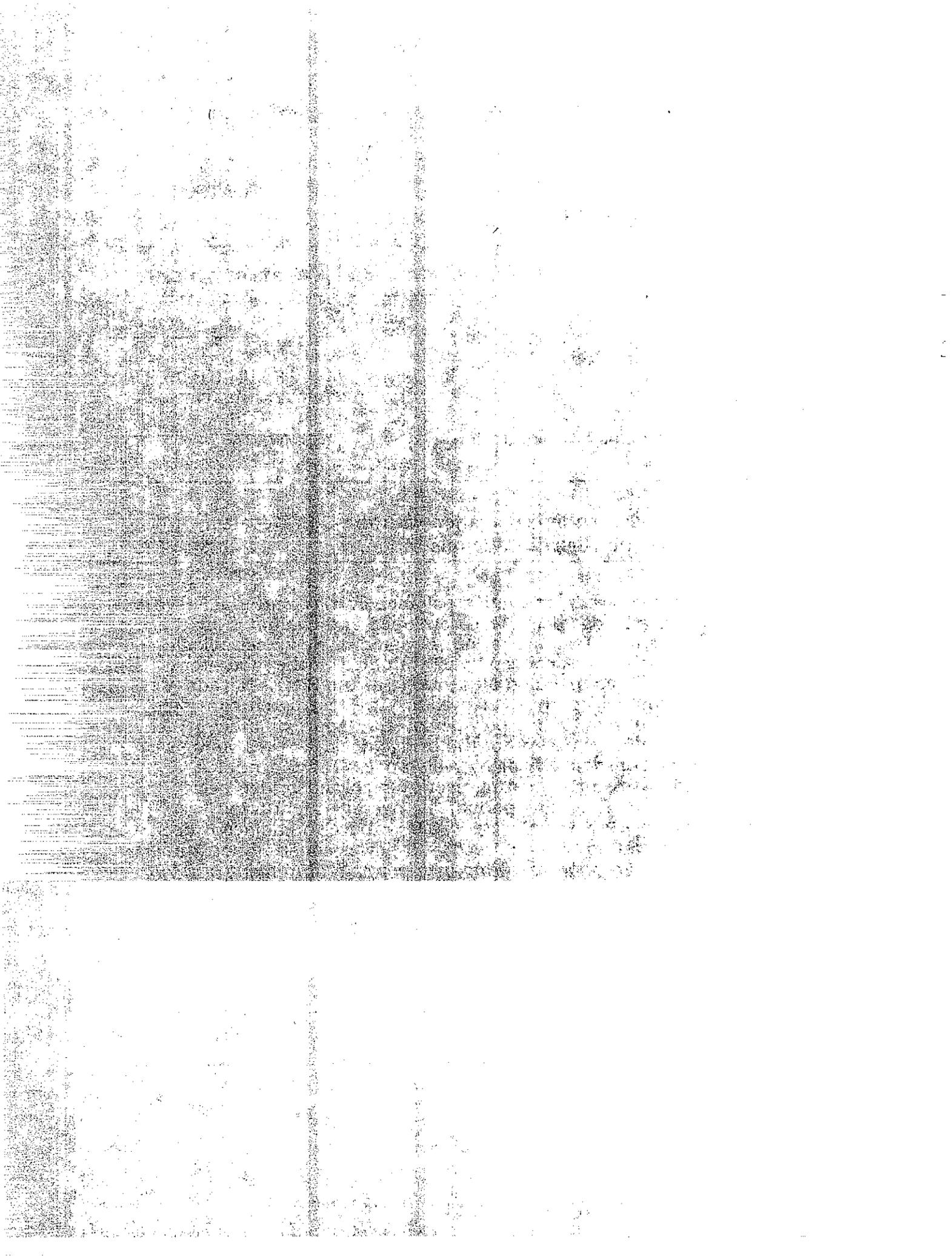
  
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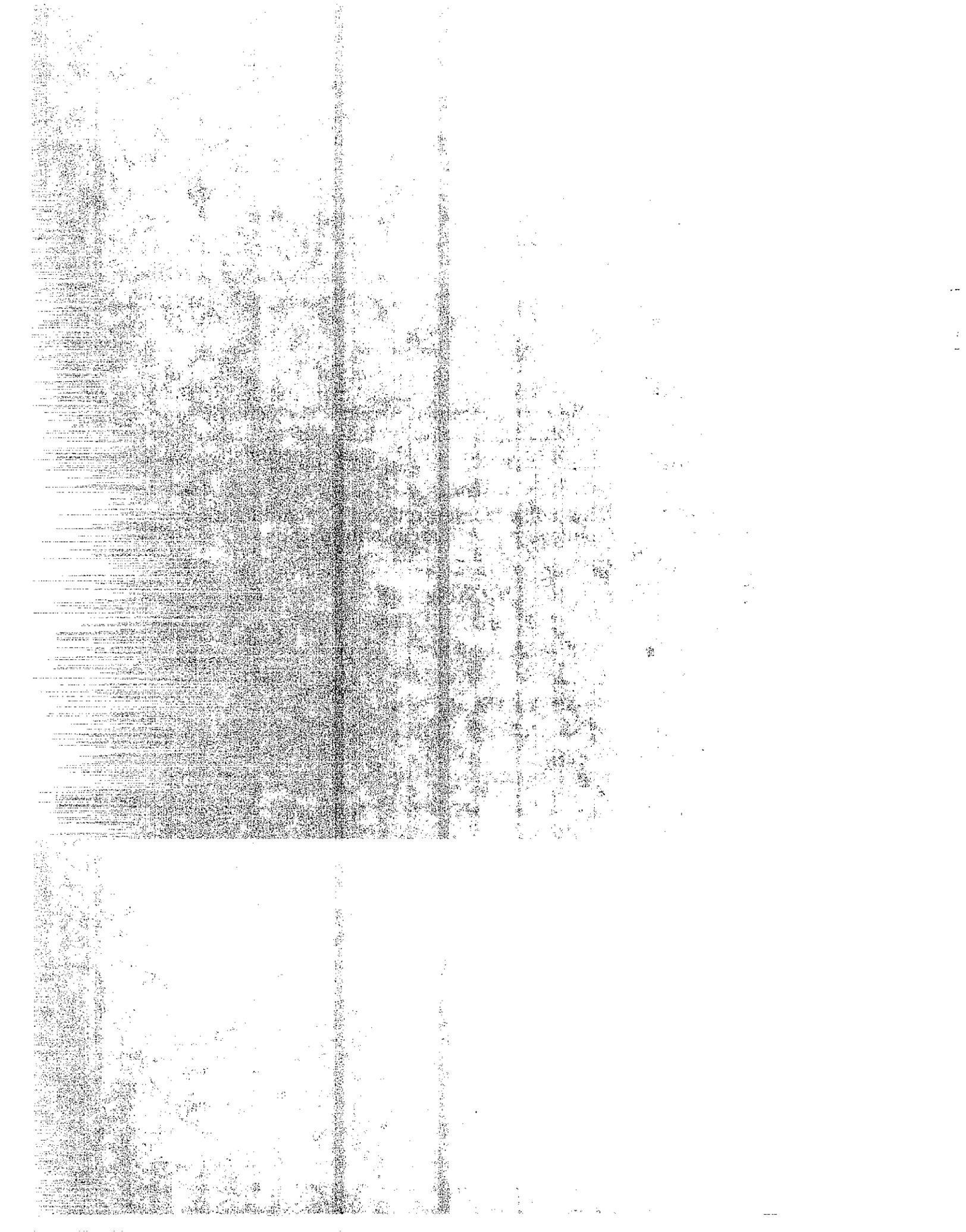
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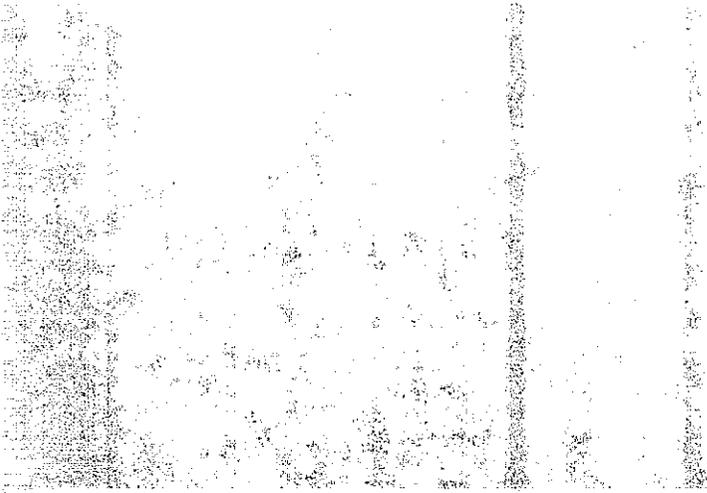
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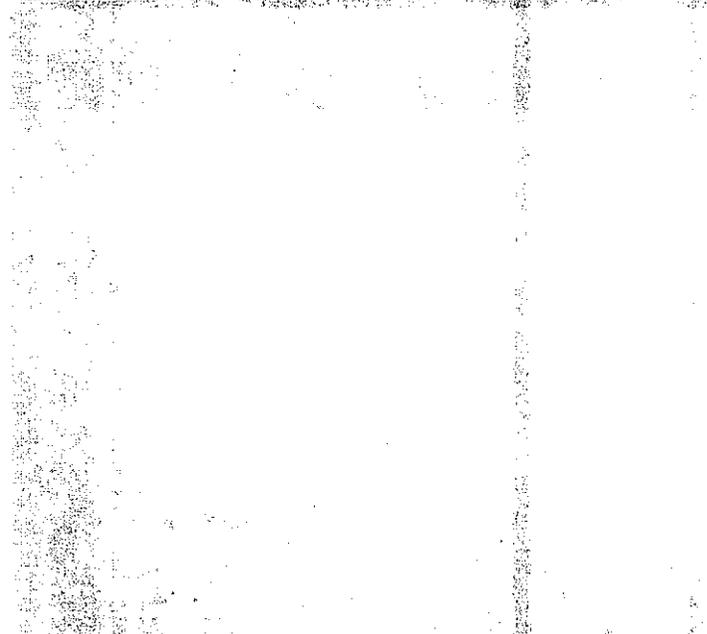
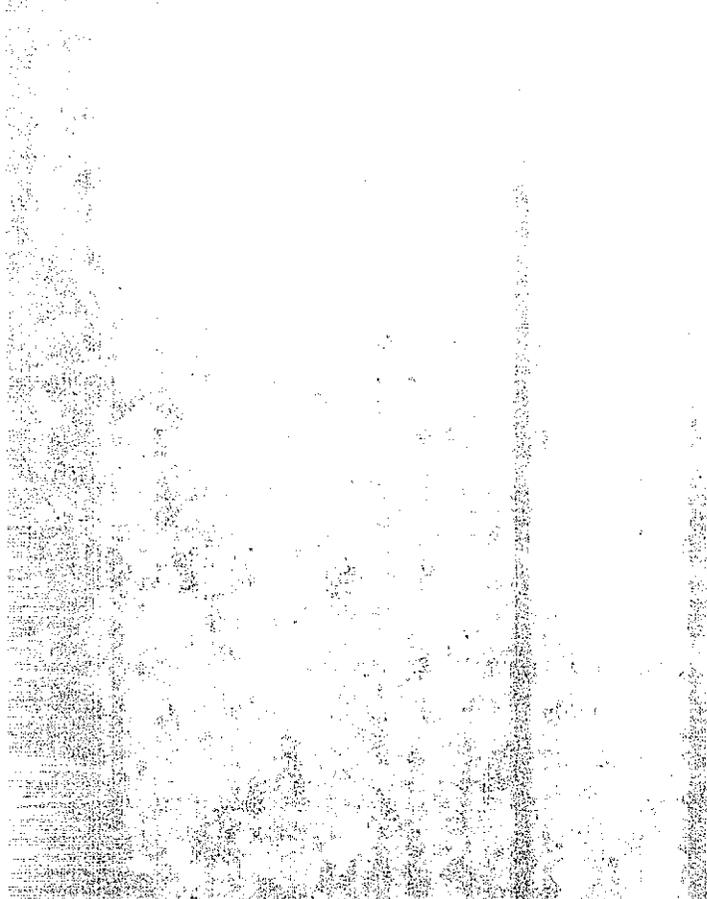
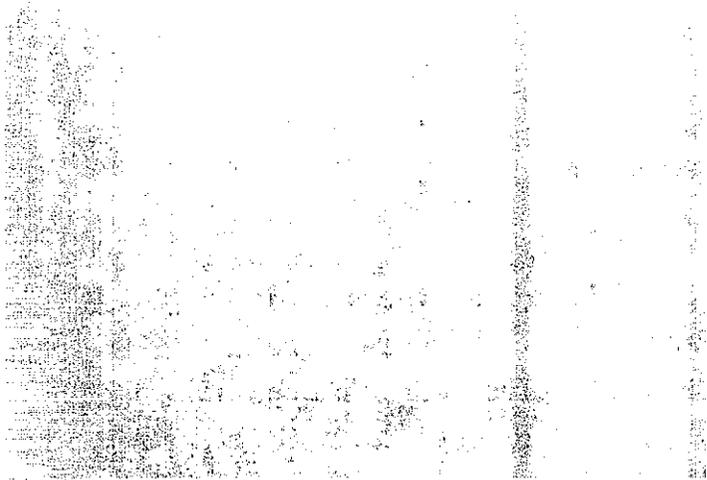
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<u>Quality</u>	<u>English Unit</u>	<u>Multiply By</u>	<u>To Get Metric Equivalent</u>
Length	inches (in) or (")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft) or (')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in <sup>2</sup> )	6.432 x 10 <sup>-4</sup>	square metres (m <sup>2</sup> )
	square feet (ft <sup>2</sup> )	.09290	square metres (m <sup>2</sup> )
	acres	.4047	hectares (ha)
Volume	gallons (gal)	3.785	litre (l)
	cubic feet (ft <sup>3</sup> )	.02832	cubic metres (m <sup>3</sup> )
	cubic yards (yd <sup>3</sup> )	.7646	cubic metres (m <sup>3</sup> )
Volume/Time (Flow)	cubic feet per second (ft <sup>3</sup> /s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph)	.4470	metres per second (m/s)
	feet per second (fps)	.3048	metres per second (m/s)
Acceleration	feet per second squared (ft/s <sup>2</sup> )	.3048	metres per second squared (m/s <sup>2</sup> )
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s <sup>2</sup> )
Density	(lb/ft <sup>3</sup> )	16.02	kilograms per cubic metre (kg/m <sup>3</sup> )
Force	pounds (lb)	4.448	newtons (N)
	kips (1000 lb)	4448	newtons (N)
Thermal Energy	British thermal unit (Btu)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb)	1.356	joules (J)
	foot-kips (ft-k)	1356	joules (J)
Bending Moment or Torque	inch-pounds (in-lb)	.1130	newton metres (Nm)
	foot-pounds (ft-lb)	1.356	newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (°)	$\frac{°F - 32}{1.8} = °C$	degrees celsius (°C)
Concentration	parts per million (ppm)	1	milligrams per kilogram (mg/kg)



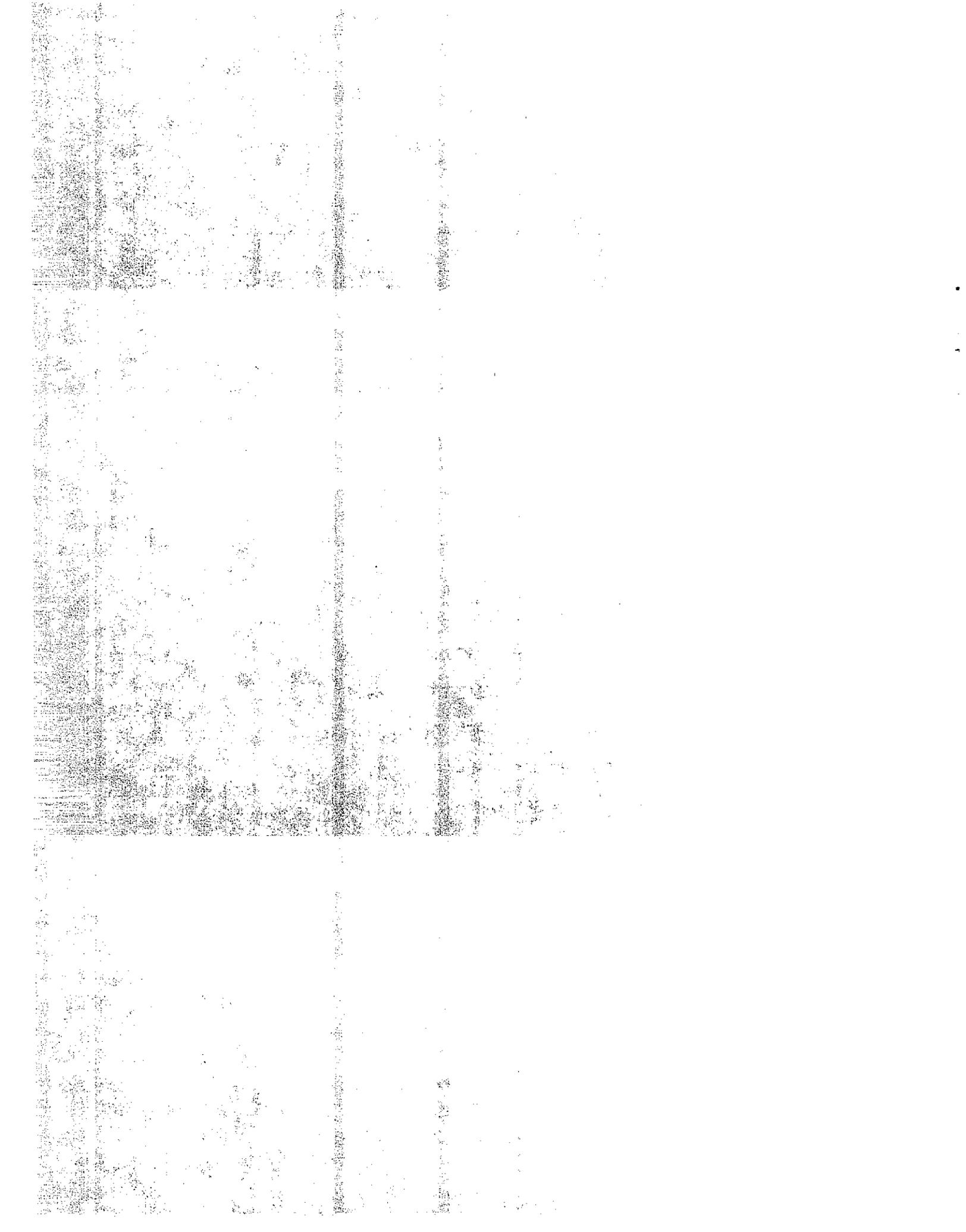
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## INTRODUCTION

The realignment of a portion of Highway 50 east of Kyburz, California, required a bridge (#25-98) over the South Fork of the American River at approximately 3560 foot elevation. Since this bridge is shaded during the winter, it experiences an excessive number of deck-ice-formation days, and, therefore requires frequent deck surface maintenance. This prompted a search for alternatives to the usual salting and sanding practices. A successful alternative would also be useful in valley and foothill areas where frost occurs (primarily on bridge decks) but snowplows and related equipment are not readily available.

Reducing ice formation on highway bridge decks has been of enduring interest for many years. Current methods involve the dispersion of abrasive and chemical deicing substances. The labor involved in bridge deck treatment can be intensive due to the necessity for constant patrols of potentially hazardous areas and the need for frequent reapplication. Icing is typically intermittent, occurring in the early morning before normal working hours, adding to the difficulty of scheduling personnel. Frequently, the bridge deck freezes while the adjoining pavements do not.

Current deicing methods utilize chemical agents which may damage the concrete, reinforcing steel, steel girders of structures and the local environment. Although various deicing chemicals are being employed and experimented with, the primary agent used is sodium chloride (NaCl). NaCl typically accelerates corrosion of reinforcing steel and steel embedments and deteriorates concrete. High salt concentrations along drainage paths can contaminate the soil, possibly degrading the local flora.

One method that would automate deicing of bridge decks and relieve structure degradation is heating the bridge deck. Various plans have been tested experimentally, including the use of resistance cables, gas tube heating, burning natural gas to heat the air in the cells of a box girder, and heat sink tubes using ground-stored energy. A new technique is heat generation within the riding surface. This technique would involve modifications to existing conductive polymer overlay technology developed for cathodic protection. Instead of impressing a voltage between the bridge reinforcing steel and the conductive bridge deck overlay to mitigate corrosion, a current is applied through the conductive overlay. This current generates heat per the applied voltage and the resistance of the overlay material. By this method, the heat would be generated at or near the riding surface.

#### CONDUCTIVE POLYMER MIX DESIGN

The experience Caltrans has had with polymer concrete overlays was employed to design a conductive polymer as a resistance heater and riding surface. A conductive polymer was originally developed as an anode and riding surface for a cathodic protection system placed on O'Brien U.C. structure on I-5 in Shasta County (Br. # 6-148L).

The mix design parameters were a result of desired physical and electrical properties. The physical characteristics needed were adequate cohesive strength, bond strength to the substrate, and a suitable surface texture. Coke breeze, a product from the processing of petroleum, coal or charcoal, provides the conductive component to the overlay while the polymer binder and mineral aggregate act as an insulator. The electrical resistance of the

final mix was dependent primarily on the quantity of coke breeze and secondarily on the amount of resin. To limit resin content, and have suitable workability to allow installation using existing equipment, the mix required efficient grading of both the coke breeze and mineral aggregate. The proper combination of these components provides the desired resistance to construct a heating overlay. The combination used for the O'Brien project appears suitable for use as a heater.

The electrical resistance principle of overlay heating raised a few unique concerns. Some of these concerns were a) potential overlay degradation due to high current densities, b) high power requirements for adequate performance, c) electrical induction into the bridge reinforcing steel, and d) uniformity of resistance.

#### OVERLAY DESIGN

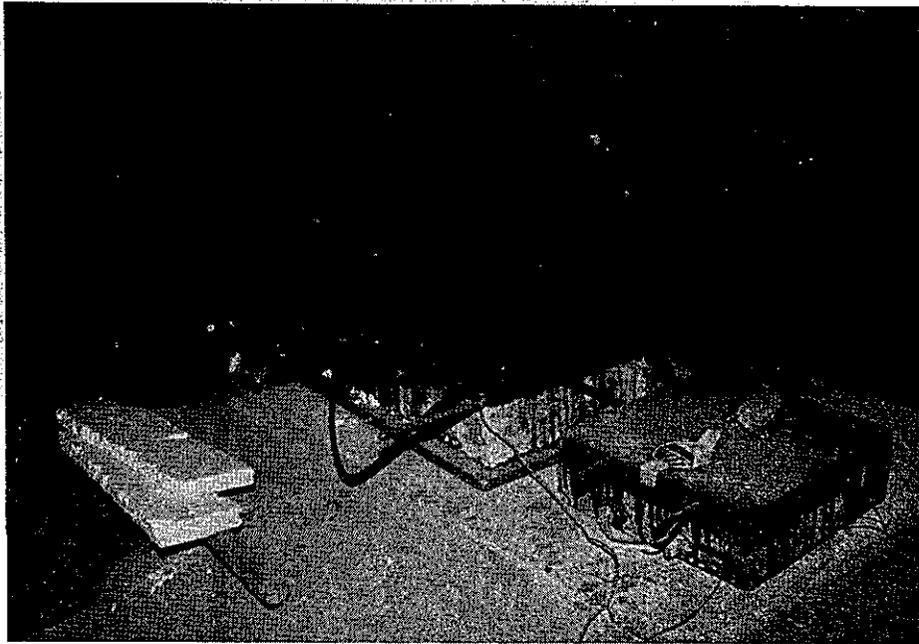
A number of specific overlay features had to be considered in the original design criteria. To mitigate propagation of stray currents into the bridge structure, an insulating prime coat of methacrylate was used rather than a conductive prime coat as used on the O'Brien cathodic protection system. The buss bar spacings, resistance values and the applied voltage were considered concurrently to achieve the designed power requirements. In accordance with a safety requirement limiting the voltage exposed to the public, a maximum of fifty volts AC was allowed to power the overlay.

#### LABORATORY TEST PROCEDURE

A model conductive polymer overlay, constructed in the laboratory, was used to validate the concept and to clarify design parameters. The model consisted of a 1' x 4' x 4" concrete slab with a 1-inch conductive overlay.

Steel reinforcing bars spaced at one-foot intervals were set in the overlay as electrical terminals, (Photos 1 and 2).

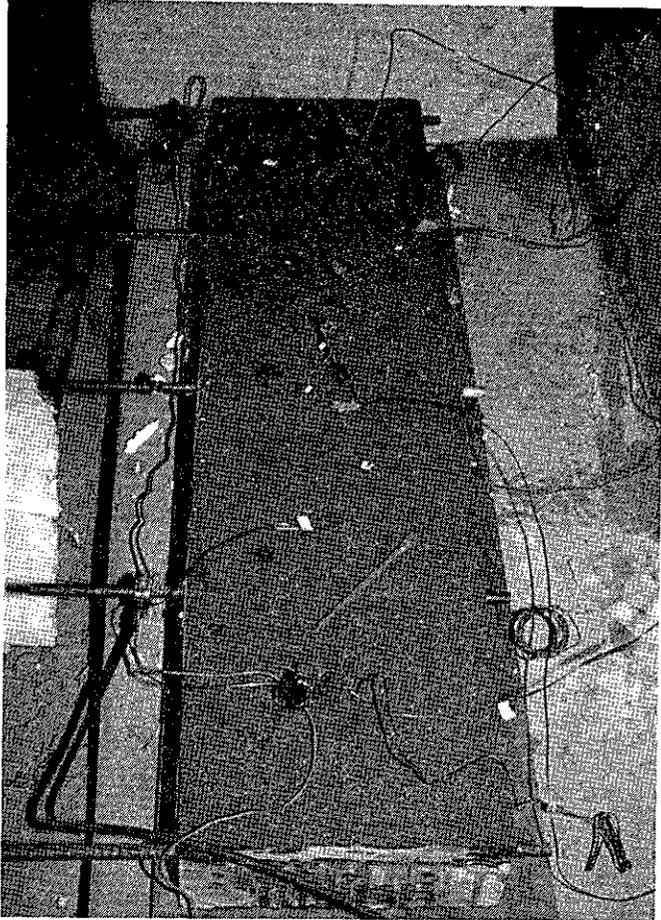
A power source was connected to the outermost steel and the power was measured at different voltages. The model was instrumented with thermocouples and placed in an environmental chamber. Figure 1 shows the temperature at various locations in the overlay, the air temperature of the environmental chamber, and the temperature of a separate slab of concrete used as a "control". The data obtained from the model provided an approximation for field temperature responses and power requirements.



**Photo 1.**

**Model Overlay Used in Lab**

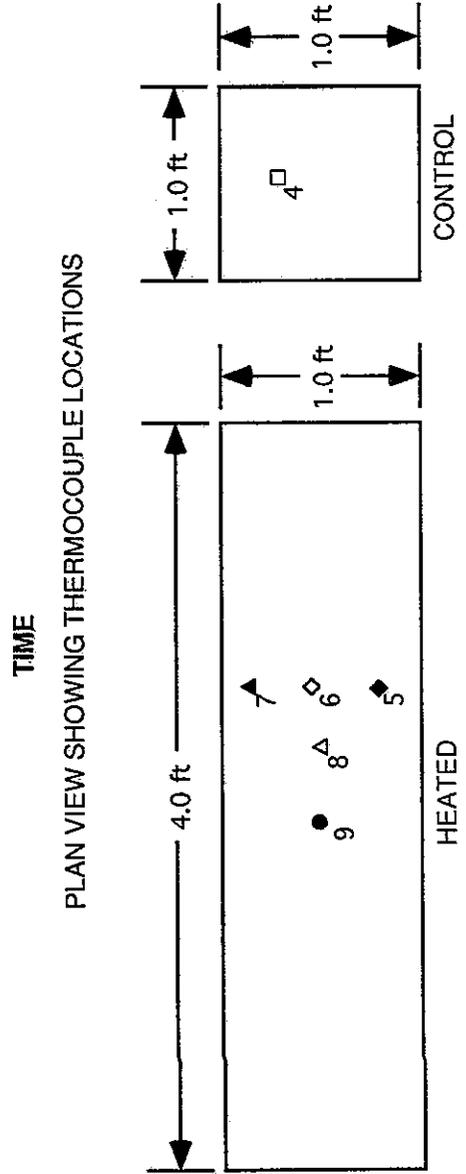
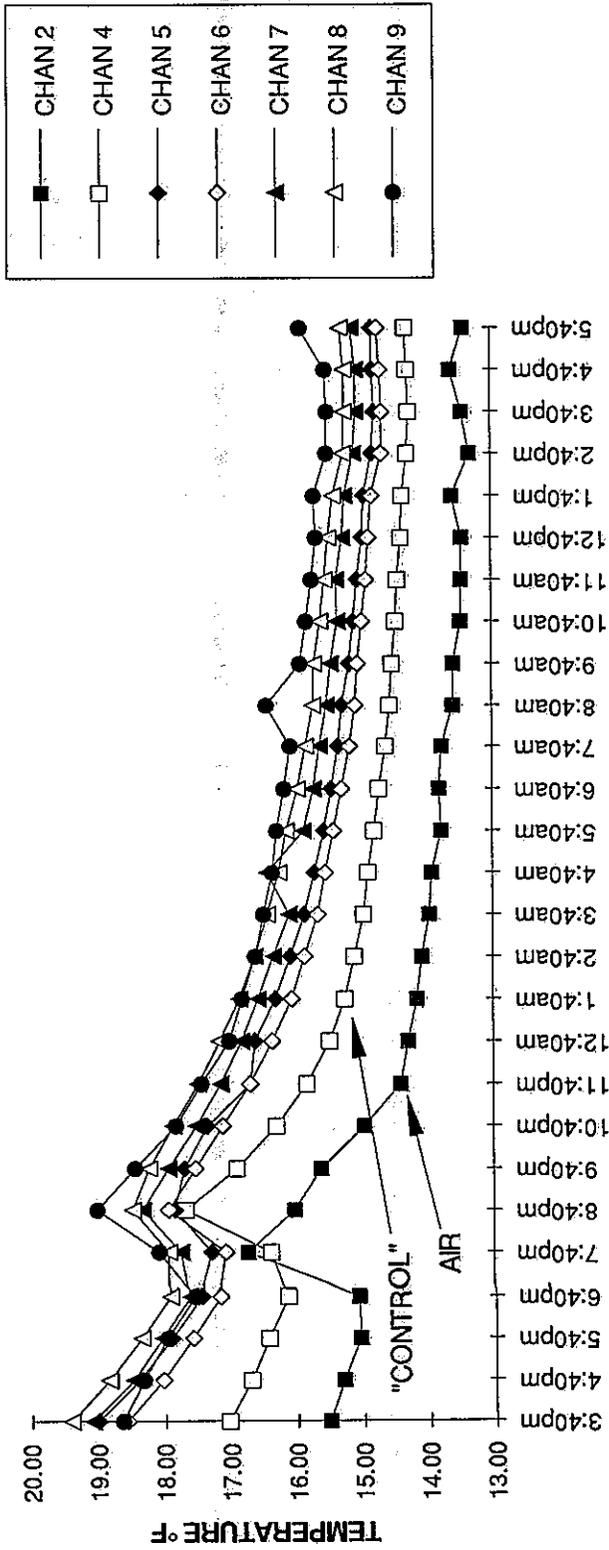
Note: Smaller Slab to the Right Used as a Control



**Photo 2**

**Model Overlay Used in Lab**

**FIGURE 1**  
**MODEL CONDUCTIVE POLYMER OVERLAY**



All Thermocouples at Middepth of Overlay

## FIELD TEST PROCEDURE

A field trial section was placed on an existing bridge deck and instrumented for data collection. The bridge was Castle Peak Undercrossing (03-Nev-80-R5.07, Bridge # 17-75R), located just above 7000' elevation. It is a concrete T-Beam 122' long by 51' wide, built in 1962. The test section was 10-feet long by 10-feet wide by one-inch thick, located on the right shoulder about 25 feet from abutment 1. The location on the bridge avoided the possibility of ice melting off the overlay and forming sheet ice in the unheated traffic lanes.

The test section was heavily instrumented with temperature and voltage sensors. Thermocouple positioners were used to ensure accurate vertical locations of sensing junctions. The positioners were fabricated from the same material as the overlay in order to provide electrical homogeneity. Photo 3 shows the thermocouple ends attached to the positioners. The data logger and power controls were stored in a traffic controller cabinet located beneath the bridge. Table 1 describes the material used to fabricate the overlay.

**TABLE 1**  
MATERIALS

	Manufacturer	Code# or Brand Name	Source
Isothalic Polyester Resin	Reichold	32043-15*	Azusa, CA
Pea Gravel	Lone Star	B-39	Monterey, CA
Sand	Lone Star	B-11	Monterey, CA
Coarse Coke Breeze	Asbury Graphite	S/N 218R	Rodeo, CA
Fluid Petroleum Coke	Loresco	DW1	Hattiesburg, MS
Methacrylate	(blend of several brands)	-----	-----

\* With 3/4% BYK 740 Wax.



**Photo 3**  
**Thermocouple and Positioner**



**Photo 4**  
**Power Cable to Rebar Distribution Rod**

The installation began on October 10, 1990 by preparing the surface of the overlay site. Some existing polyester concrete and patches of asphalt in the adjoining No. 3 lane were removed with chisels and hammers. The area was swept off and cleaned by a portable 12-inch wide steel shot blaster. It was necessary to go over the area 4 or 5 times to clean the deck sufficiently.

Using a roto-hammer drill, one-half-inch holes were drilled through the deck. After all the holes were drilled in the overlay area, the four stray current sensors were installed. The connecting wires were put through the deck and tied off to a column. All holes were back-filled with high alumina cement patching material. After the material had set, the area was given a rough sweep with a stiff broom and a finish sweep with a hand brush. The high molecular weight methacrylate (HMWM) prime coat was then applied.

The following day, holes for the deck temperature thermocouples outside the test patch were drilled. The power lines and all the sensing wire leads were fed through the holes. The area underneath the bridge was coned off where the wires met the road and the excess wire was coiled up and taped to the column. Bar reinforcing steel (#4), epoxied to the deck was used to deliver the current to the overlay, (Photo 4).

Two lengths of 1" x 1" steel angle 10  $\frac{1}{2}$  feet long were used as the screed rails. Each angle was temporarily epoxied to the deck. The strikeoff, a 3-inch diameter pipe, was rolled on the screed rails to check the uniformity of depth of the overlay and the final depth of the thermocouples before placement of any overlay material.

A general mixing and placement procedure was followed for each batch. A five cubic foot gasoline powered concrete drum mixer was used. The batched weight of uninitiated polyester resin was placed in the rotating mixer drum (this helped to keep the interior clean and prevented any remaining polyester concrete from setting up). When a batch was needed, the peroxide initiator was added to the resin and allowed to mix for approximately 15-30 seconds. The pea gravel was then added to help blend the peroxide and the resin thoroughly. Finally, the sand and the coke were added and mixing continued for no less than 2 minutes. The drum of the mixer was tilted so that the entire batch was consistent in quality and fluidity.

After the mixed material was discharged into a wheelbarrow and transported to the screed, it was spread with a shovel in front of the strikeoff. The strikeoff rolled easily on the steel angle screed rails, consolidating the material to the desired elevation. The edges of the overlay were finished off with steel trowels. Before the resin on the surface was set, Number 2 sandblast sand was broadcast to provide skid resistance. Construction progressed from the bridge rail toward the traveled way.

A total of 7 batches, some differing in resin content, were used. The weights used are given in Table 2.

**TABLE 2**

ACTUAL BATCH WEIGHTS (lbs)

BATCH	SAND	ROCK	COKE BREEZE	PETROLEUM COKE	RESIN	TOTAL
1	50	50	50	16.7	37	204
2	50	50	50	16.7	34	201
3	50	50	50	16.7	33	200
4	50	50	50	16.7	32	199
5	50	50	50	16.7	32	199
6	50	50	50	16.7	32	199
7	16.4	16.4	16.4	5.5	10.4	65

Note: Air and deck temperatures, when placement began (14:15), were 62°F and 78°F respectively. Placement was completed in approximately 1 hour.

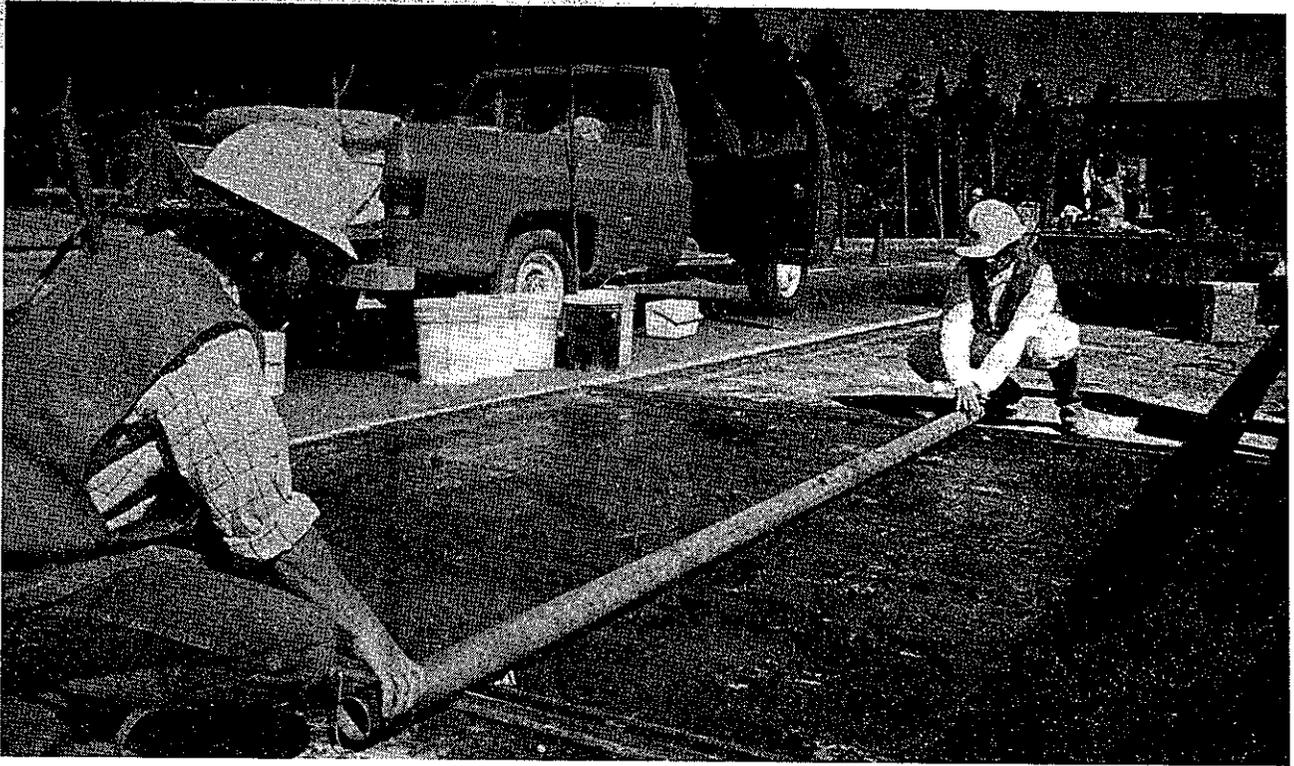


Photo 5  
Strike-Off and Screed Rails



Photo 6  
Batching and Mixing Conductive Polymer Concrete

## INSTRUMENTATION

The test overlay and the adjacent bridge deck were instrumented with thermocouples and voltage sensors. The power supply voltage and current were also monitored. Nine of the thermocouples were positioned  $\frac{1}{4}$ -inch below the surface of the heating overlay and one was placed approximately  $\frac{1}{2}$ -inch below the center of the overlay in the original PCC deck. Three thermocouples were located 5 ft beyond each end of the heating overlay (see Figure 2 for thermocouple locations). Another thermocouple, placed next to the air temperature sensing bulb, was used to sense the air temperature below the bridge. The sensing bulb was connected to a relay and controlled the power delivery to the overlay. Overlay power was energized when the temperature dropped below about 35°F. A Fluke data acquisition system was used to record data to paper tape and to memory every three hours when the temperature was above 35°F, and every 30 minutes when the air temperature fell below 35°F.

Voltage sensors consisted of two-inch PK nails which were set into three-inch holes drilled into the deck. These were placed in the overlay to check uniformity, the supply voltage, and bridge rebar potential. The current flow through the overlay was also measured.

# CASTLE PEAK HEATING OVERLAY

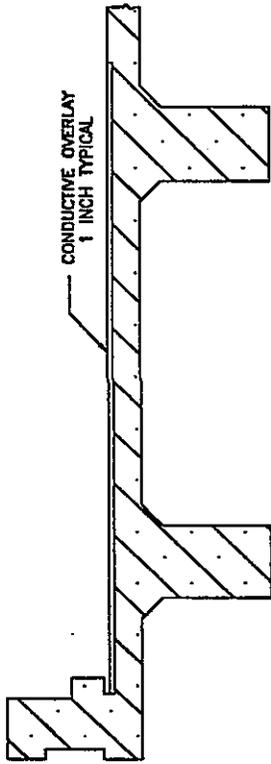
## THERMOCOUPLE LOCATIONS

BRIDGE NO. 17-075R CALIFORNIA DEPARTMENT  
03-NEV-80-R.5.07 OF TRANSPORTATION

MARCH 27, 1992 R.MELINE

DIVISION OF NEW TECHNOLOGY,  
MATERIALS AND RESEARCH

NOTE: NOT TO SCALE  
PK SENSORS NOT SHOWN  
GIRDER WIDTH MAY VARY  
CIRCLED NUMBERS REPRESENT  
T/G CHANNEL AND LOCATION



SECTION A-A

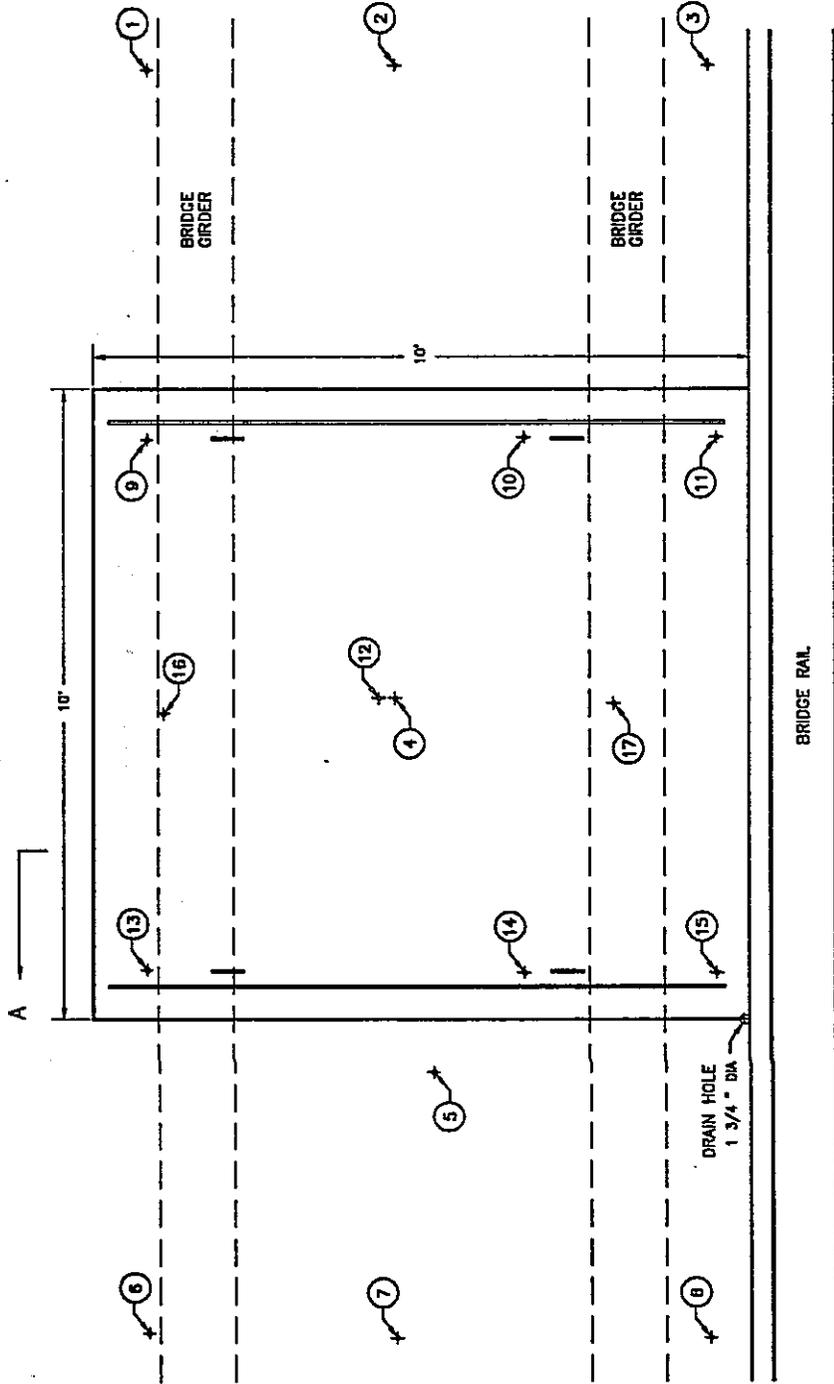


FIGURE 2

PLAN

## RESULTS

The placed overlay generally met the initial design criteria. Visual inspection revealed a sufficient uniformity in thickness and surface texture. A resistance of 8 ohms-cm was obtained, exceeding the targeted value of 2 ohms-cm. This unexpectedly higher resistance was probably due to a resin content above the lab tested mix design. The resistance between the rebar electrode and the half-inch diameter voltage sensor measured less than 0.15 ohms. This indicated that electrical contact between the overlay and the rebar used as the electrode was sufficient.

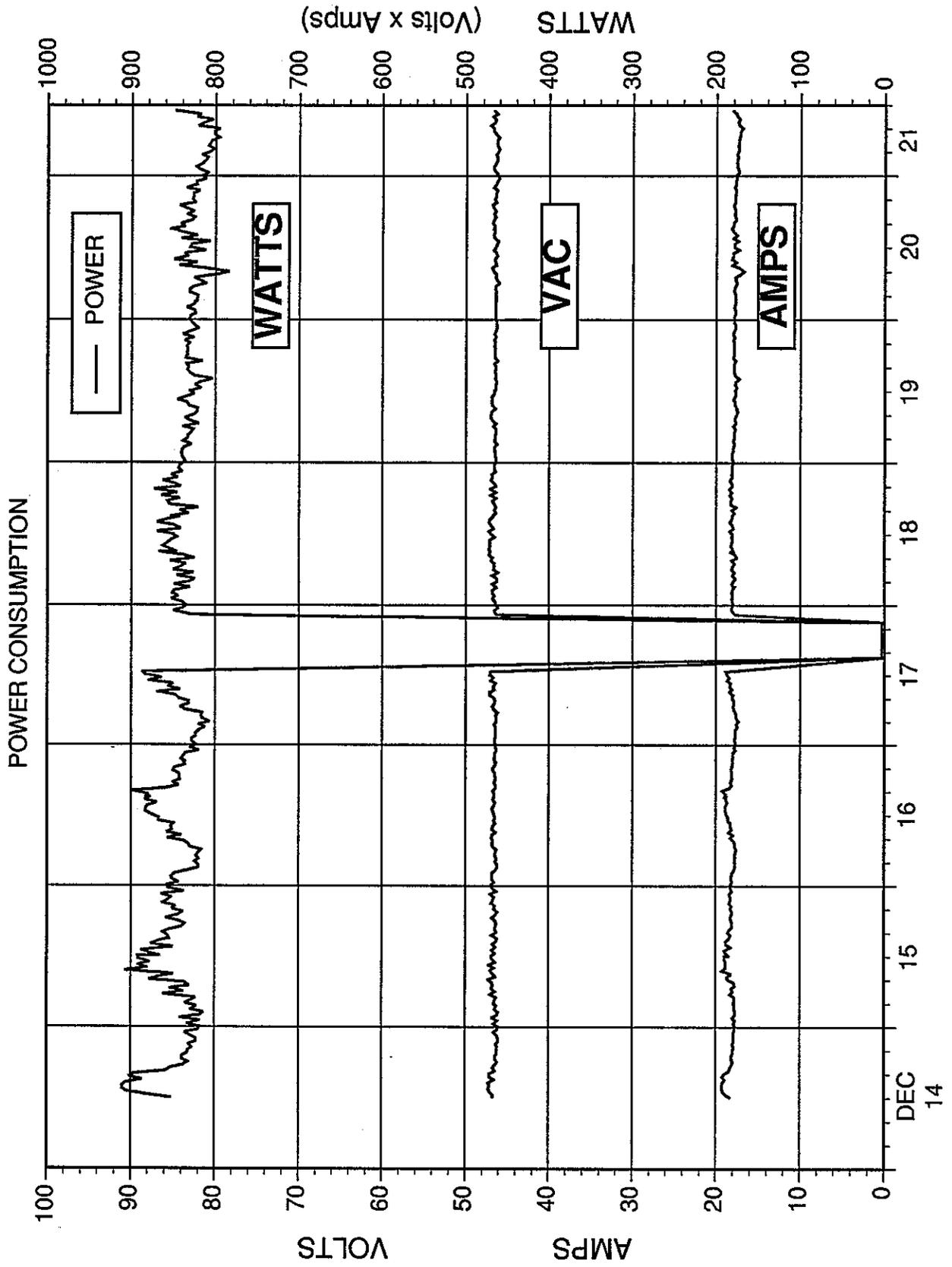
The information retrieved from the data acquisition system indicated all the components were functioning properly except #5 and #8 thermocouples (see Figure 2 for the locations). The current and voltage information showed that the control system was delivering power to the overlay when the air temperature was below 35°F. The deck and air temperatures are graphically shown in appendix A and B. The complete data is listed in Appendix C and D.

The power consumption graphs, Figures 3 and 4, for the periods of December 14 to 21 and December 28 to January 12, 1991, illustrate the power used on a half hourly basis. The voltage and current data drop to zero when the overlay was turned off and are not included in the following calculation. The power consumed to heat the overlay averaged 834 Watts or 8.34 Watts per square foot from December 28 to January 12. Over the same period the overlay maintained a current flow averaging 17.8 amps or a flux density of about 0.15 amps/inch<sup>2</sup>.

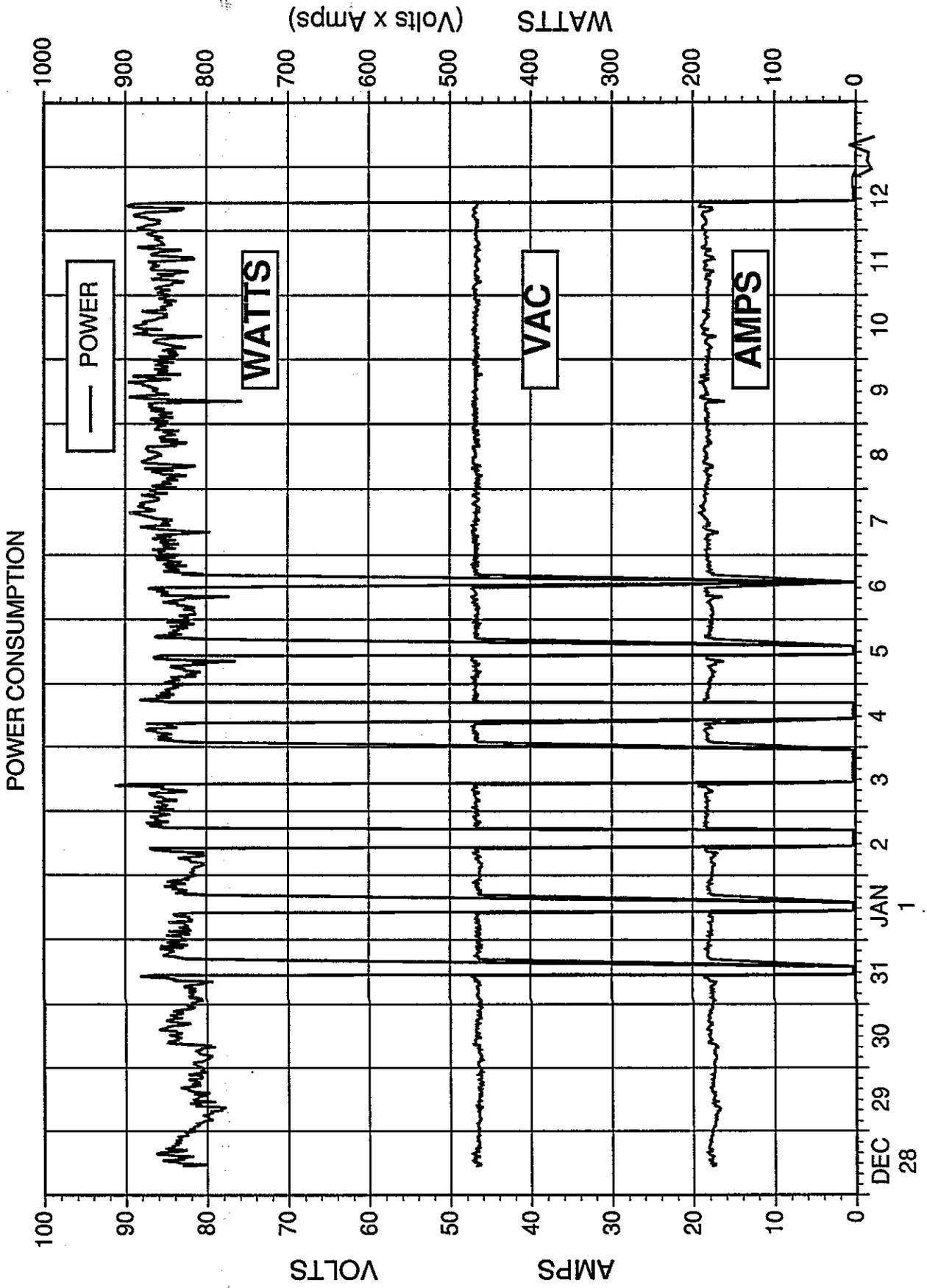
There was an indication that the resistance of the overlay increased with decreasing temperature. In both Figures 3 and 4 there was a cyclic component to the power curve which corresponded with temperature fluctuations in the overlay from day to night. Overlay temperatures on December 19, 20, 21, 28 and 29 were low and reduced current flow and a corresponding drop in the power level resulted on those days. Figure 5, a plot of resistance over time, contains the same type of pattern. Two explanations consistent with conductive material behavior theories were formed concerning the cyclic resistance data. The first possibility is the change in resistance due to the change in temperature of the material. The second is a change in the resistance due to a change in material stress caused by the initial shrinkage of the overlay and the coefficient of thermal expansion difference between the overlay and the reinforced concrete substrate. A combination of these could also be possible. However, the overlay displayed no discernible change in conductivity due to continued curing or aging, eliminating this explanation for the resistance changes.

Interpretation of voltage induced into P.K. nails and underlying reinforcing steel proved difficult and inconclusive. According to the Structures Electrical Section, the P.K. nails did not serve their intended purpose.

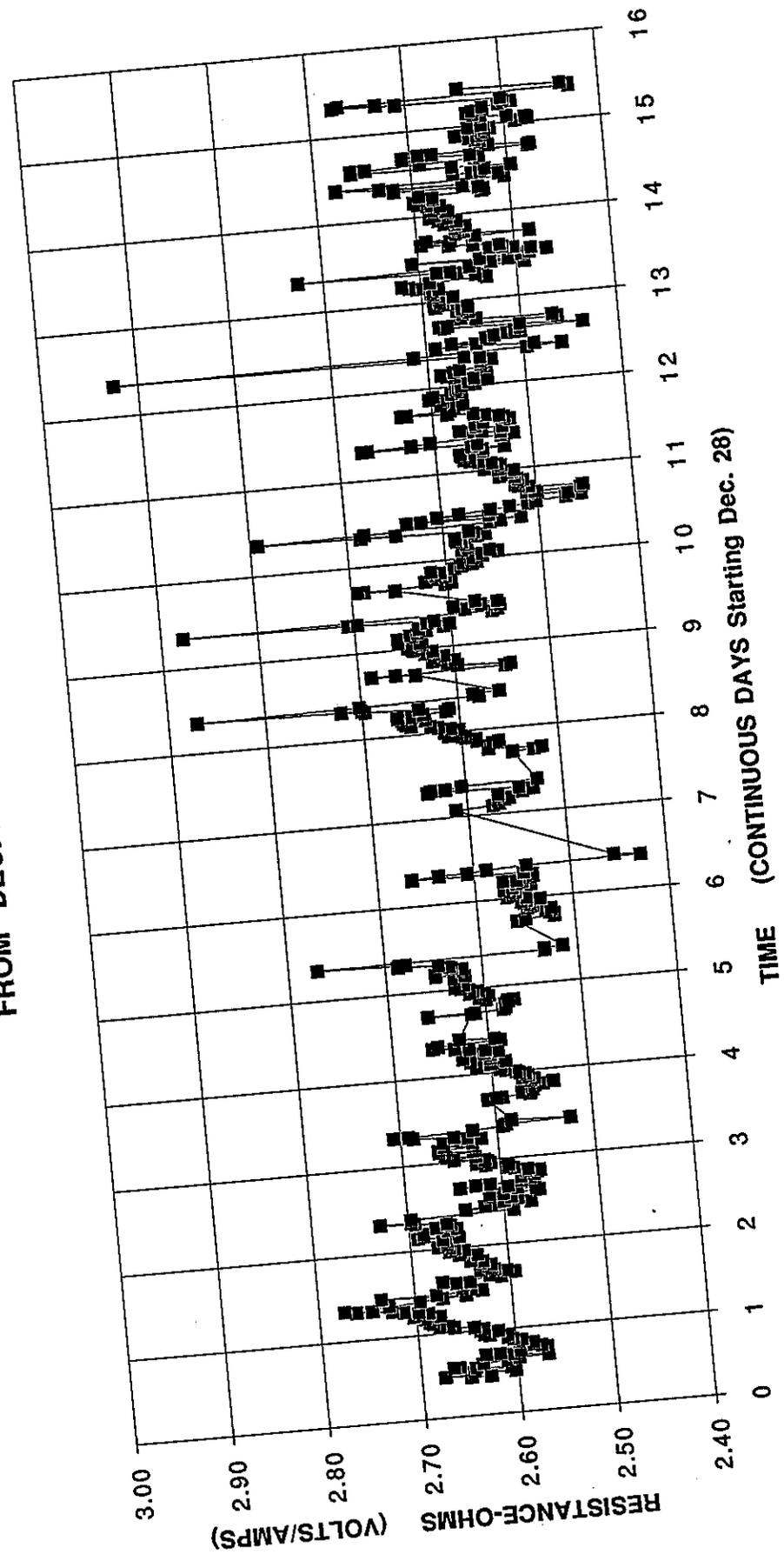
**FIGURE 3**  
**CASTLE PEAK HEATING OVERLAY, DEC. 14 - 21, 1990**



**FIGURE 4**  
**CASTLE PEAK HEATING OVERLAY, DEC. 28, 1990 - JAN. 12, 1991**



**FIGURE 5**  
**RESISTANCE CHANGES WITH RESPECT TO TIME**  
**FROM DEC. 28 TO JAN. 12, 1991**



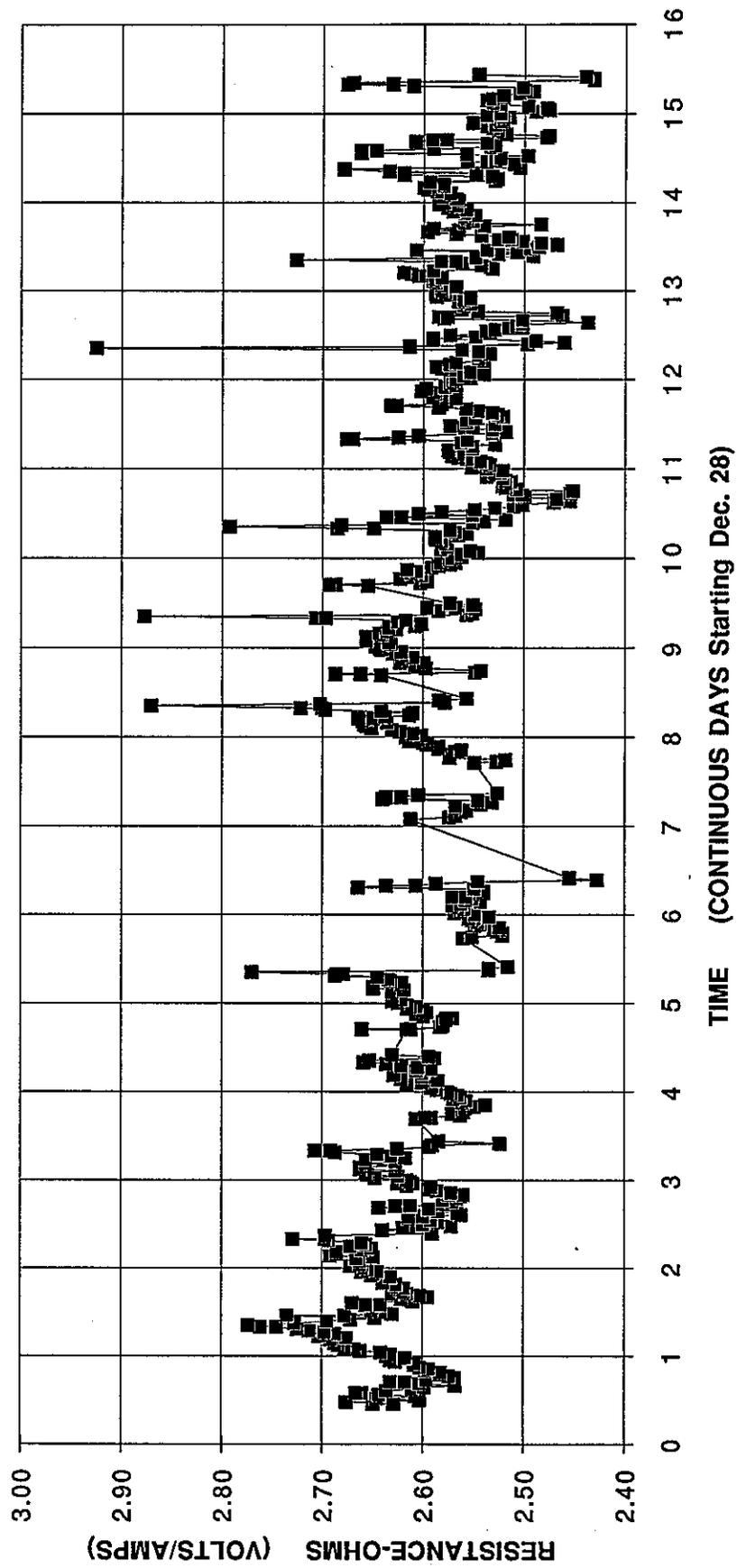
## TEMPERATURE RESPONSE OF OVERLAY

The temperature data from within the conductive overlay showed a consistently higher temperature than the area outside the overlay. The differences increased with an absence of solar radiation on the deck. During a typical day the temperatures generally increased significantly from 0800 hours to a peak at 1400 hours then steadily decreased until the next morning. This pattern is interrupted during severe storm conditions and can be seen in the temperature data taken on December 15, 19, 20 and 21, in Appendices A, B, C, and D. Record cold temperatures were logged in the latter half of December 1990. More typical weather conditions were recorded from December 30 through January 6, (Appendices F, G, and H).

During December 30, all of the data points are 30 minutes apart indicating the air temperature below the bridge never rose above 35°F and the overlay power was on all day. However, during December 31, from 1100 to 1630 hours the longer data spacing means the overlay power was turned off. This pattern is repeated through January 6, as well as other days.

A visual inspection of figures from December 30 to January 6 reveal a distinct differences in temperature inside and outside the overlay. The figures in Appendix H, December 30 through January 2, show clear examples of the heating capability. As mentioned previously, the temperature differences are greatest when solar radiation is not present, due to the elimination of solar heat contribution to the deck. For this reason average temperature data was calculated over specified nighttime hours. Figure 6 and Table 3 show examples of average temperatures calculated.

**FIGURE 5**  
**RESISTANCE CHANGES WITH RESPECT TO TIME**  
**FROM DEC. 28 TO JAN. 12, 1991**



## TEMPERATURE RESPONSE OF OVERLAY

The temperature data from within the conductive overlay showed a consistently higher temperature than the area outside the overlay. The differences increased with an absence of solar radiation on the deck. During a typical day the temperatures generally increased significantly from 0800 hours to a peak at 1400 hours then steadily decreased until the next morning. This pattern is interrupted during severe storm conditions and can be seen in the temperature data taken on December 15, 19, 20 and 21, in Appendices A, B, C, and D. Record cold temperatures were logged in the latter half of December 1990. More typical weather conditions were recorded from December 30 through January 6, (Appendices F, G, and H).

During December 30, all of the data points are 30 minutes apart indicating the air temperature below the bridge never rose above 35°F and the overlay power was on all day. However, during December 31, from 1100 to 1630 hours the longer data spacing means the overlay power was turned off. This pattern is repeated through January 6, as well as other days.

A visual inspection of figures from December 30 to January 6 reveal a distinct differences in temperature inside and outside the overlay. The figures in Appendix H, December 30 through January 2, show clear examples of the heating capability. As mentioned previously, the temperature differences are greatest when solar radiation is not present, due to the elimination of solar heat contribution to the deck. For this reason average temperature data was calculated over specified nighttime hours. Figure 6 and Table 3 show examples of average temperatures calculated.

The temperature measurements taken nearest the bridge rail are not included for reasons discussed later in this section.

**FIGURE 6**

**Average Nighttime Deck Temperatures °F\***

Traffic →				
6 20.0	13 29.2	16 34.8	9 31.4	1 19.8
7 19.5	14 28.0	12 31.8	10 27.0	2 18.7
8 x	15 x	17 x	11 x	3 x
Bridge Rail				

Chan. #  
Temp.

\*Avg. temp. from 0200 to 0800 hours, 12/28/90 to 1/11/91

**TABLE 3**

**Average Temperature Comparison**

Channels Used for Average Temperature Comparison		Average Values °F	Difference Between Averages °F (Inside-Outside)
Outside	1,2,6,7	19.5	
Inside	9,10,12,13,14,16	30.4	
Inside	12 only	31.8	10.9

The calculated average temperatures confirm an elevation in temperatures within the overlay. The averages were determined from data taken during the coldest part of the night, 0200 to 0800 hours. During this time period the average temperature of the four noted thermocouples outside the overlay was 19.5°F and the six within the overlay was 30.4°F. The average difference between the overlay interior and exterior was then calculated to be 10.9°F

for the time period listed. From this information an empirical heat transfer rate may be calculated.

The average power consumption rate was calculated to be 834 Watts or, using the test area of 100 ft<sup>2</sup>, 8.34 W/ft<sup>2</sup>. In order to approximate a corresponding heat transfer rate, this value was divided by the average temperature difference of 10.9°F. The resulting power needed to raise the temperature of the heating overlay above the temperature of the deck, for this time period, was 0.77 W/ft<sup>2</sup>°F. This value should, in the future, serve as a guideline but may not apply linearly to different climatic conditions or to different bridge configurations.

Examination of the temperature response graphs and the average temperature differences within the overlay revealed an apparent temperature gradient. Of the averaged values listed in Table 3, the maximum difference was eight degrees Fahrenheit between channels 10 and 16. Although channel 10 averaged over three degrees below the overlay average, it was still 7.5°F above the average of the thermocouples outside the overlay.

A number of factors could cause uneven heating in the overlay. The most obvious of which would be an inconsistent resistance within the overlay. This variance in resistance could be caused either by a changing ohm-cm value in the overlay material during placement or a variation in overlay thickness. Any changes in the material composition, i.e. aggregate, sand, coke breeze or resin, could change the ohm-cm value.

Another factor that could cause uneven heating is the geometry of the bridge. Figure 2 shows the locations of the girders with respect to the

overlay. Both outer rows of thermocouples, the ones nearest the lane and the ones nearest the bridge rail, are near or directly above girders adding a thermal mass below certain sections of the overlay. This added thermal mass will effect the temperatures in the overlay. Bridge configurations resulting in uneven thermal radiation will also cause temperature gradients.

The close proximity of the bridge rail will influence radiative heat transfer rate in two ways. Photos 7 and 8 indicate shade being cast across the edge of the deck due to the low winter sun. This shade moves across the edge of the deck during the day causing an uneven heating effect that is difficult to track. It also causes a residual pattern that influences the deck temperature after the solar radiation is no longer present. The second way the bridge rail influences the deck is by limiting the exposure to the night sky. A large portion of the deck's thermal energy is radiated outward. The rate the energy is lost varies depending on atmospheric conditions. The rail acts to shield part of the deck immediately next to it from the night sky thus decreasing the shape factor by up to 50%, which could decrease thermal radiation loss by 50%.

Another event that effects the temperature of the overlay is the accumulation of snow or ice. A clear example of this occurs during the December winter storm. December 14 in Appendix B shows the thermocouples nearest the bridge rail, channels 15, 17 and 11, hovering between 30°F and 35°F. This pattern continues for a number of days while other temperatures within the overlay fluctuate. Although snow generally acts as an insulator, melting snow forms an "ice bath" that consumes heat as a result of the phase change. This keeps the temperature around 32°F, or lower if the deck is salted. For the days of December 15, 19, 20 and 21, it

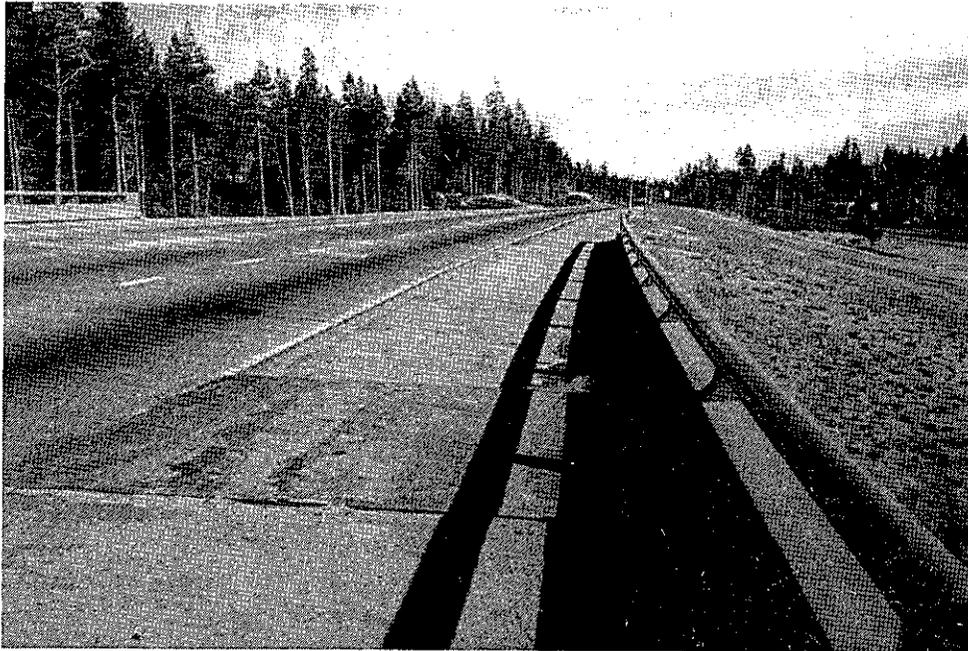
closest to the lane are the least likely to be covered by snow, water or sand. For this reason, it was judged that these channels more accurately represented actual lane conditions.

Channels 4 and 12 can be used to indicate the direction of heat travel perpendicular to the bridge deck. Both of the channels are located in the center of the overlay, with channel 4 approximately  $1 \frac{1}{4}$ -inch deeper than channel 12. As expected, a thermal lag was indicated in channel 4 when the temperature of the bridge was increasing or decreasing (see Appendix E). The consistency of this information demonstrated the precision of the data acquisition unit.

The thermocouple measurements outside the overlay, (Appendix F), also showed that the temperature readings were consistent. On January 5, channels 1 and 6 remain within a degree of each other for most of the day. These channels are the same distance from the bridge rail but are 20 ft apart.



**Photo 7**



**Photo 8**  
**Portion of Deck Shaded by Rail (Photos 7 &8)**

## CONCLUSIONS

Heat generation using a conductive polymer overlay is possible and may be cost effective considering the relatively low power requirements demonstrated by the test overlay. A power consumption rate of  $8.34 \text{ W/ft}^2$ , for an average  $10.9^\circ\text{F}$  increase over the surrounding bridge deck temperature, justifies further testing. Efficient performance may rely on the overlay's ability to provide heat at the surface. This emerging technology will require careful planning and strict quality control for its successful implementation.

Bridge decks in the foothill and valley areas which are subject to localized ice formation (due to the thermal lag between the deck and the adjoining pavement) may also benefit from this new technology.

## RECOMMENDATIONS

To obtain the designed resistance of the overlay, more extensive quality control testing will be necessary. This should include a conductivity test on the coke breeze. In addition, the mix must not be modified in the field, especially once part of the overlay has been placed.

The information gathered from the test patch provided a number of ideas to improve the performance of the heating overlay system. In order to avoid potential problems concerning the 50-volt limitation on the power supplied to the overlay, a secondary set of conducting bars should be included. The secondary set of bars will allow for a greater flexibility concerning the power supply and control capability.

The control system for the overlay could monitor the roadway temperature and the overlay temperature. It could supply just enough power to the overlay to keep it about the same temperature as the approaching roadway. This would minimize power consumption. Alternatively, if bridge salting was an issue and wanted to be discontinued, the minimum temperature would then need to be above 32°F.

Now that a feasibility study has been successfully completed, a more comprehensive evaluation should be attempted. This is especially true due to the relative ease in which a conventional polymer concrete overlay can be modified into a conductive polymer overlay.

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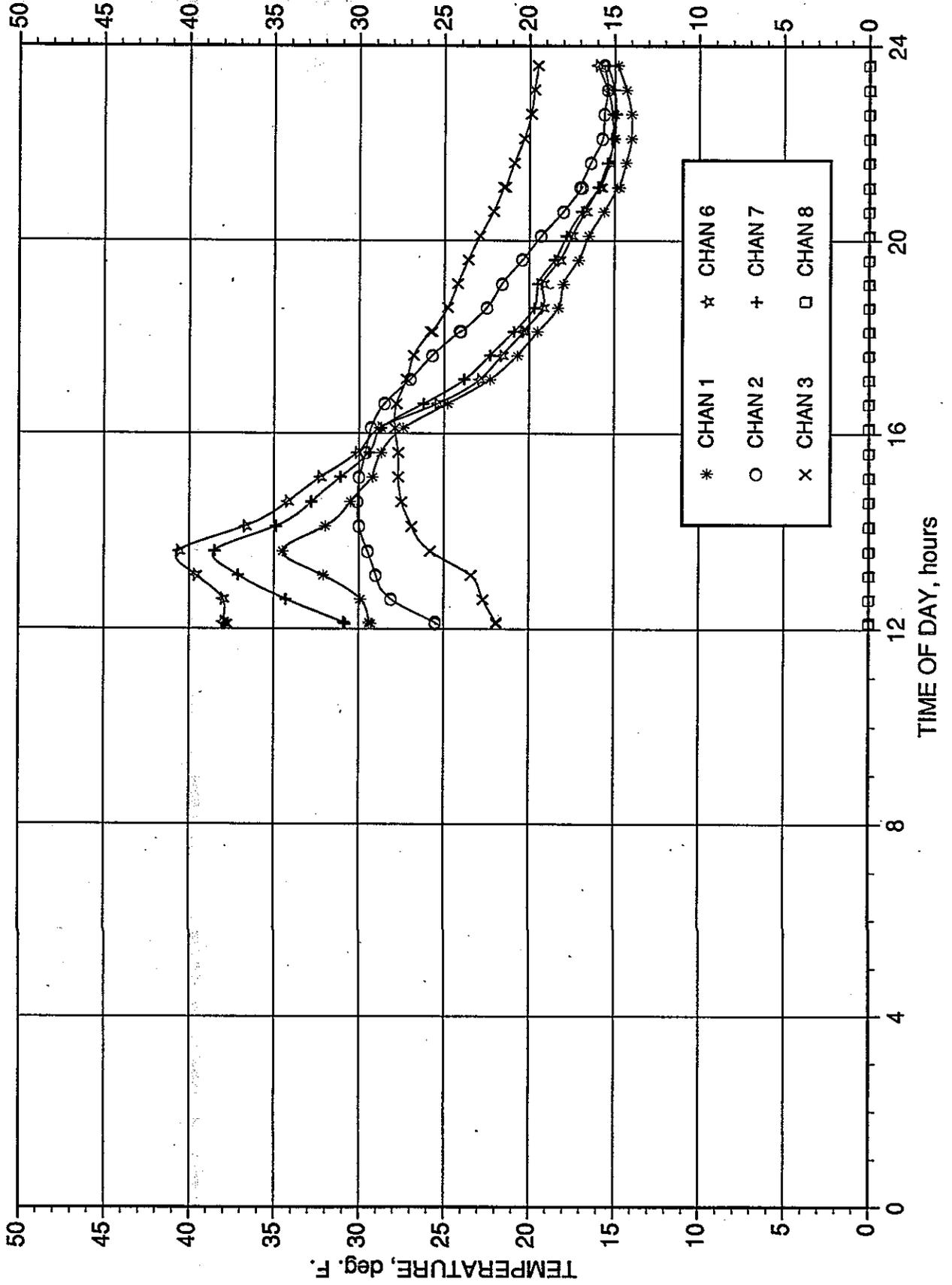
Transportation Research Board & National Academy of Sciences Special Report 185: Snow Removal and Ice Control Research, Proceedings of the Second International Symposium held May 1978.

# **APPENDIX A**

**DECEMBER 14 - 21, 1990**

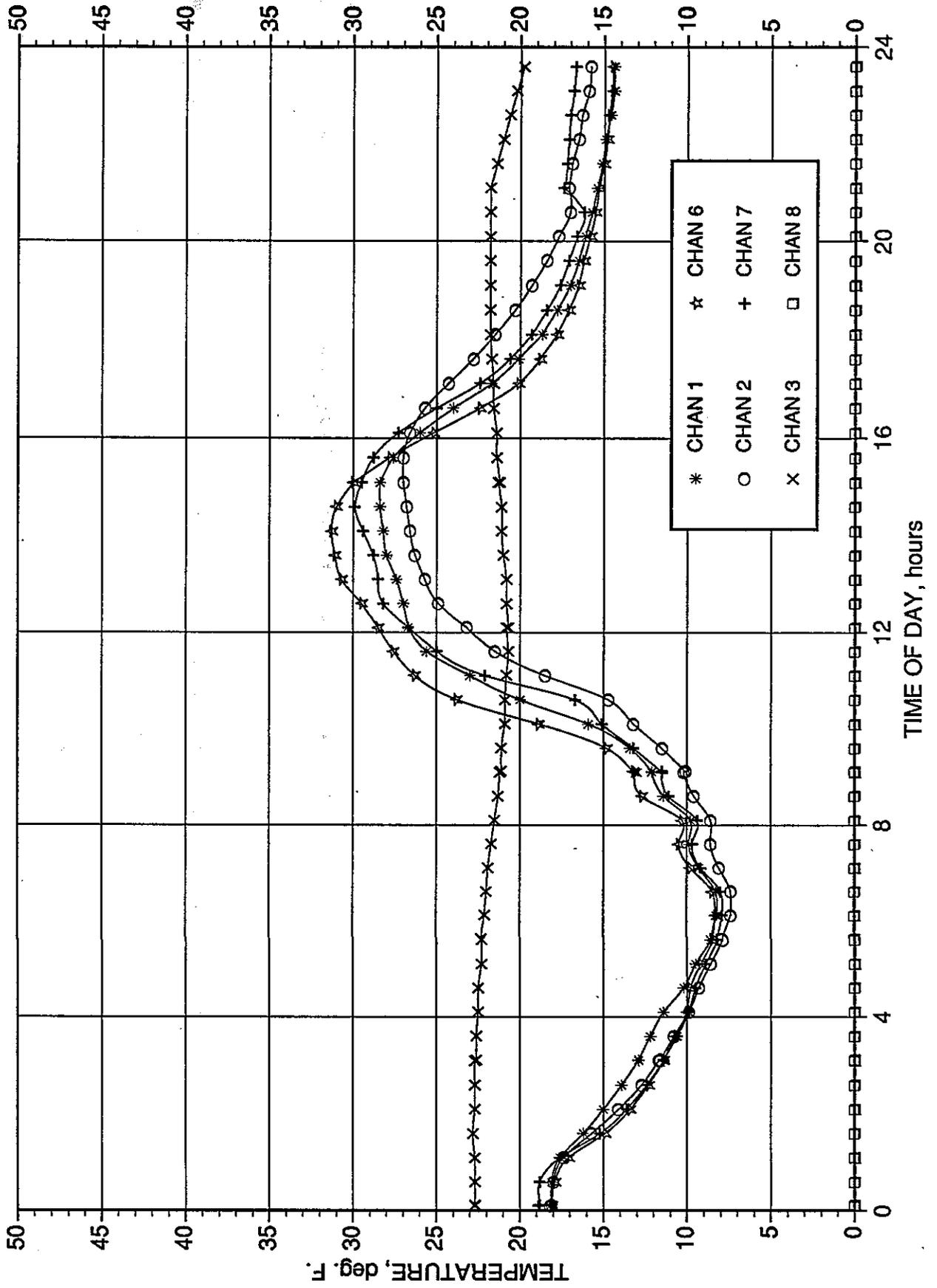
**COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY**

CASTLE PEAK HEATING OVERLAY DEC. 14, 1990  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY

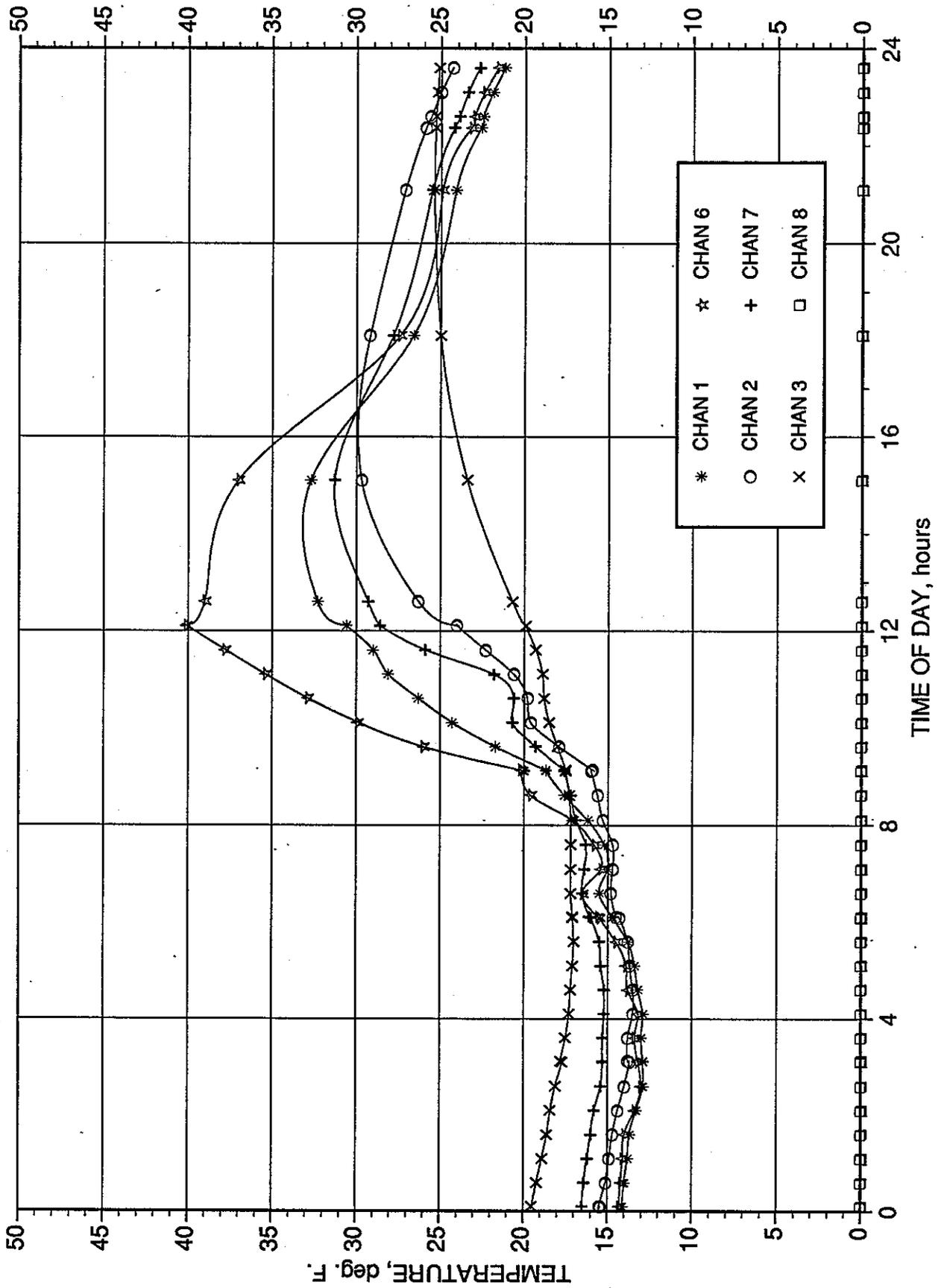




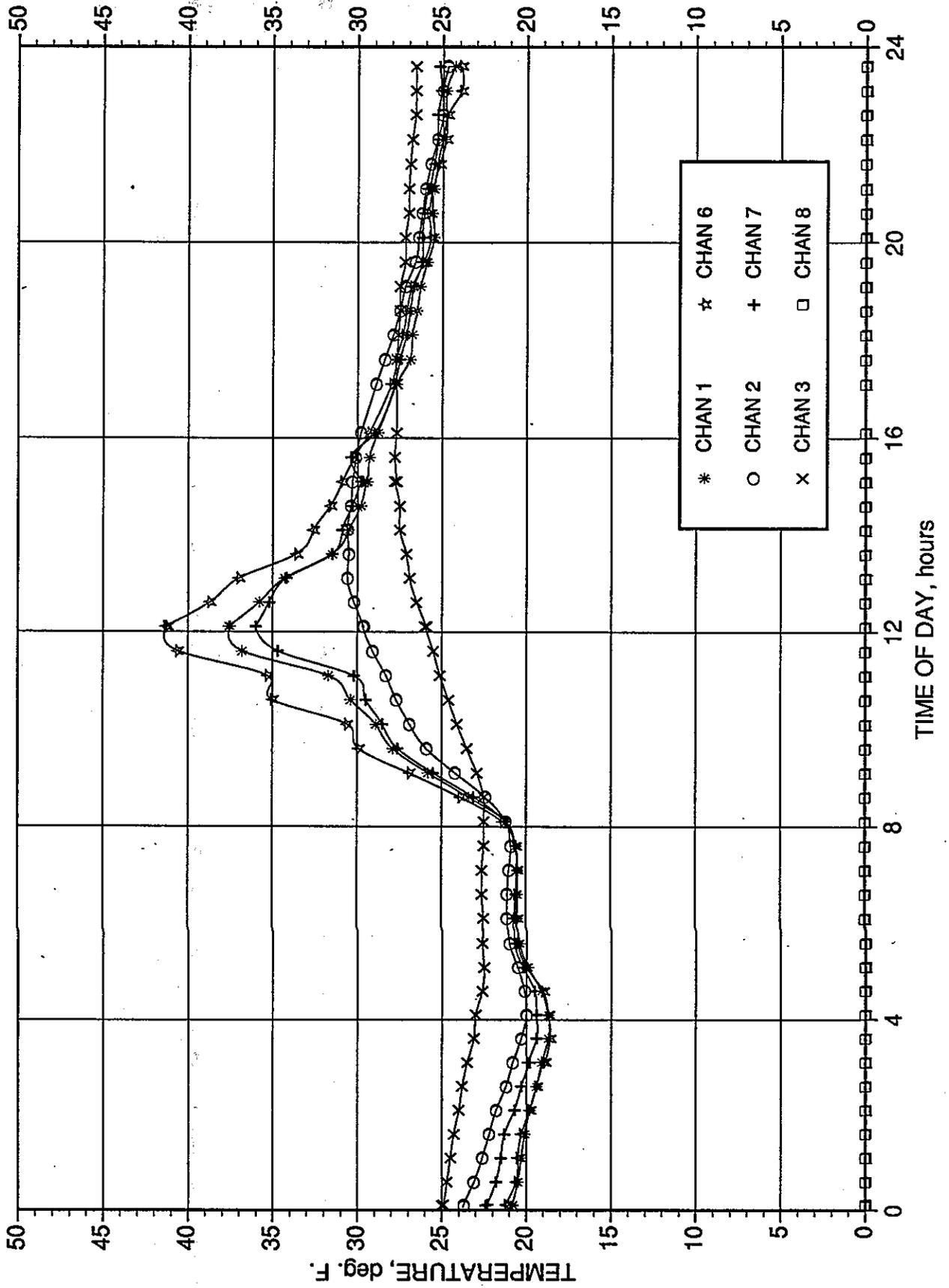
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COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



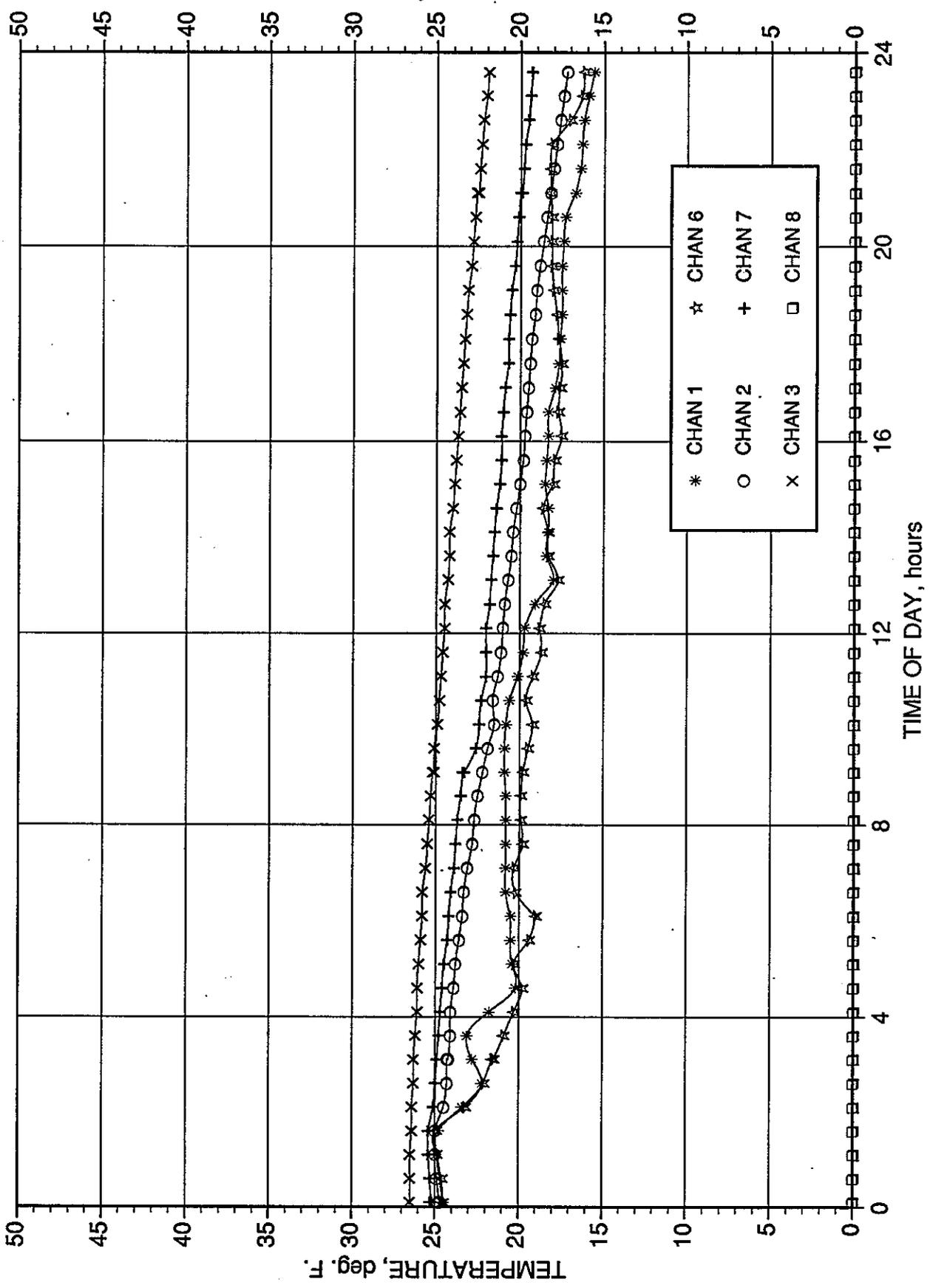
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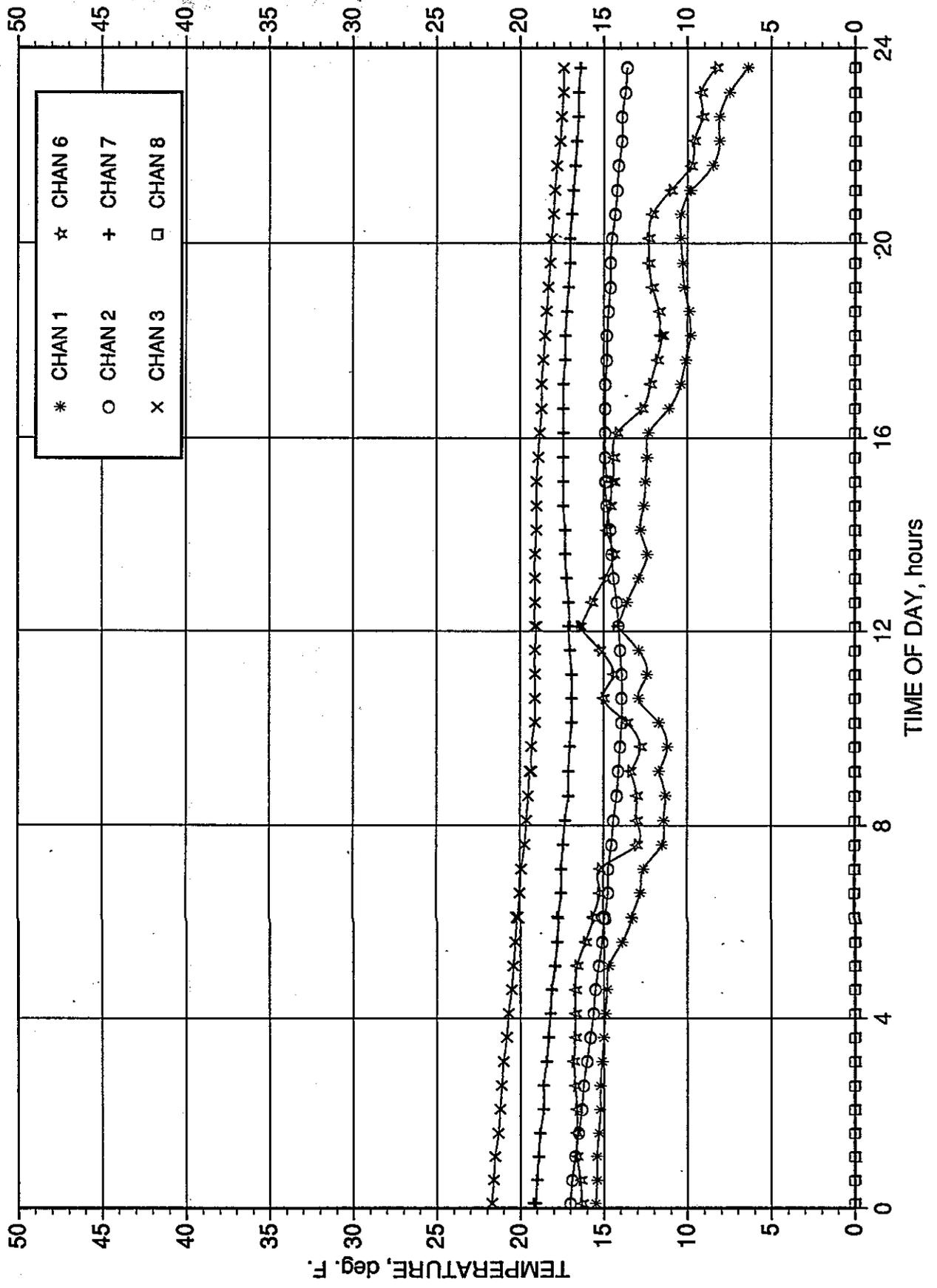
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 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



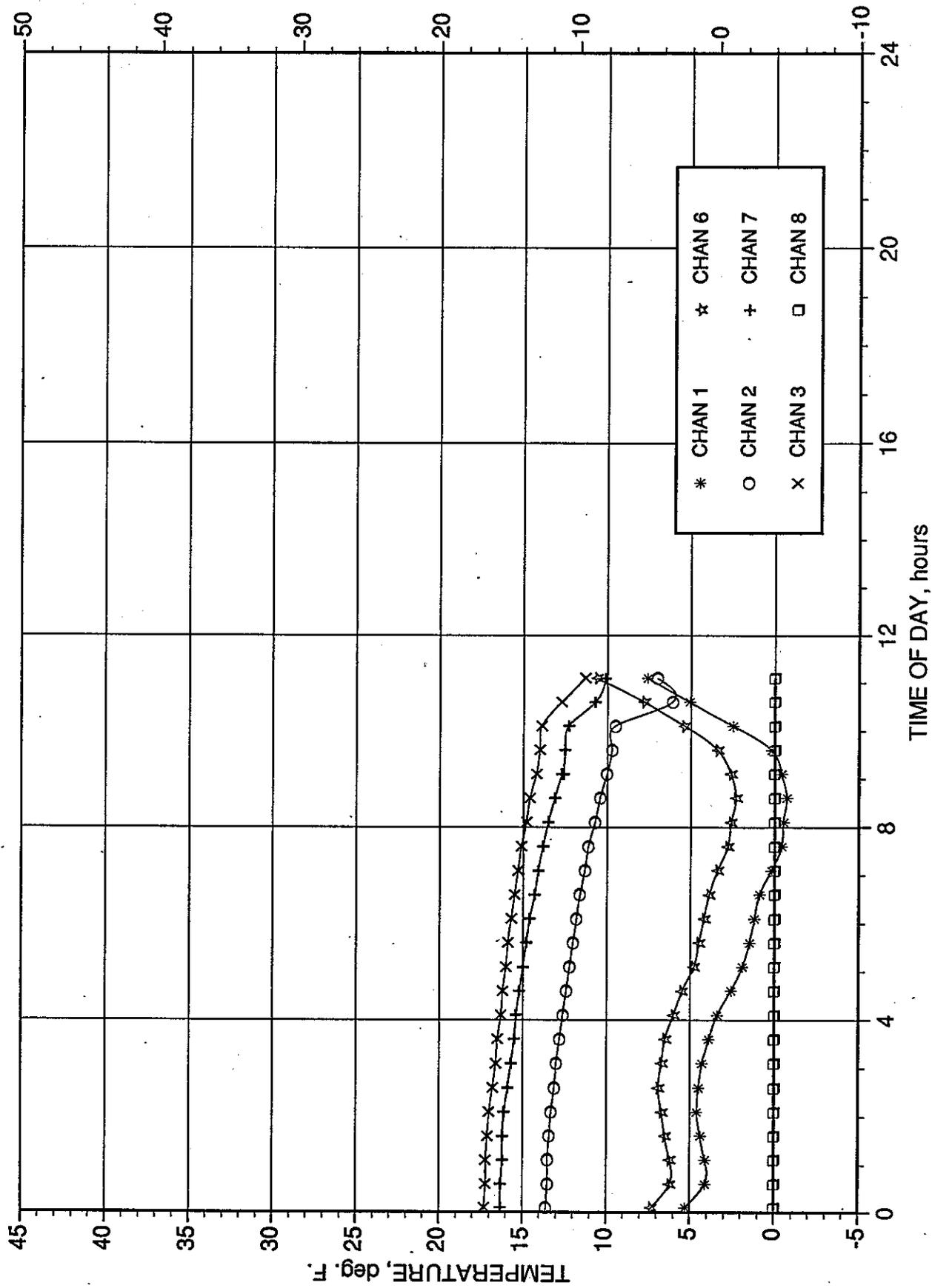
CASTLE PEAK HEATING OVERLAY DEC. 19, 1990  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



CASTLE PEAK HEATING OVERLAY DEC. 20, 1990  
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CASTLE PEAK HEATING OVERLAY DEC. 21, 1990  
COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY

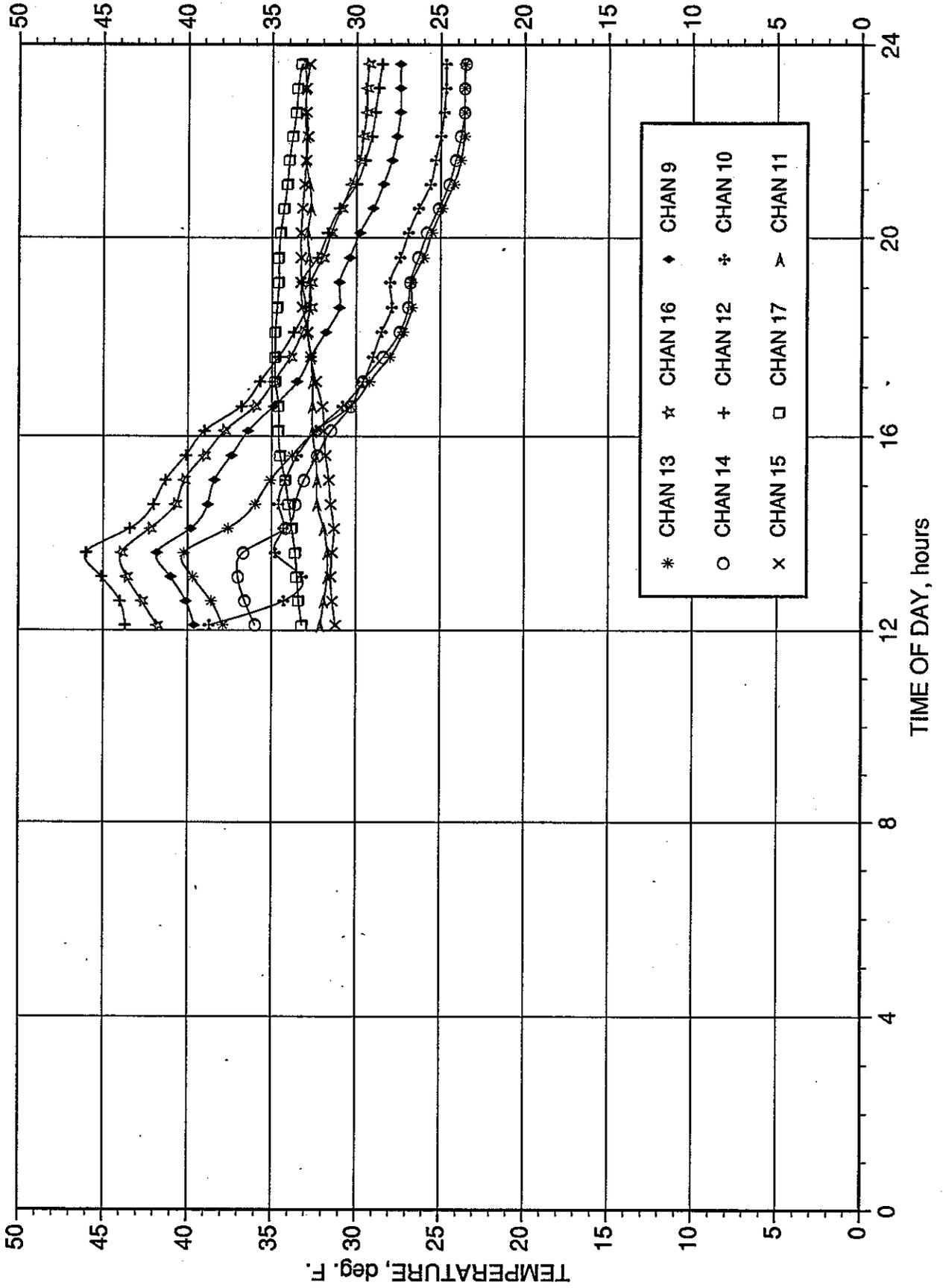


# **APPENDIX B**

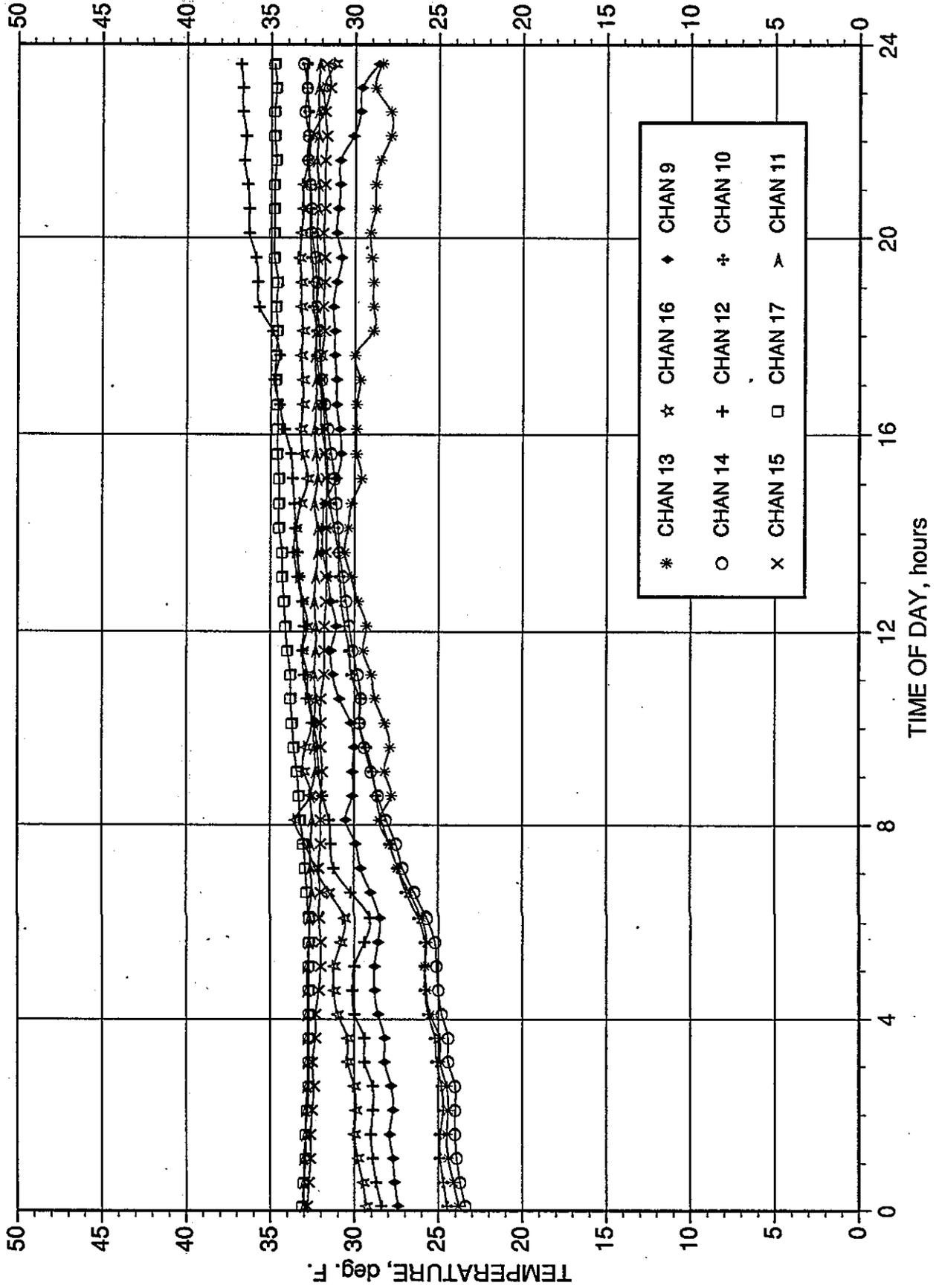
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**COMPARISON OF TEMPERATURES WITHIN OVERLAY BOUNDARY**

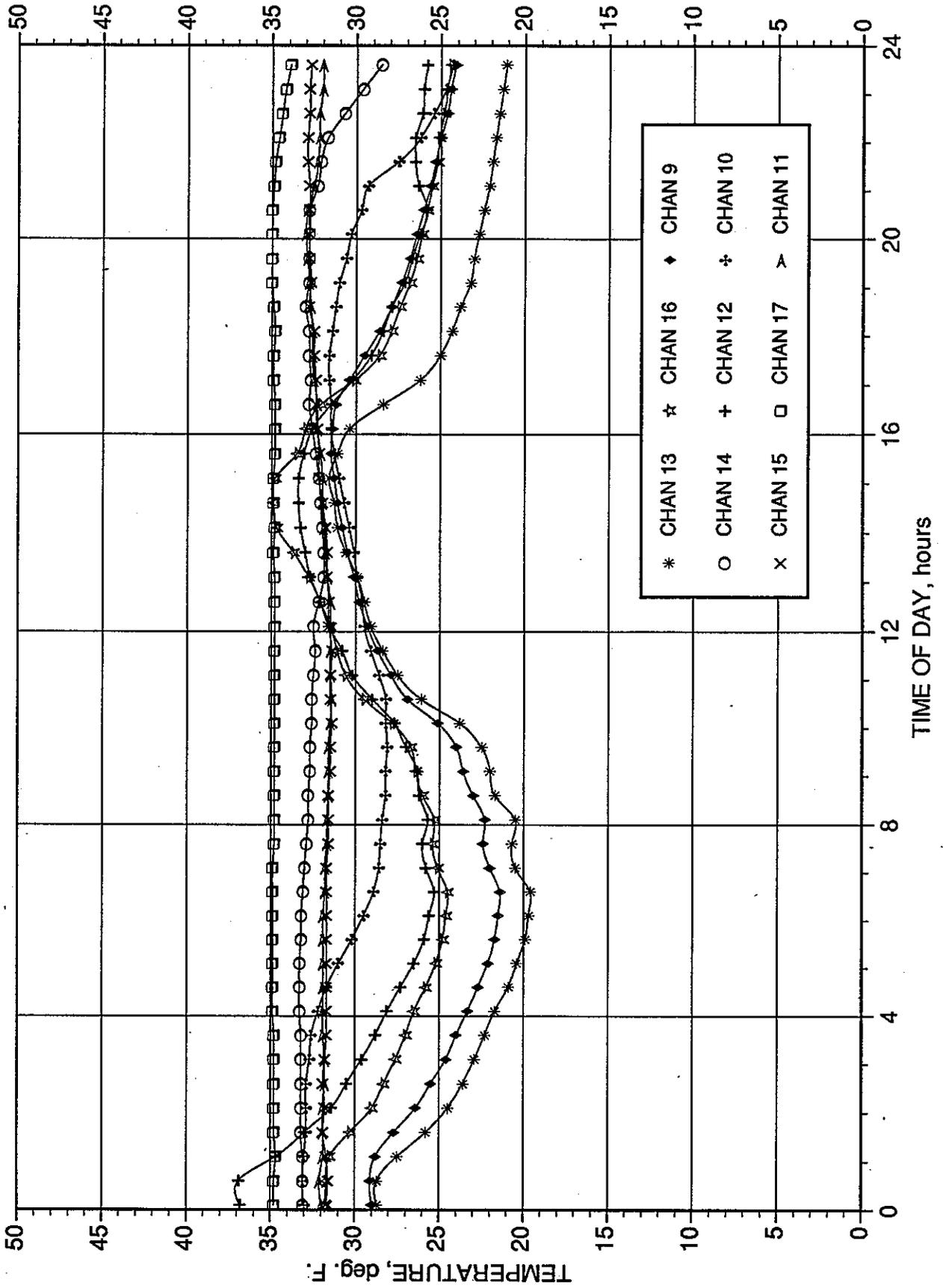
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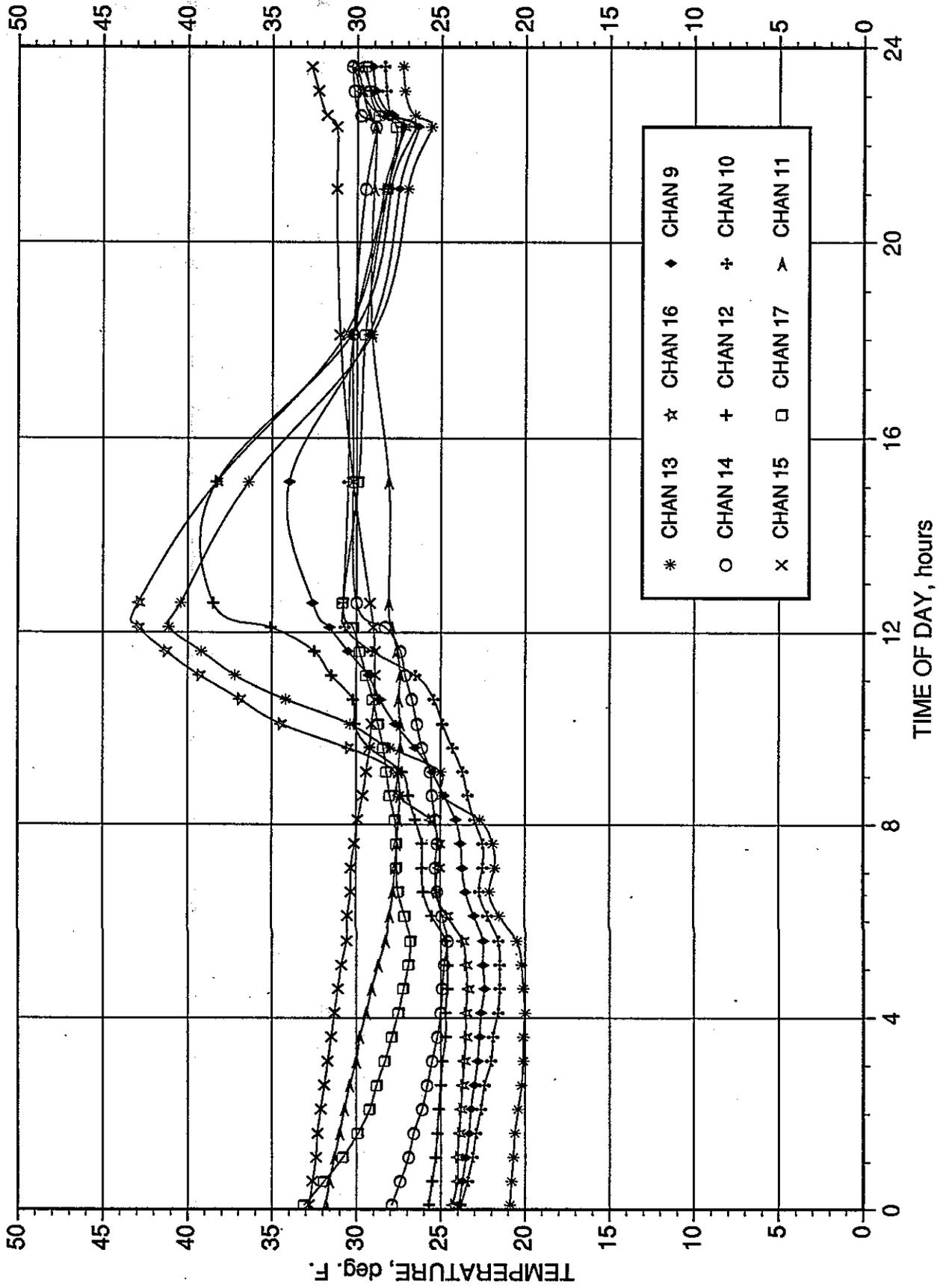
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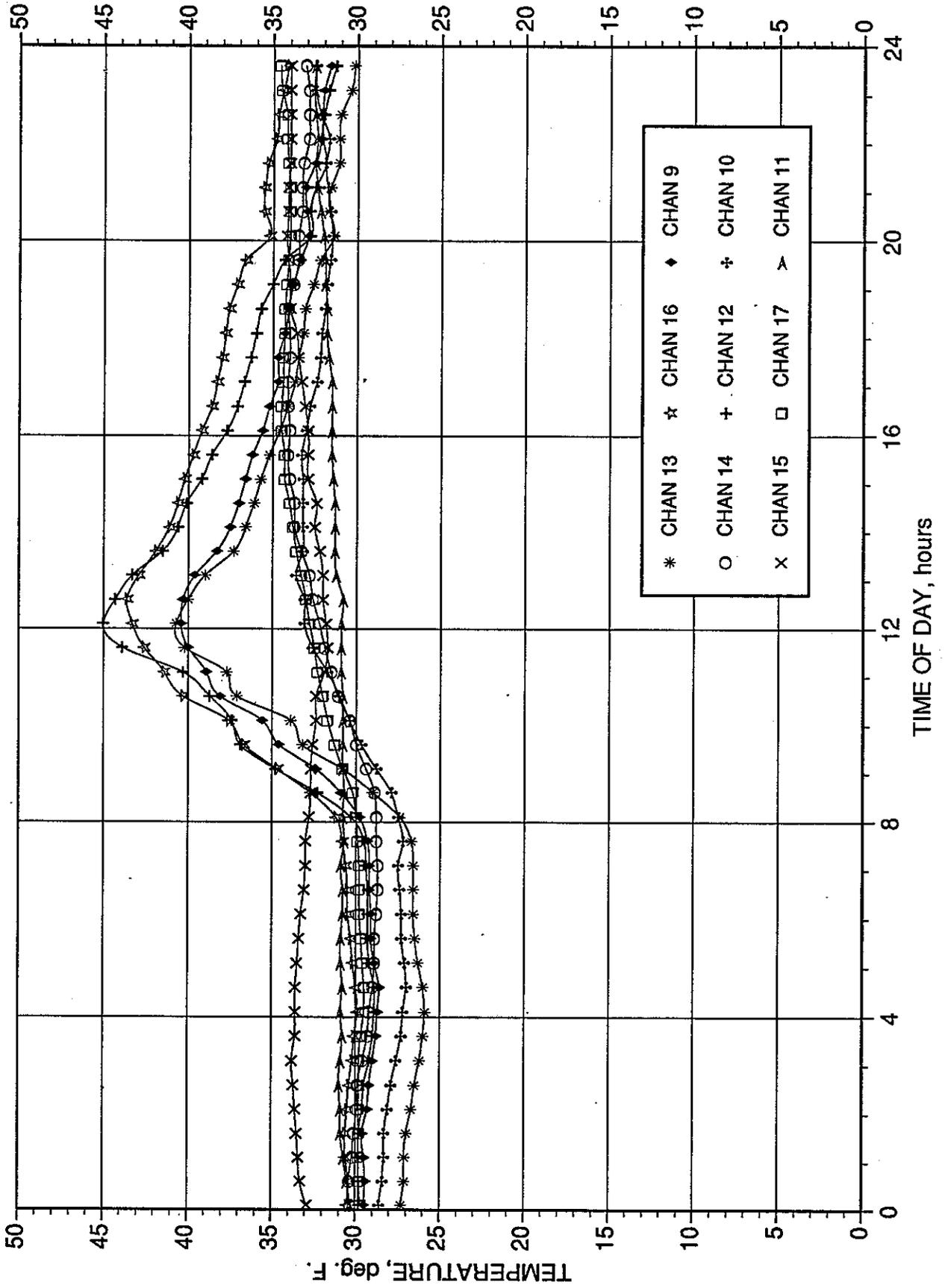
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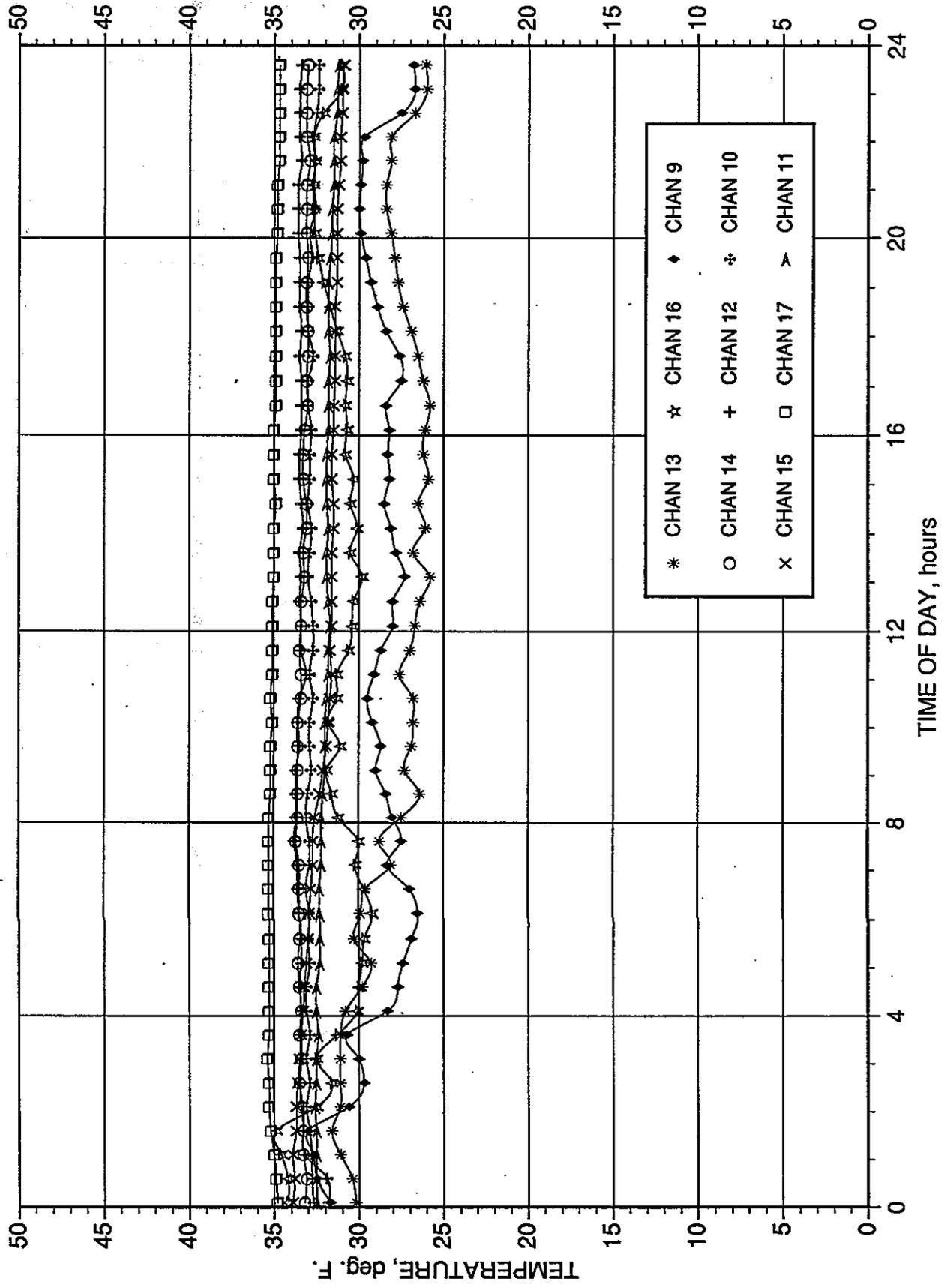
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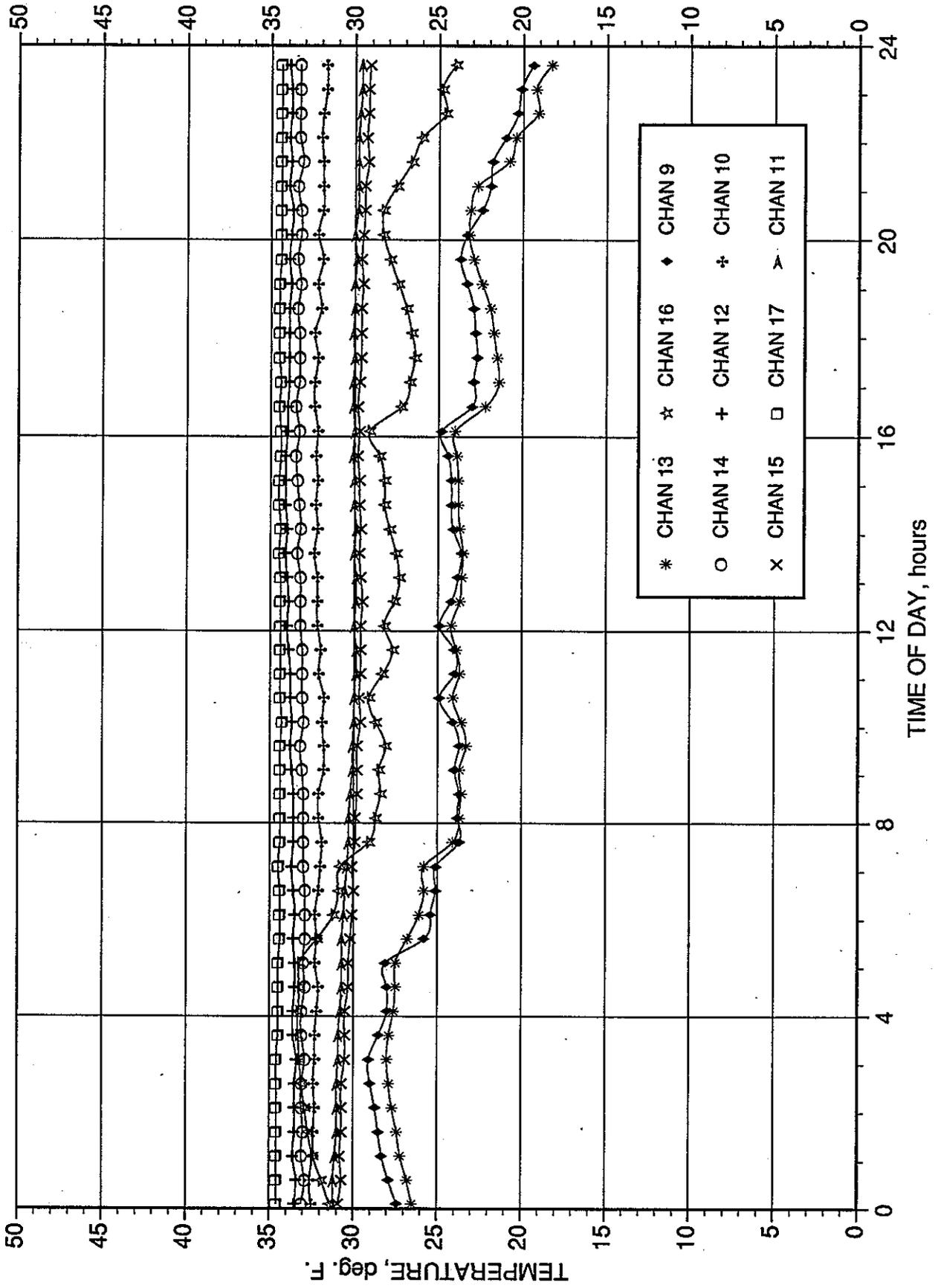
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 COMPARISON OF TEMPERATURES WITHIN OVERLAY BOUNDARY



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 COMPARISON OF TEMPERATURES WITHIN OVERLAY BOUNDARY





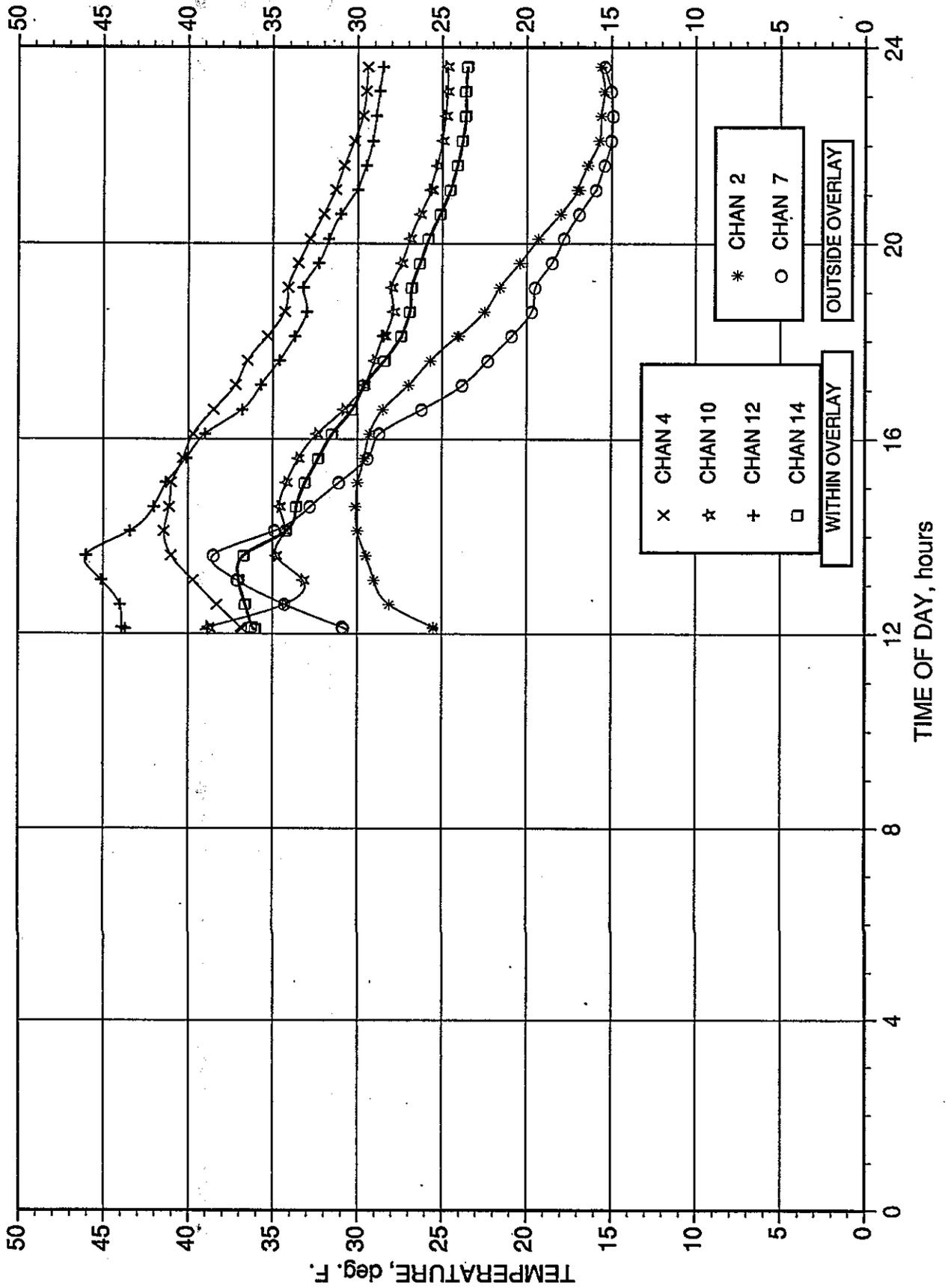
# **APPENDIX C**

**DECEMBER 14 - 21, 1990**

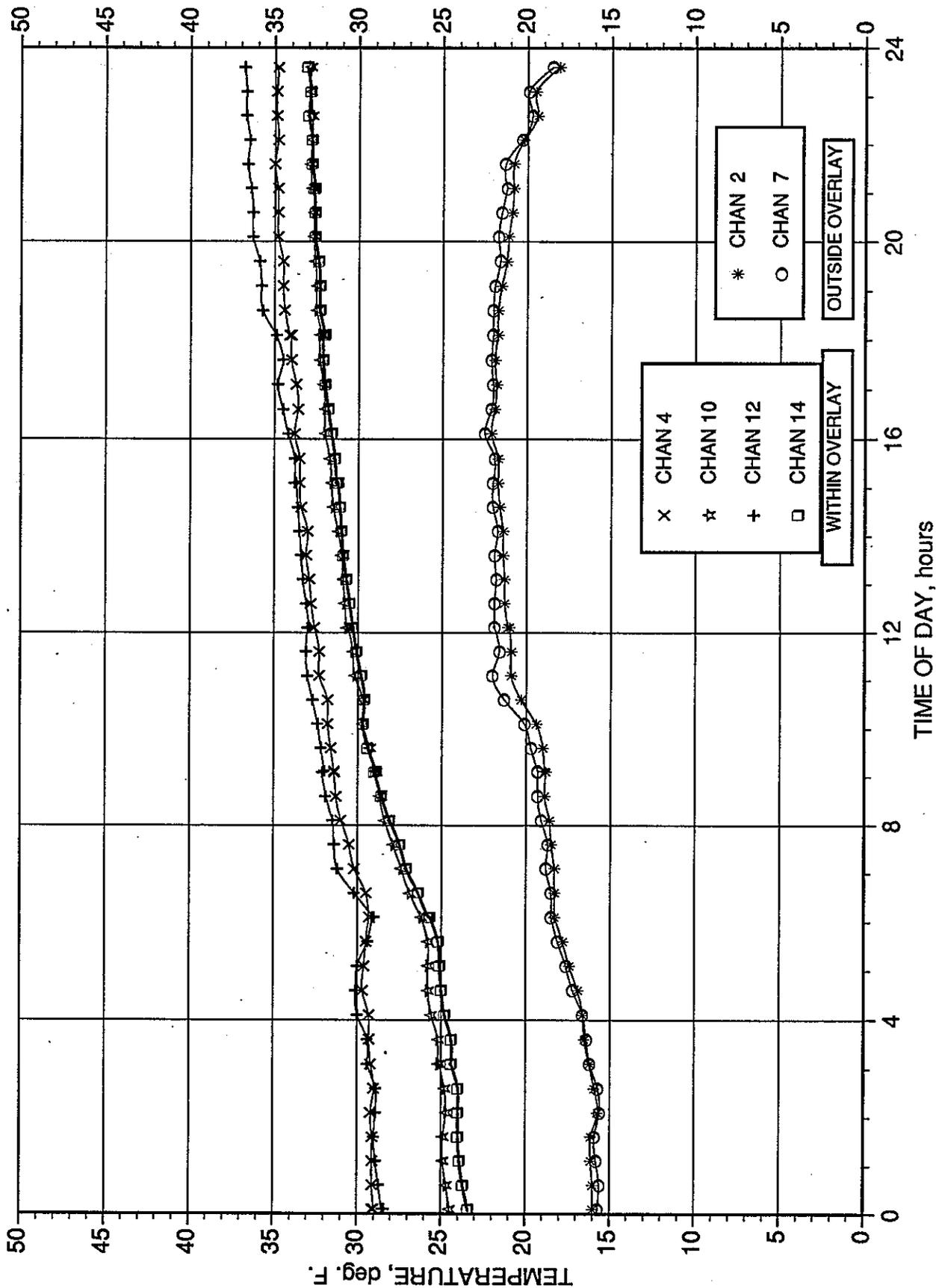
**COMPARISON OF CENTER ROW TEMPERATURES -**

**(MIDWAY BETWEEN LANE AND RAIL)**

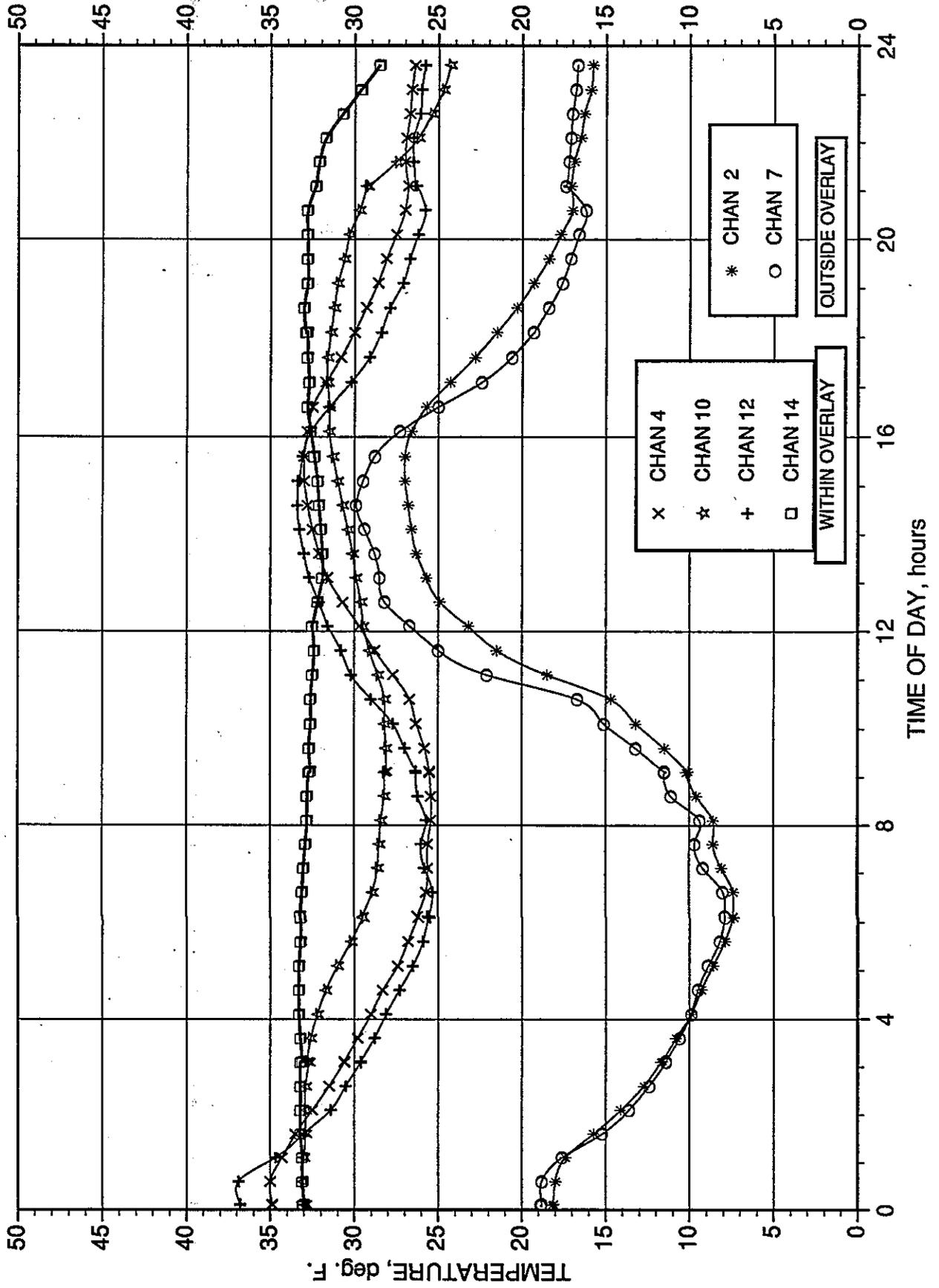
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 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



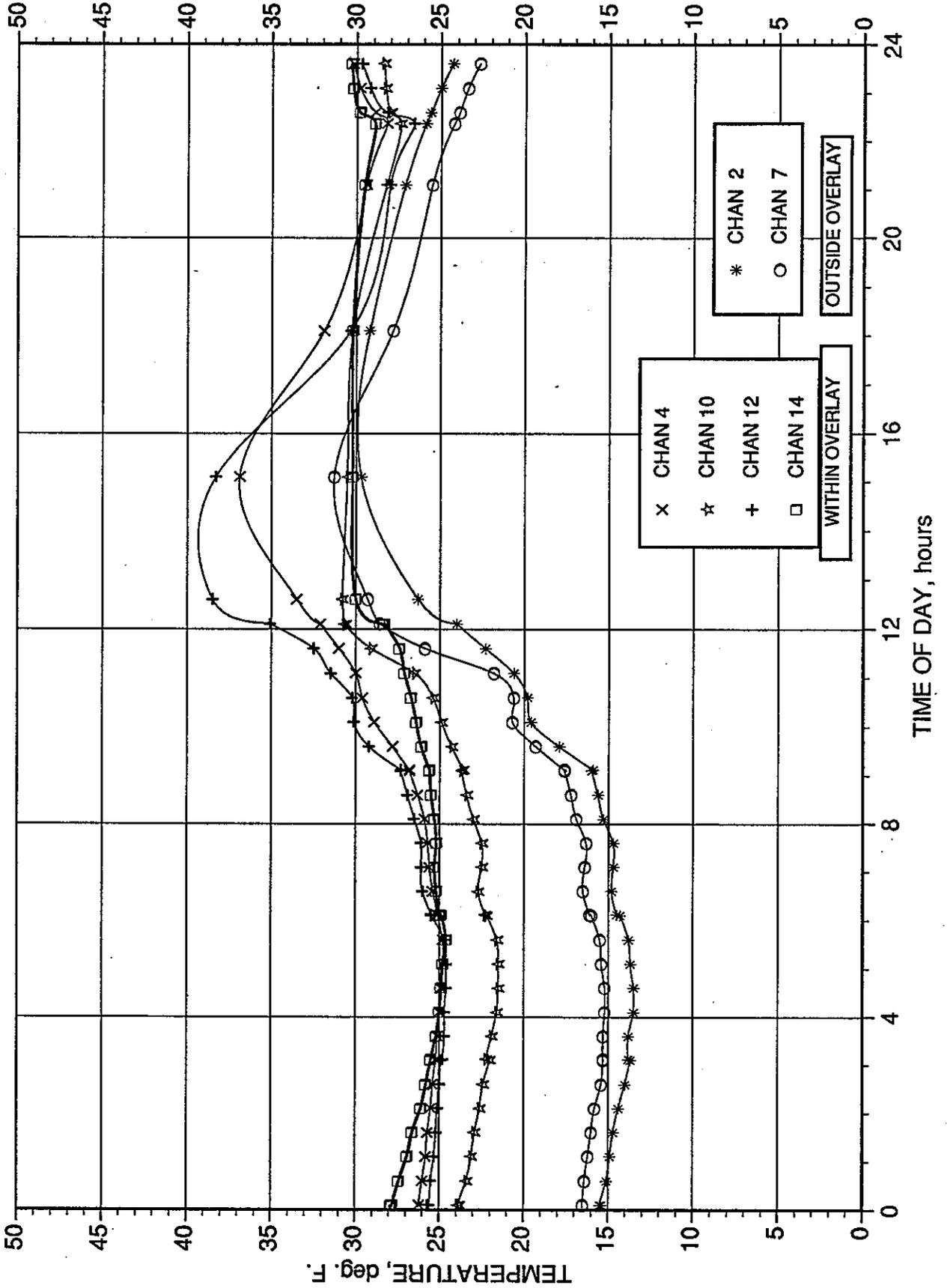
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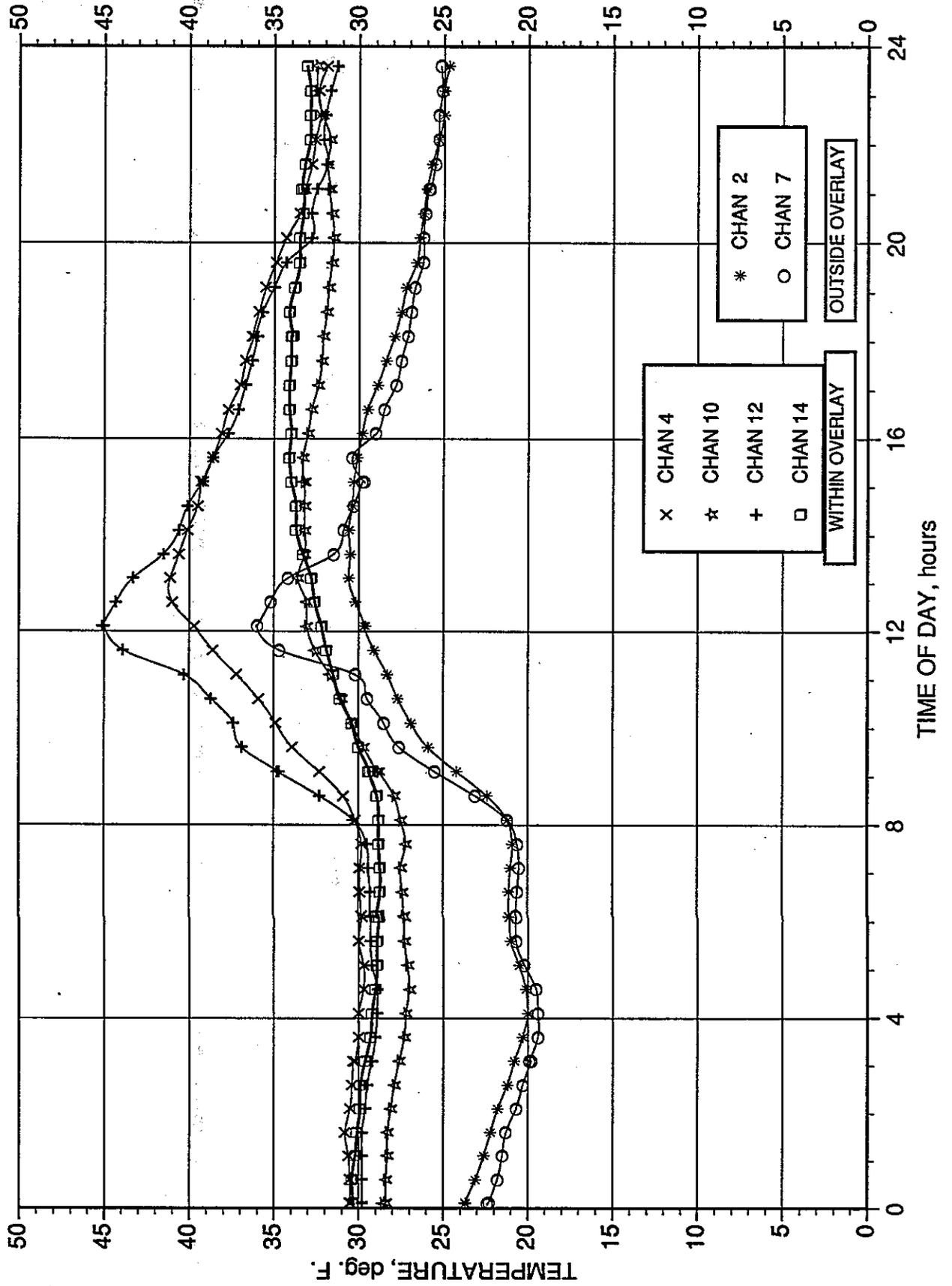
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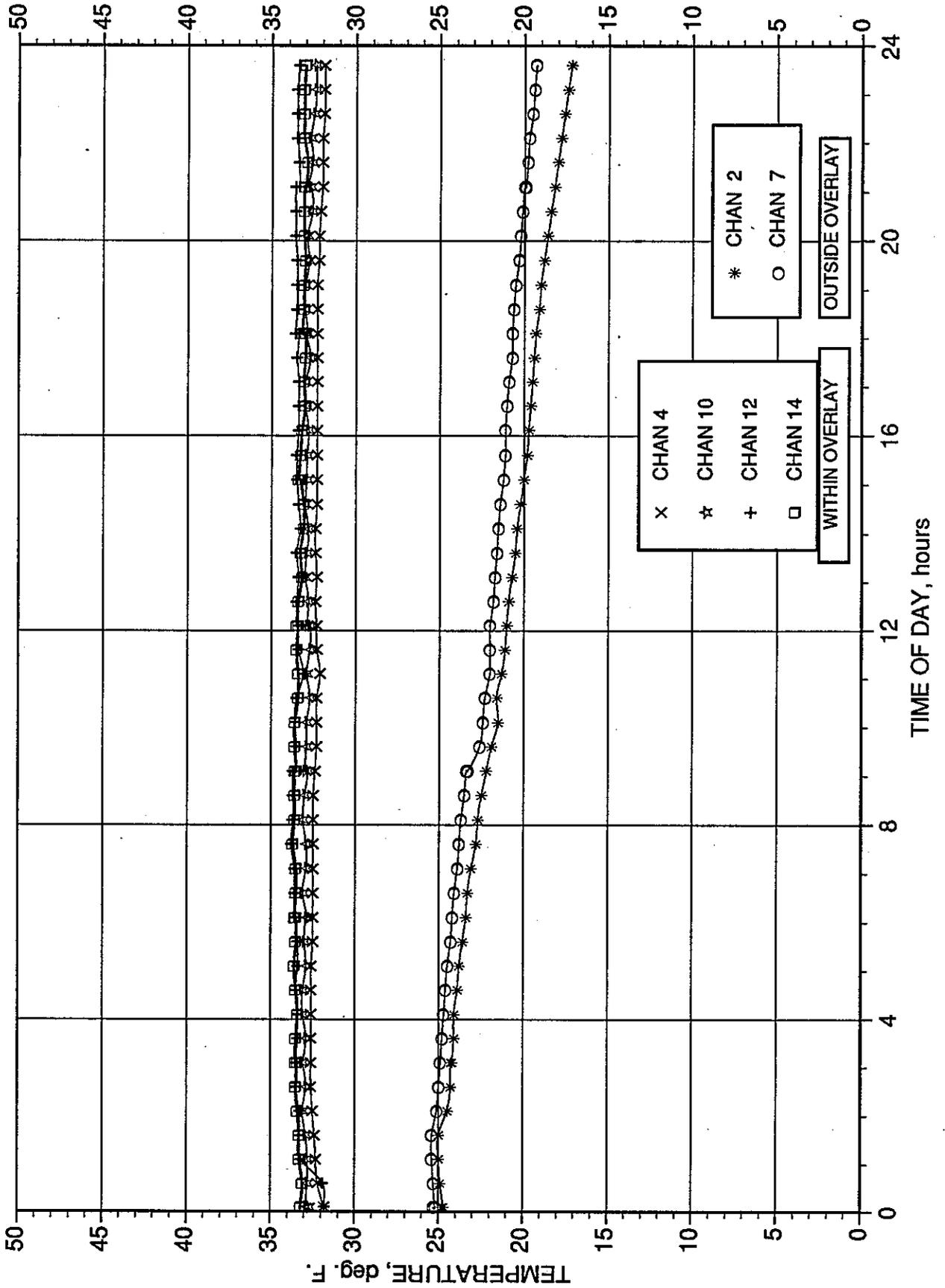
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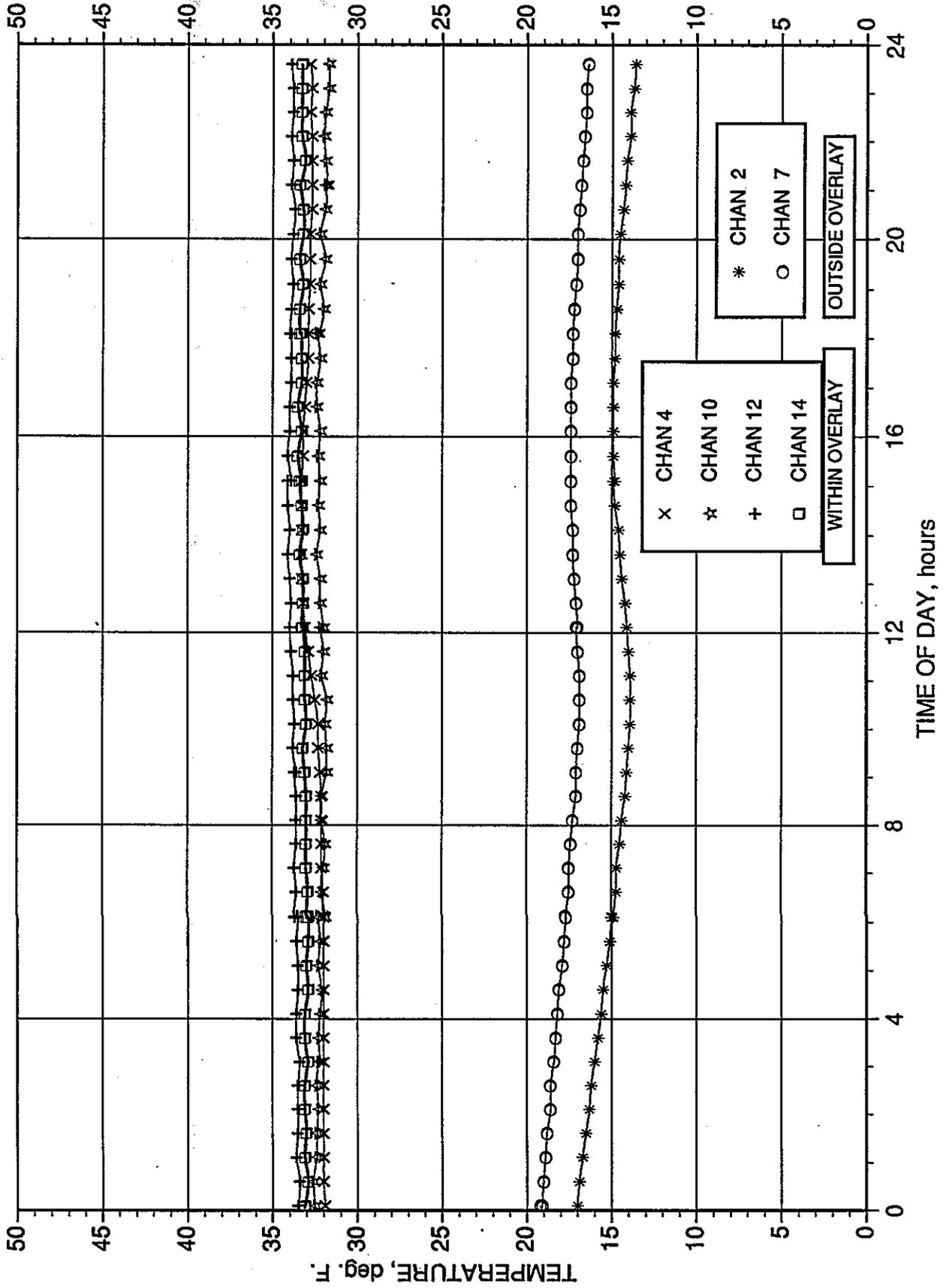
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 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



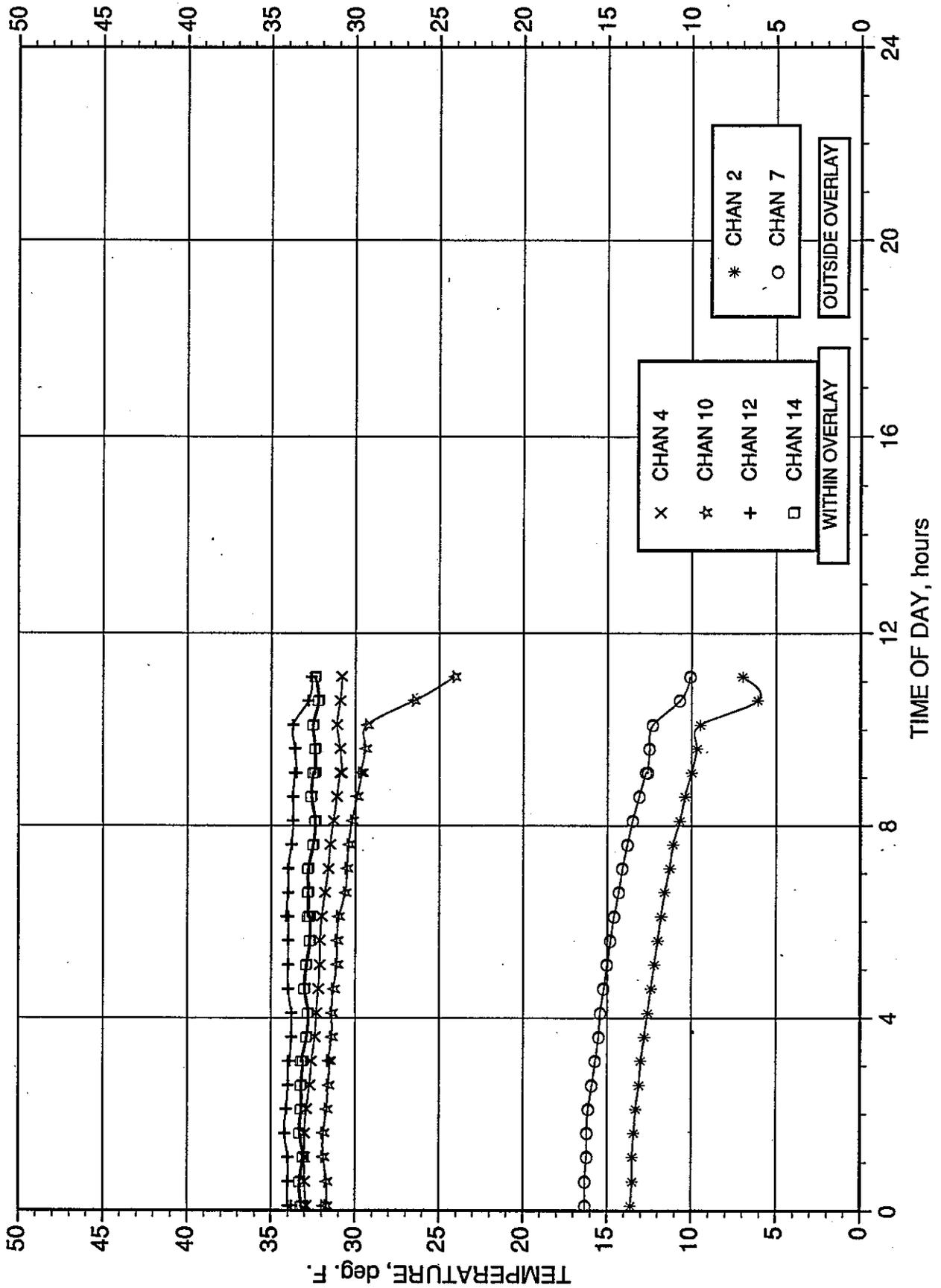
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 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



CASTLE PEAK HEATING OVERLAY DEC. 20, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



CASTLE PEAK HEATING OVERLAY DEC. 21, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



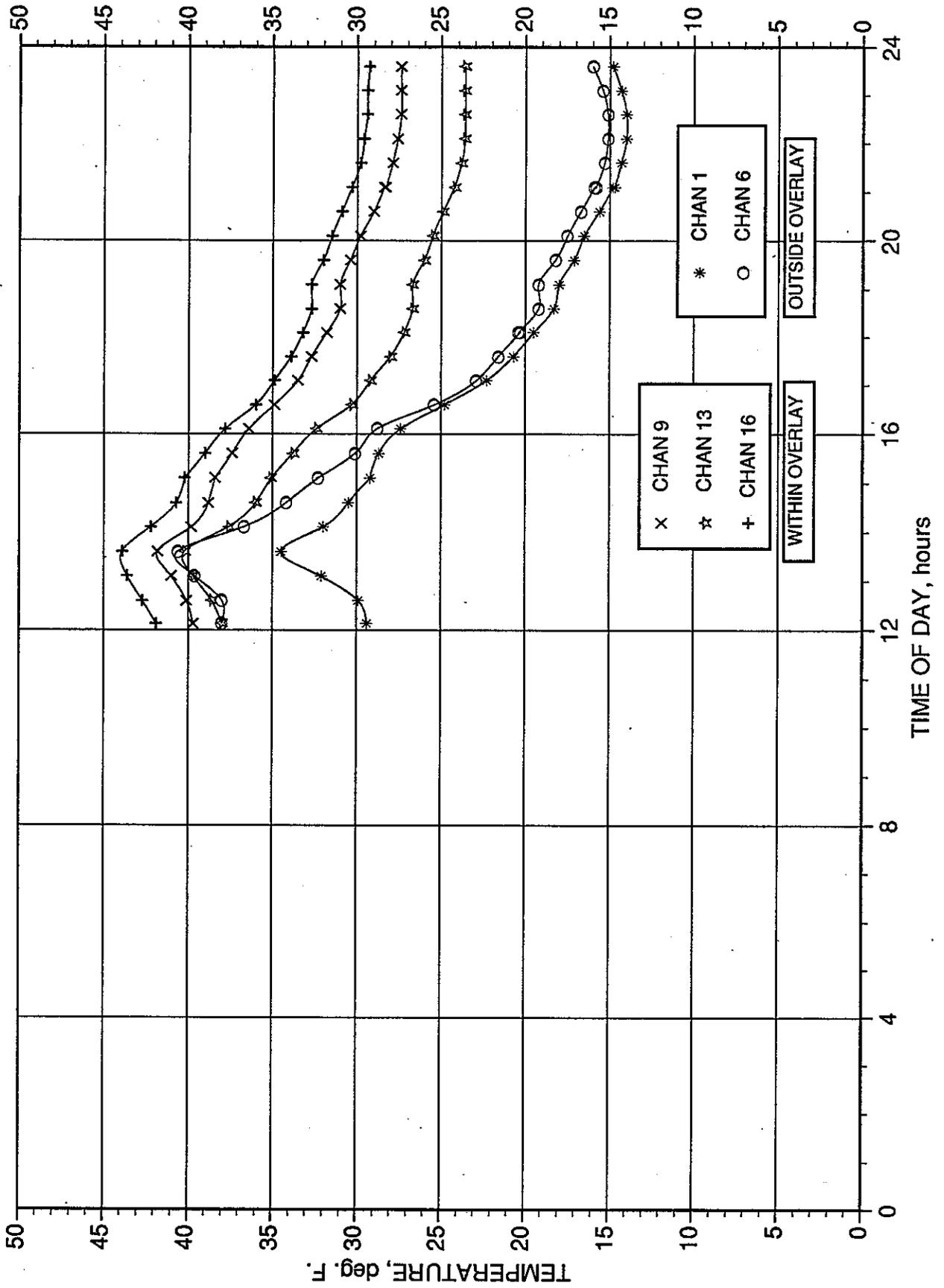
# **APPENDIX D**

**DECEMBER 14 - 21, 1990**

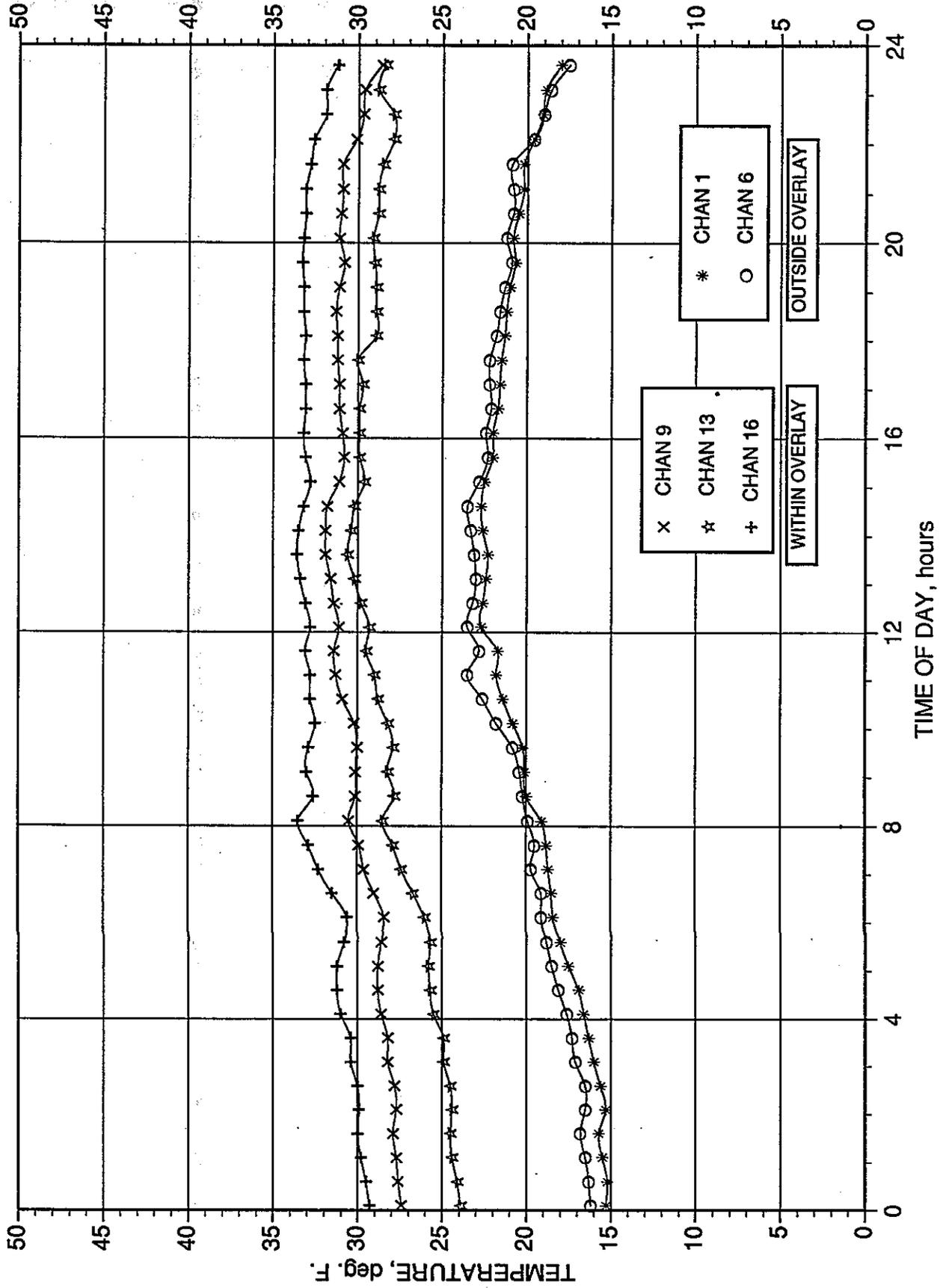
**COMPARISON OF INNER ROW TEMPERATURES -**

**(CLOSEST TO LANE)**

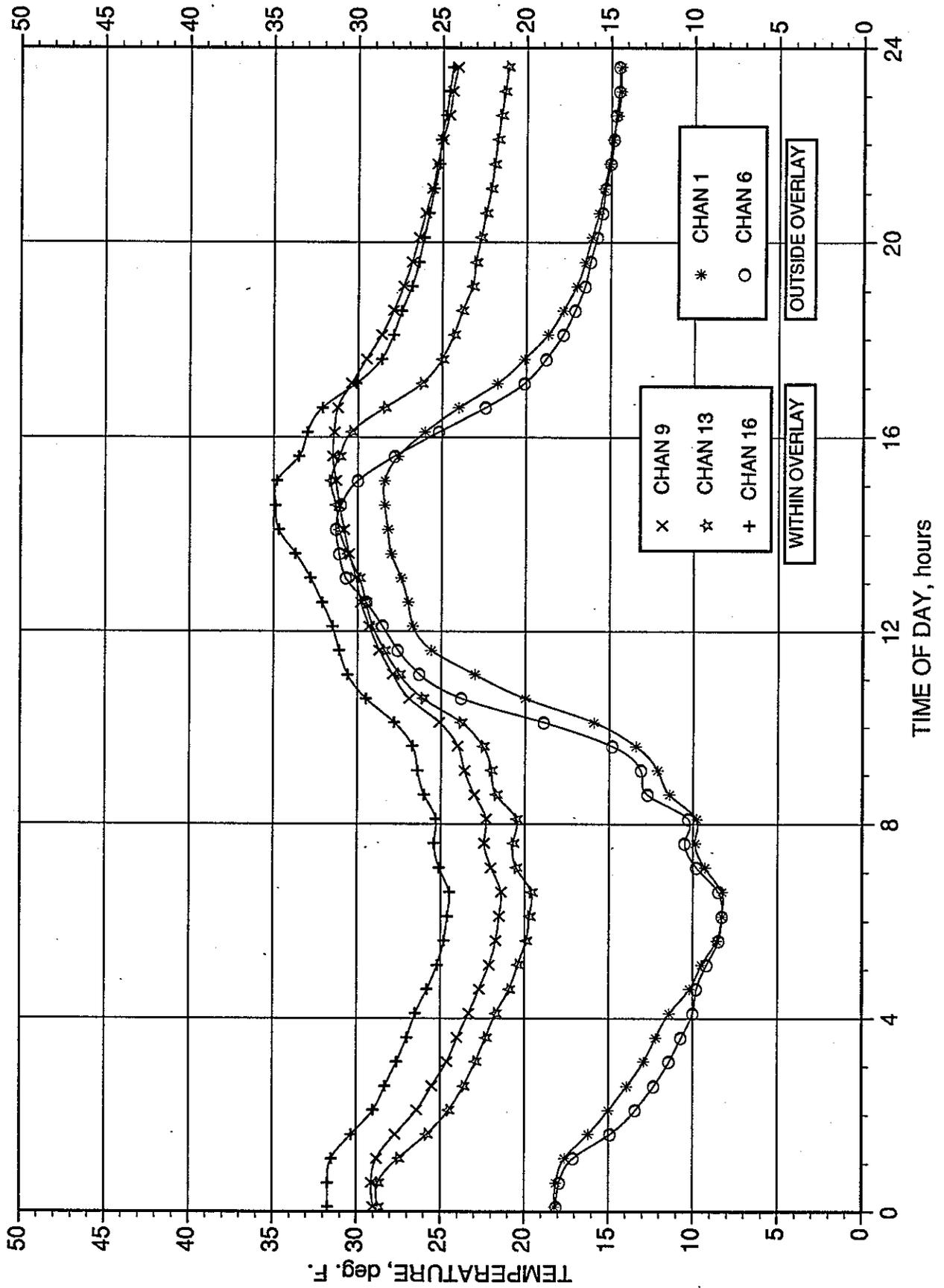
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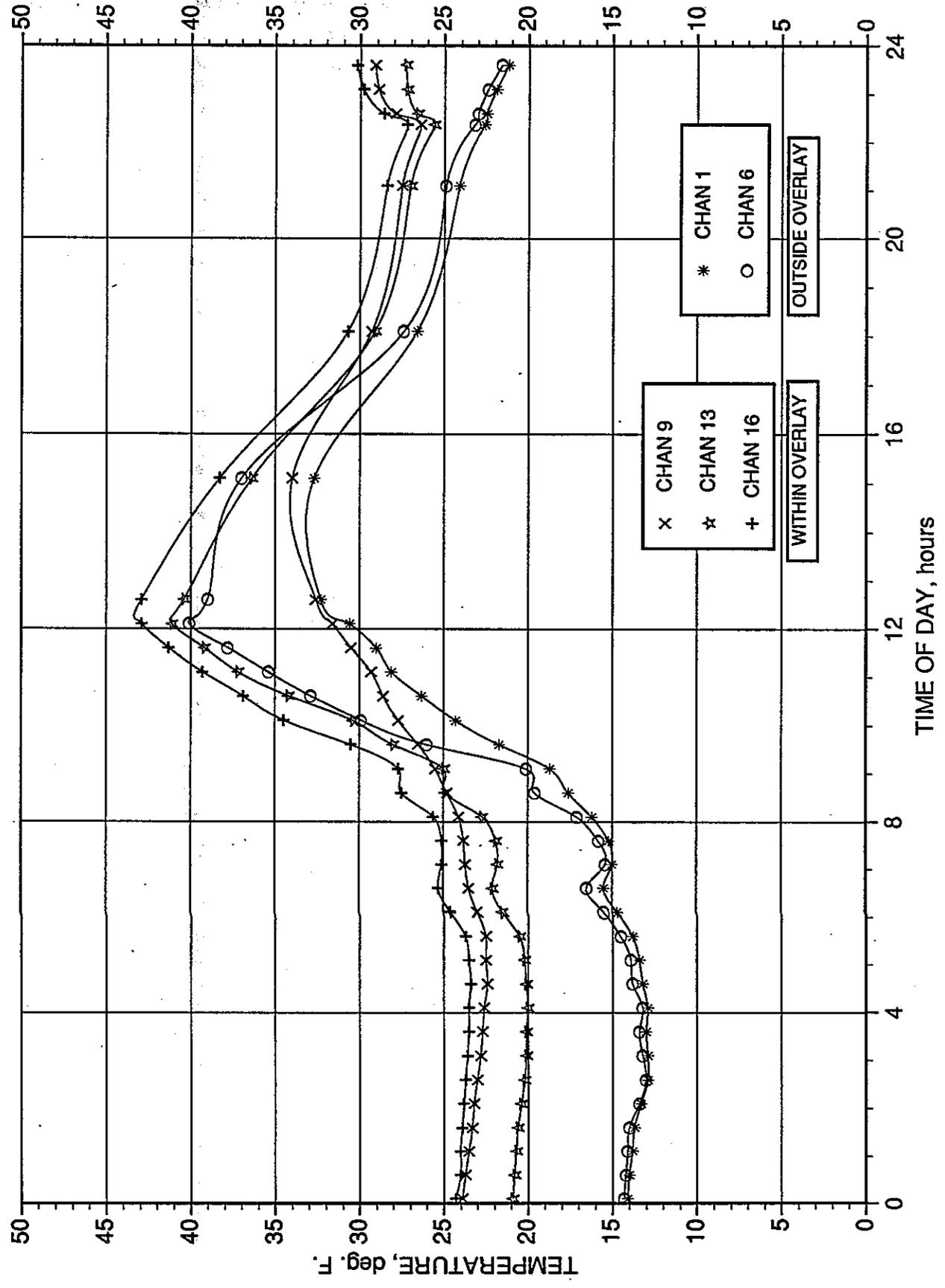
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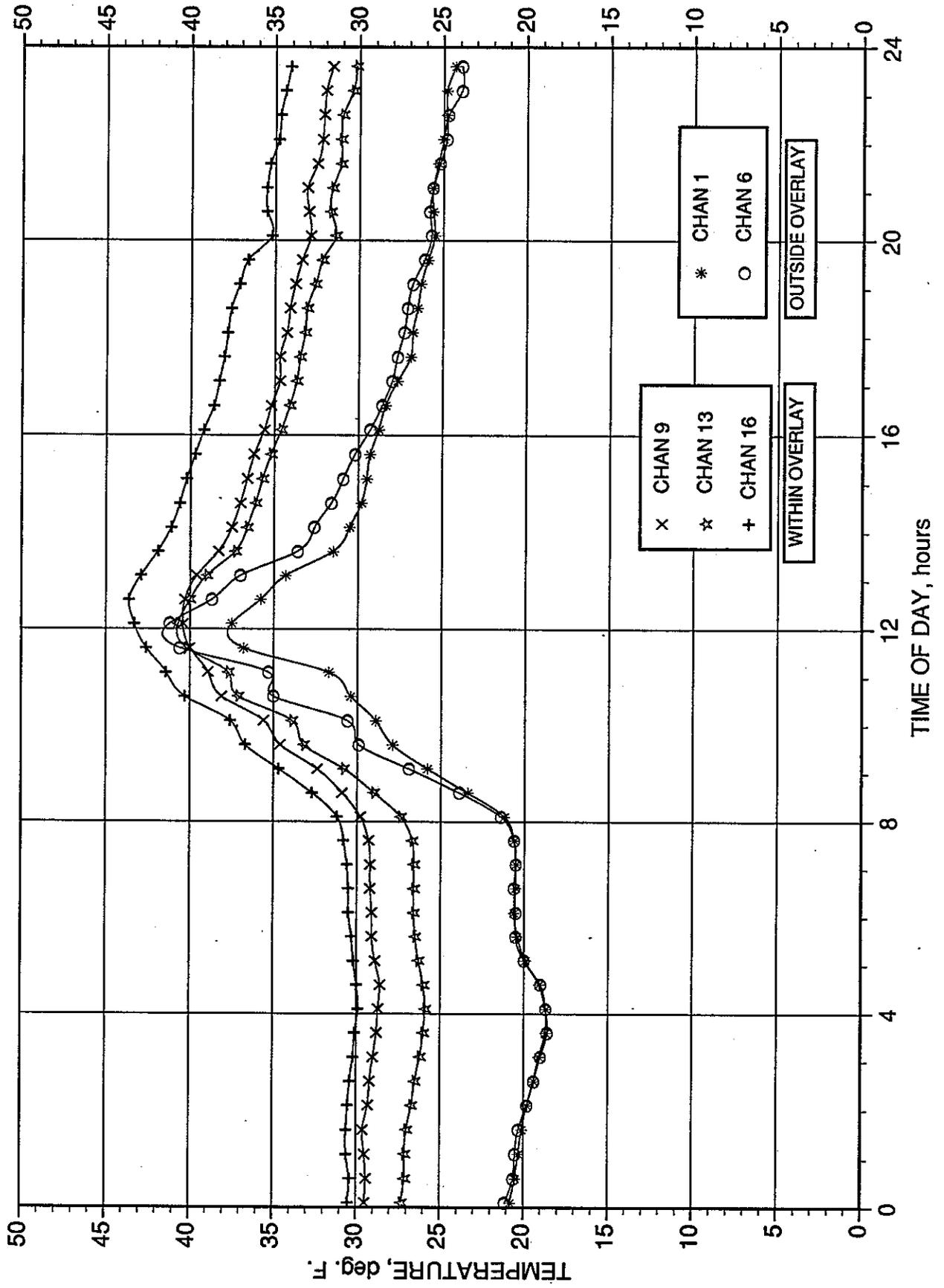
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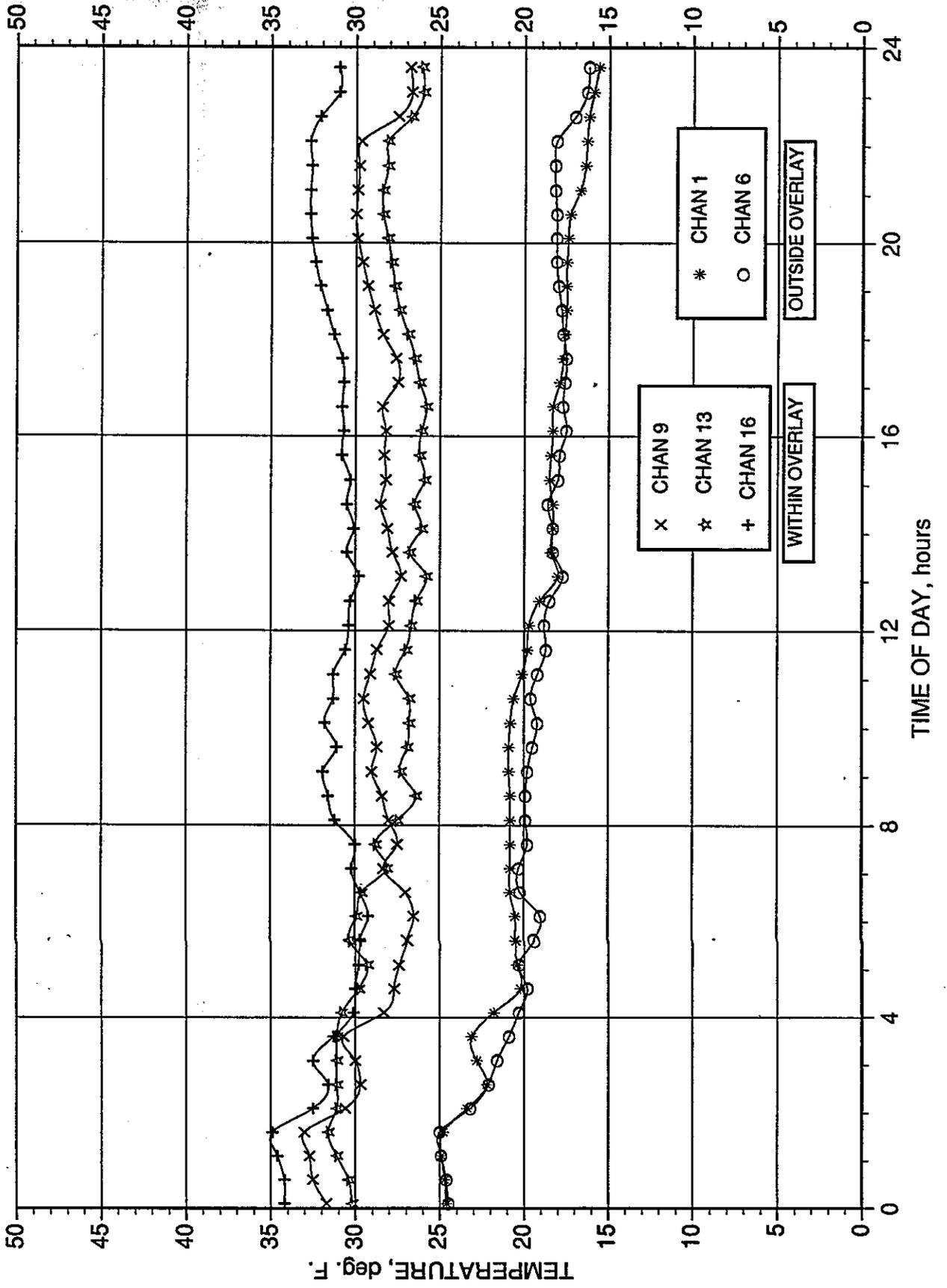
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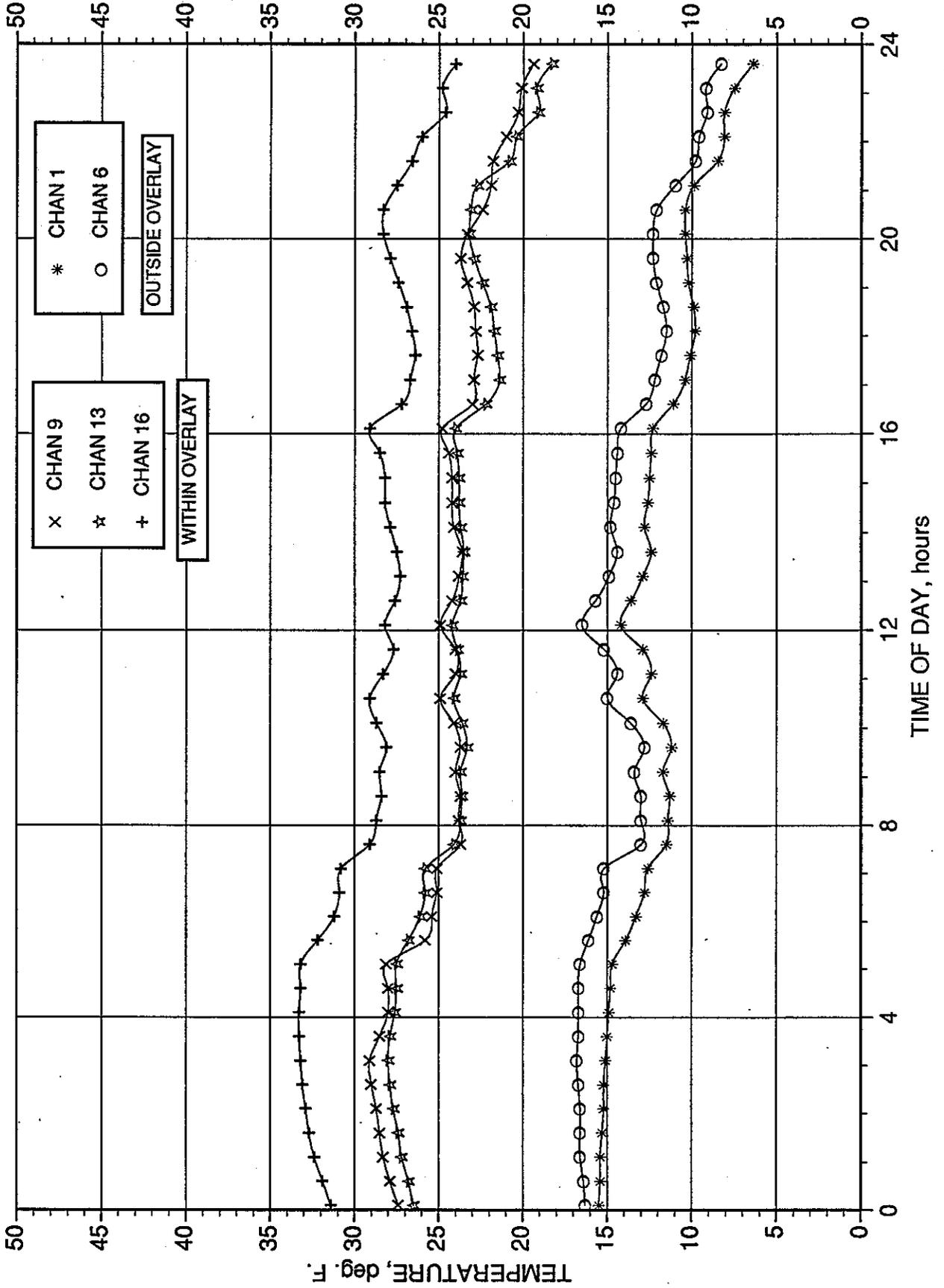
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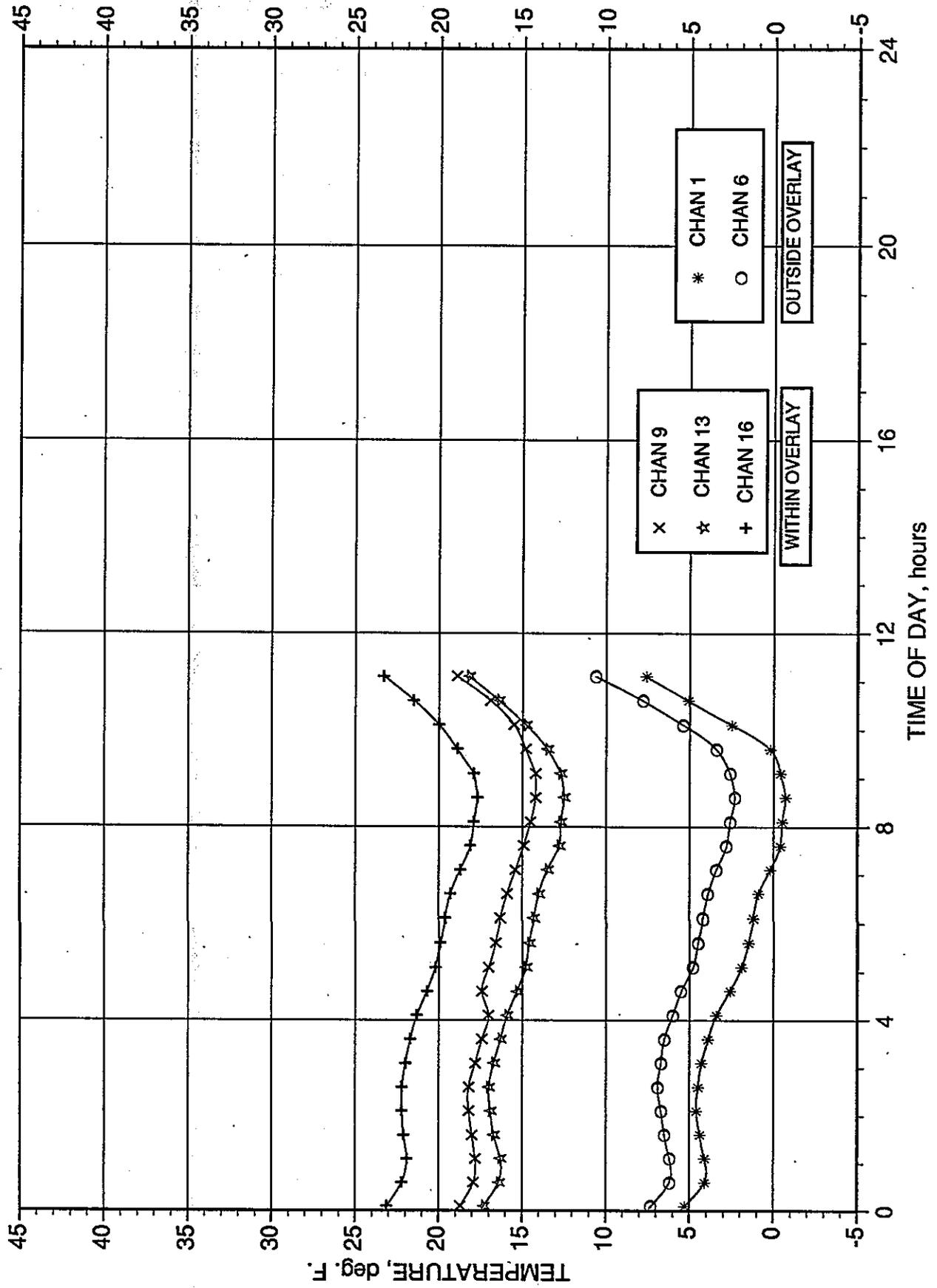
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 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



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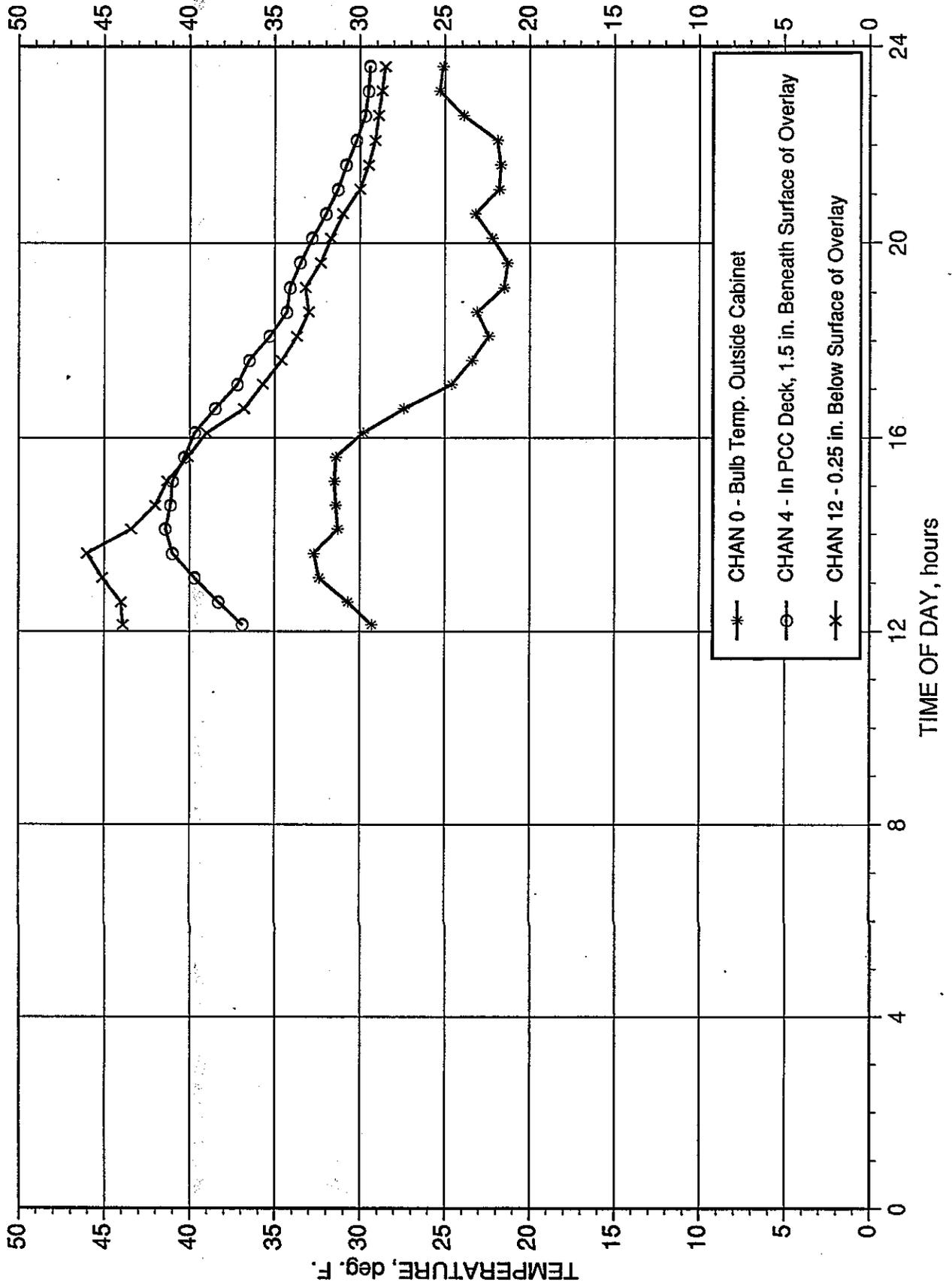


# **APPENDIX E**

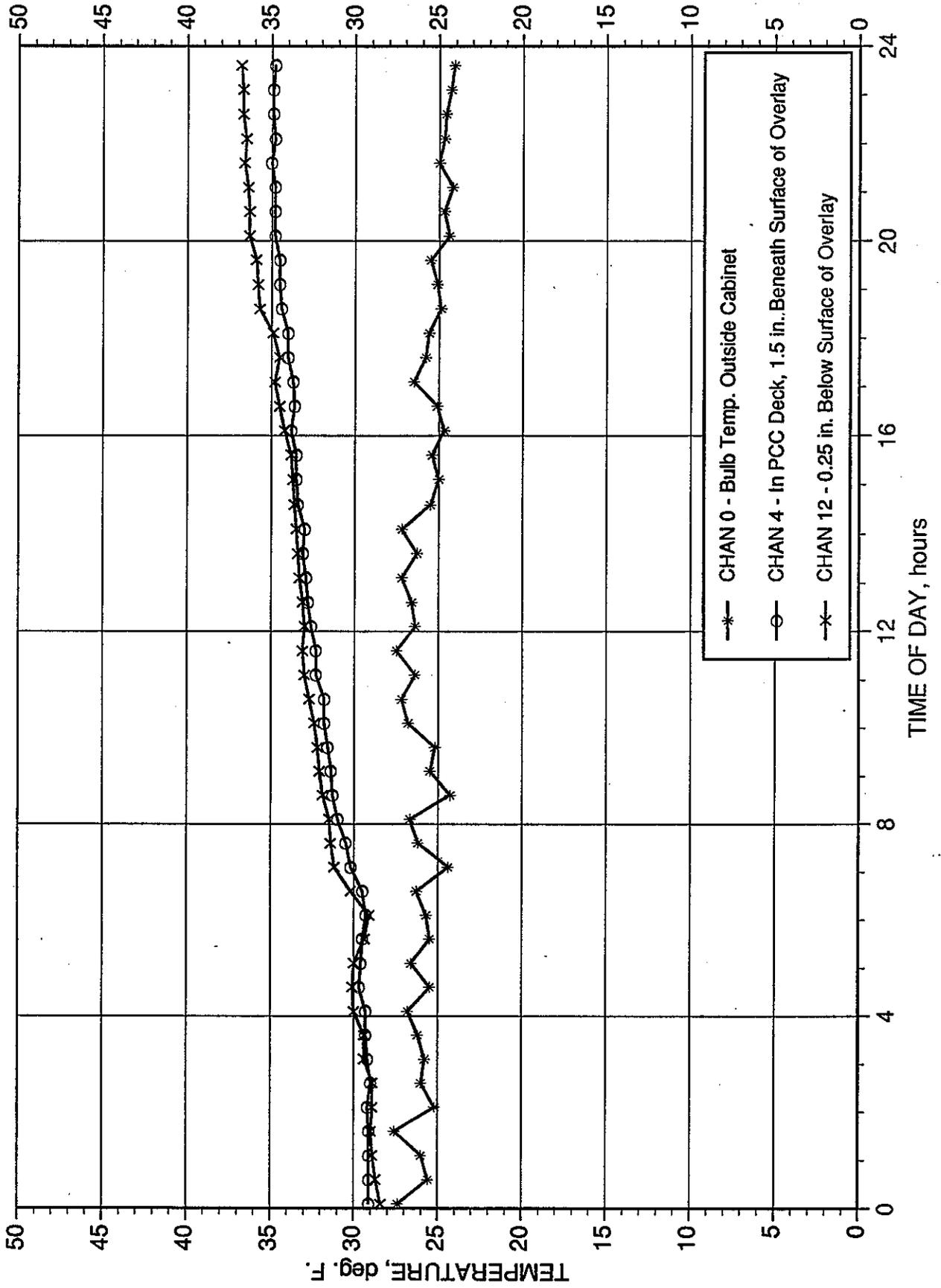
**DECEMBER 14 - 21, 1990**

**COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY**

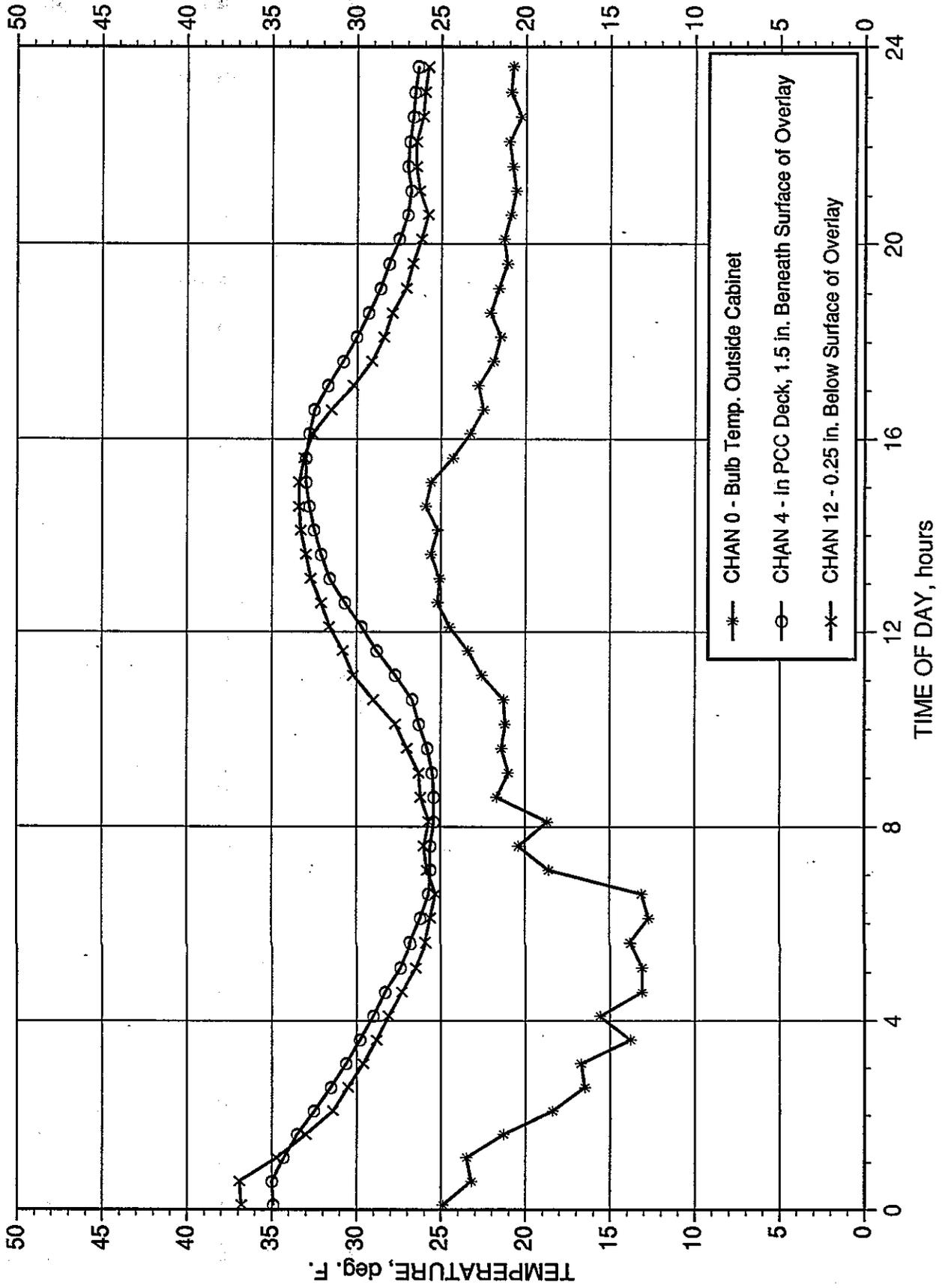
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 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



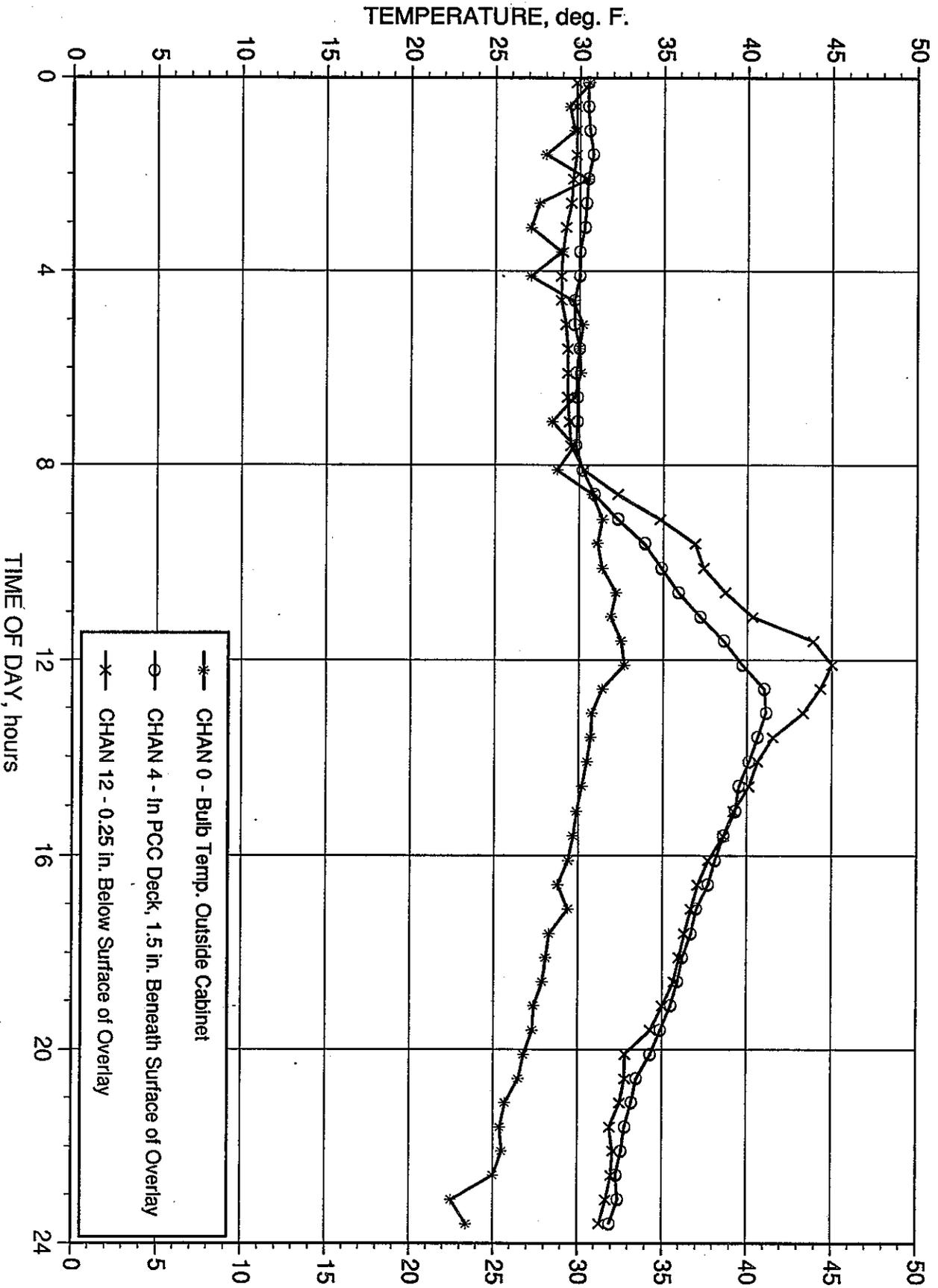
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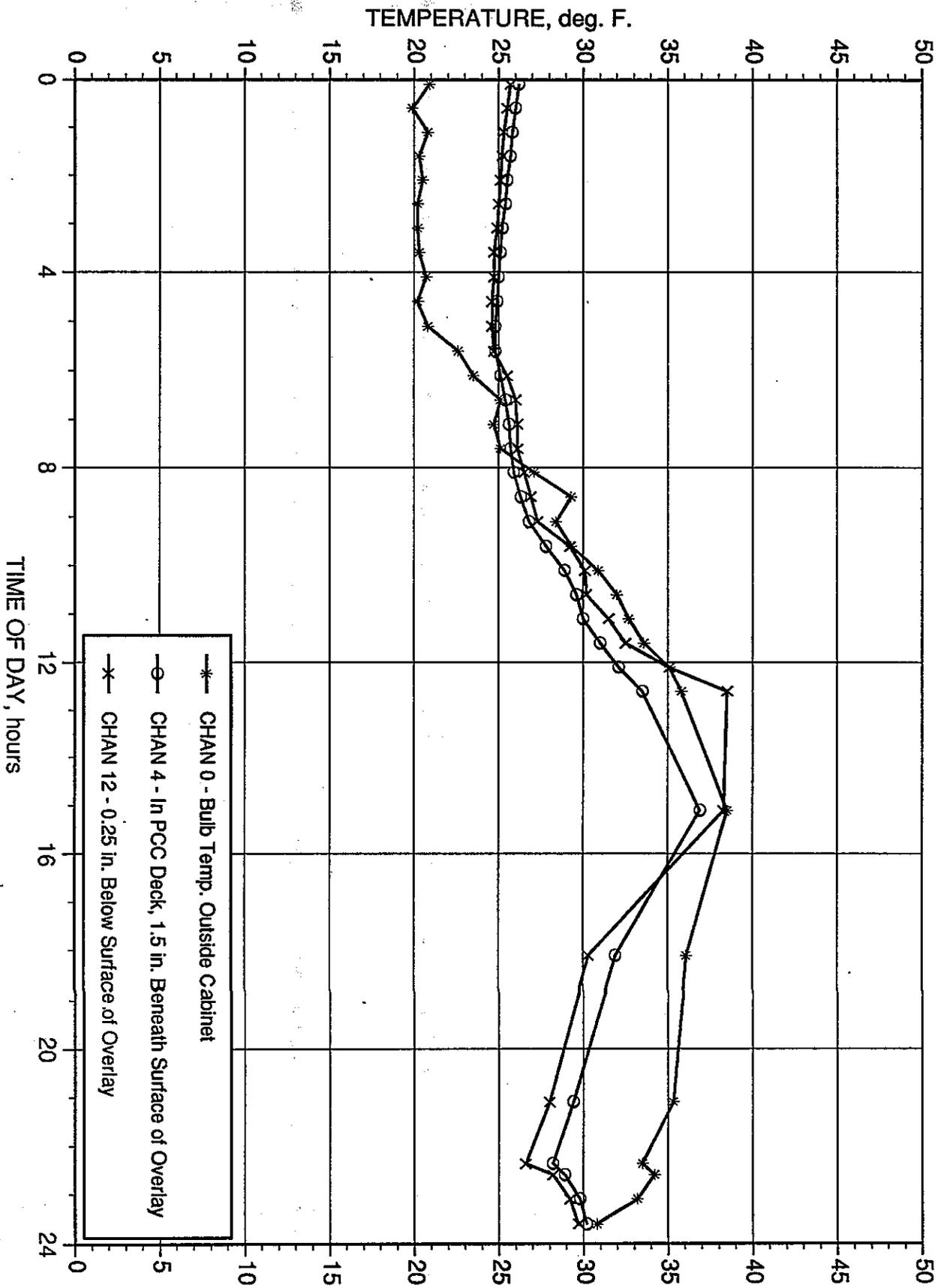
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 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



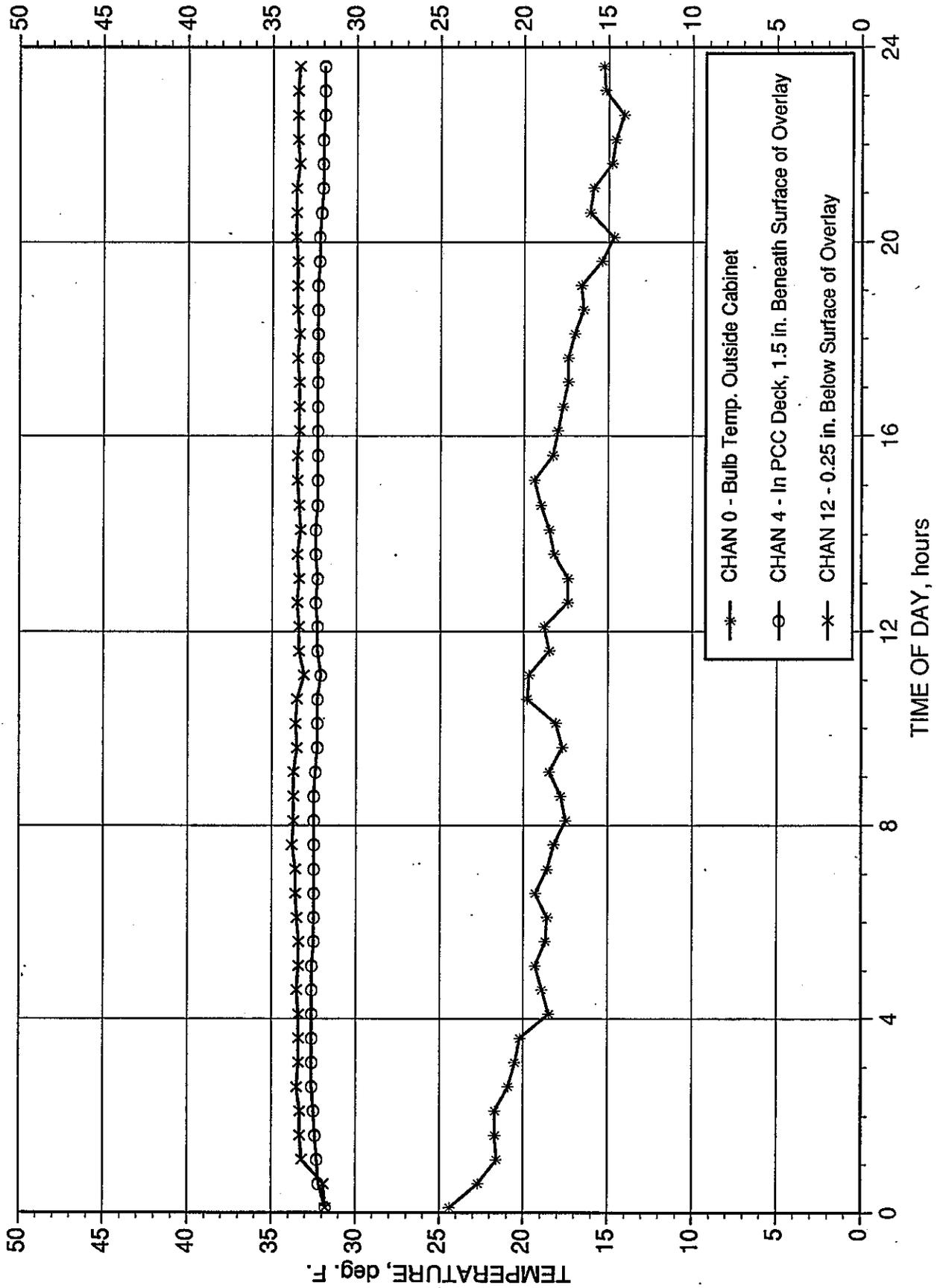
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 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



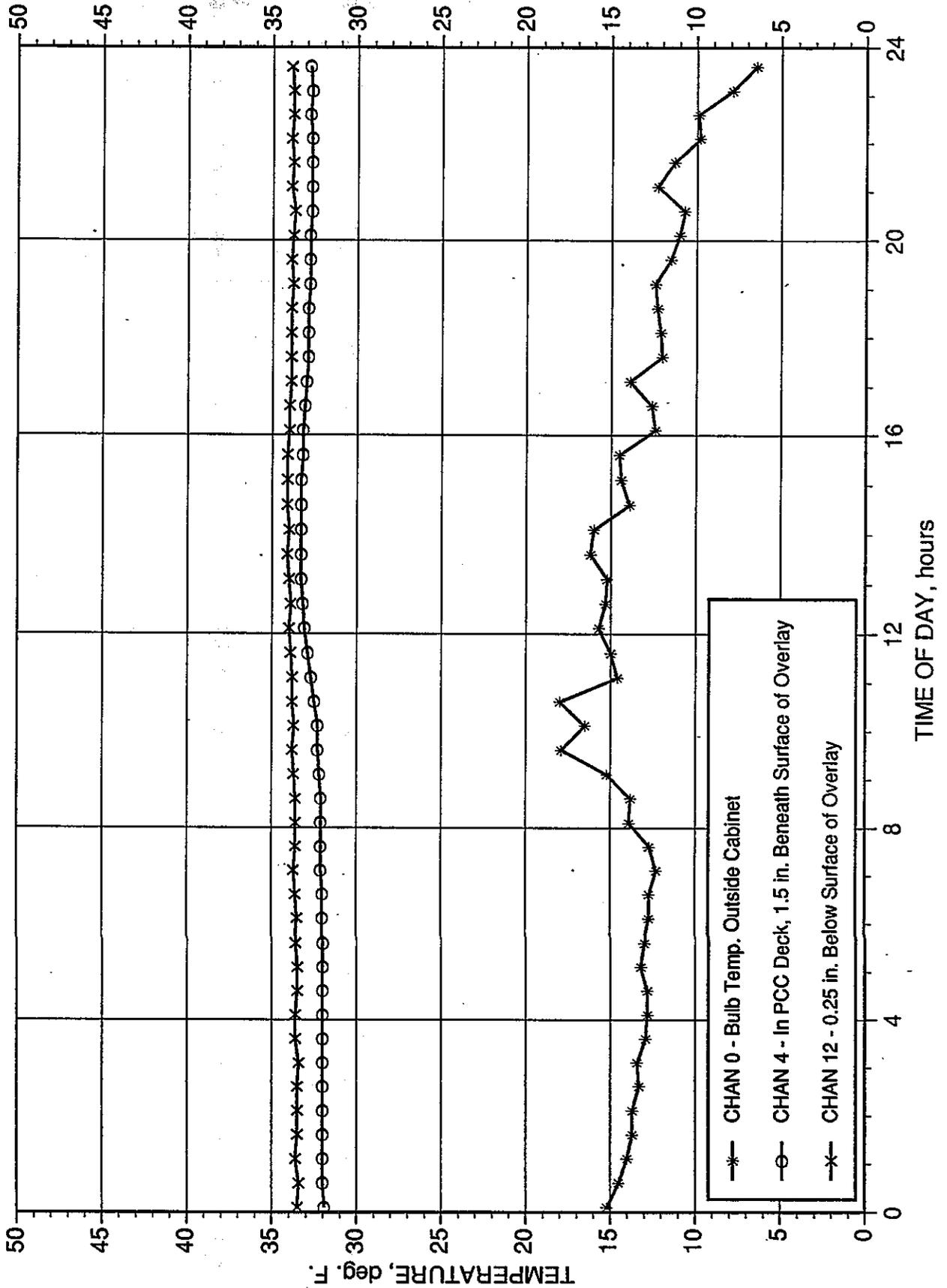
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 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



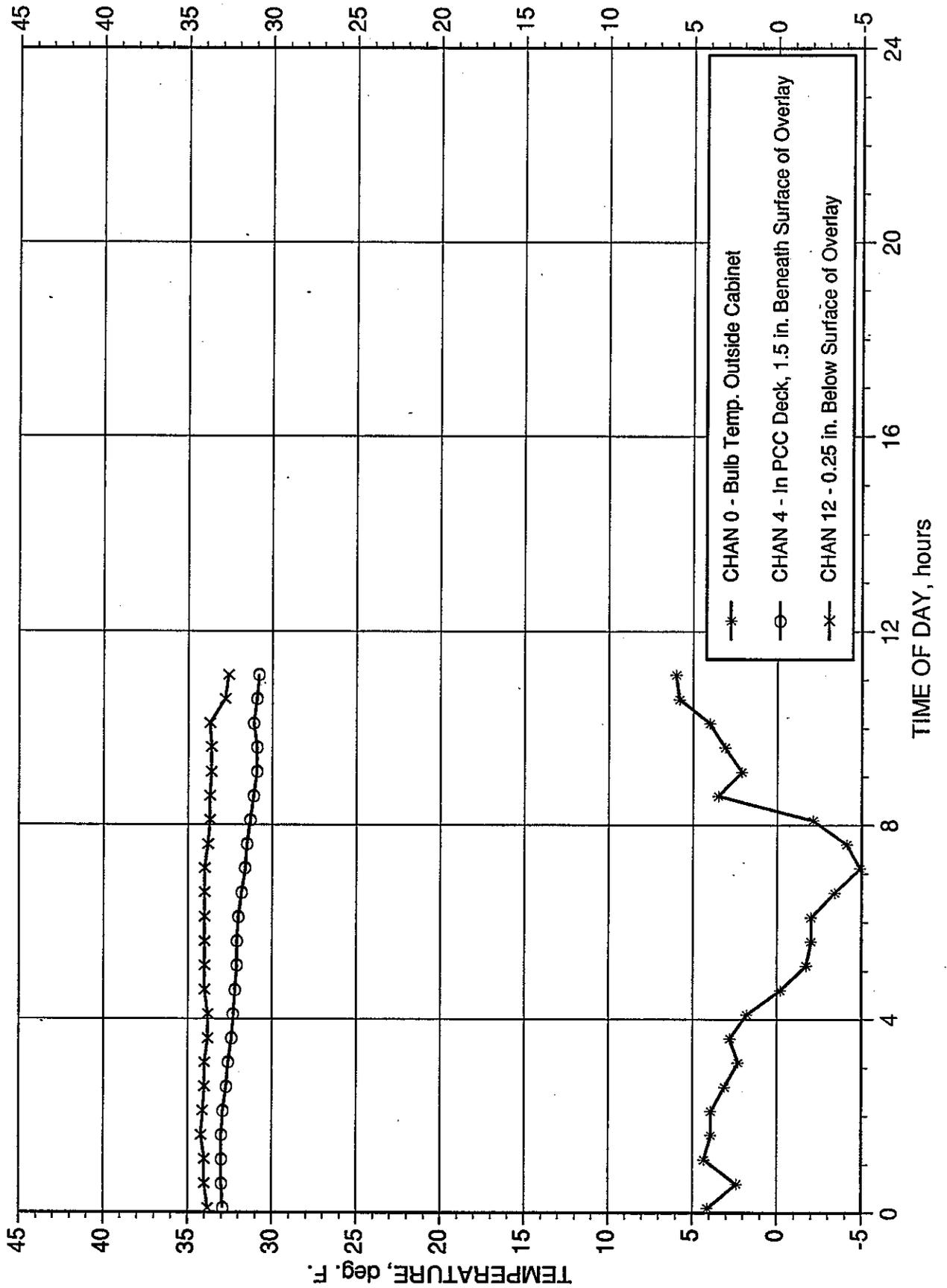
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 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



CASTLE PEAK HEATING OVERLAY DEC. 20, 1990  
 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY



CASTLE PEAK HEATING OVERLAY DEC. 21, 1990  
 COMPARISON OF TEMPERATURES IN CENTER OF OVERLAY

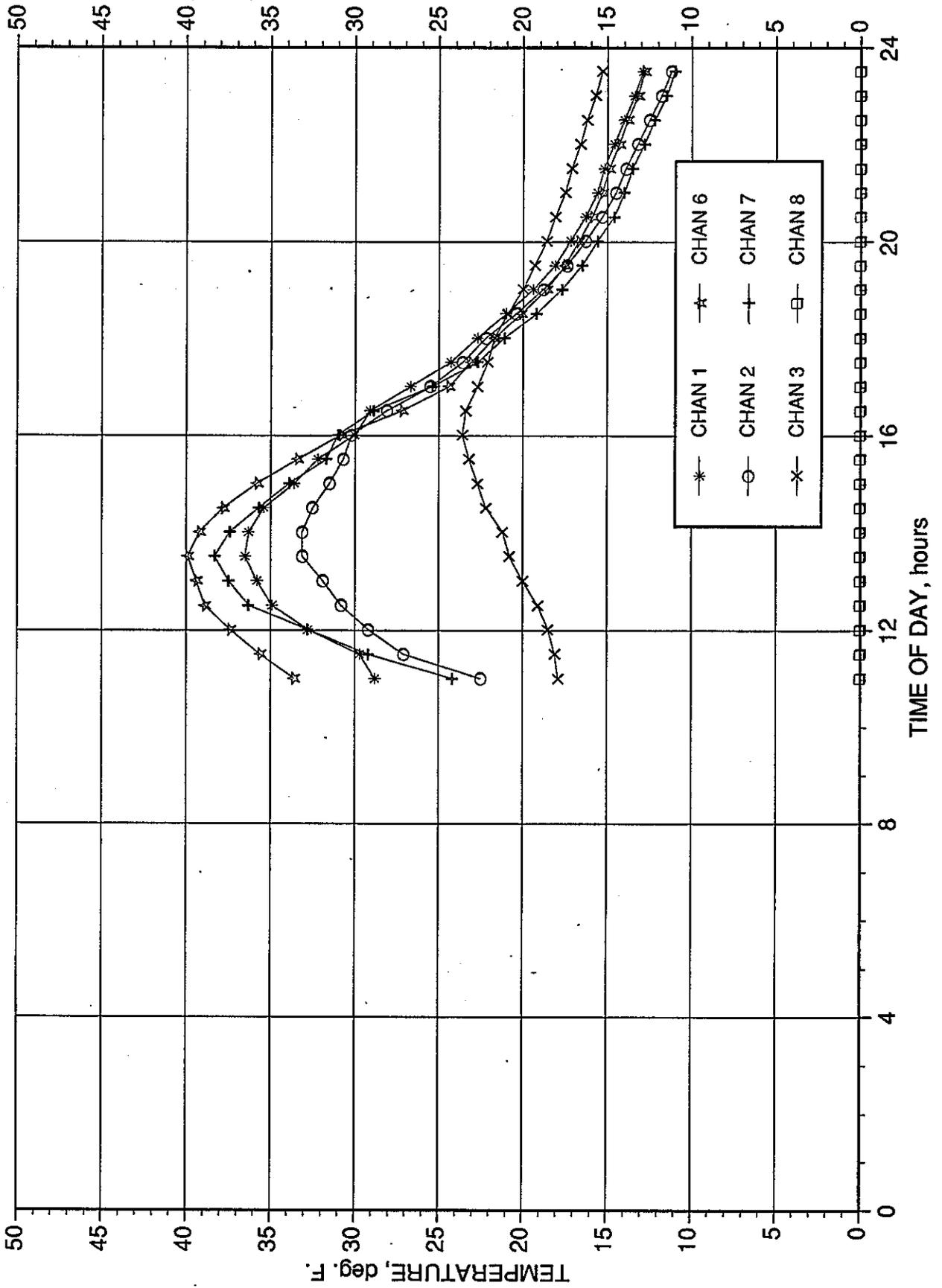


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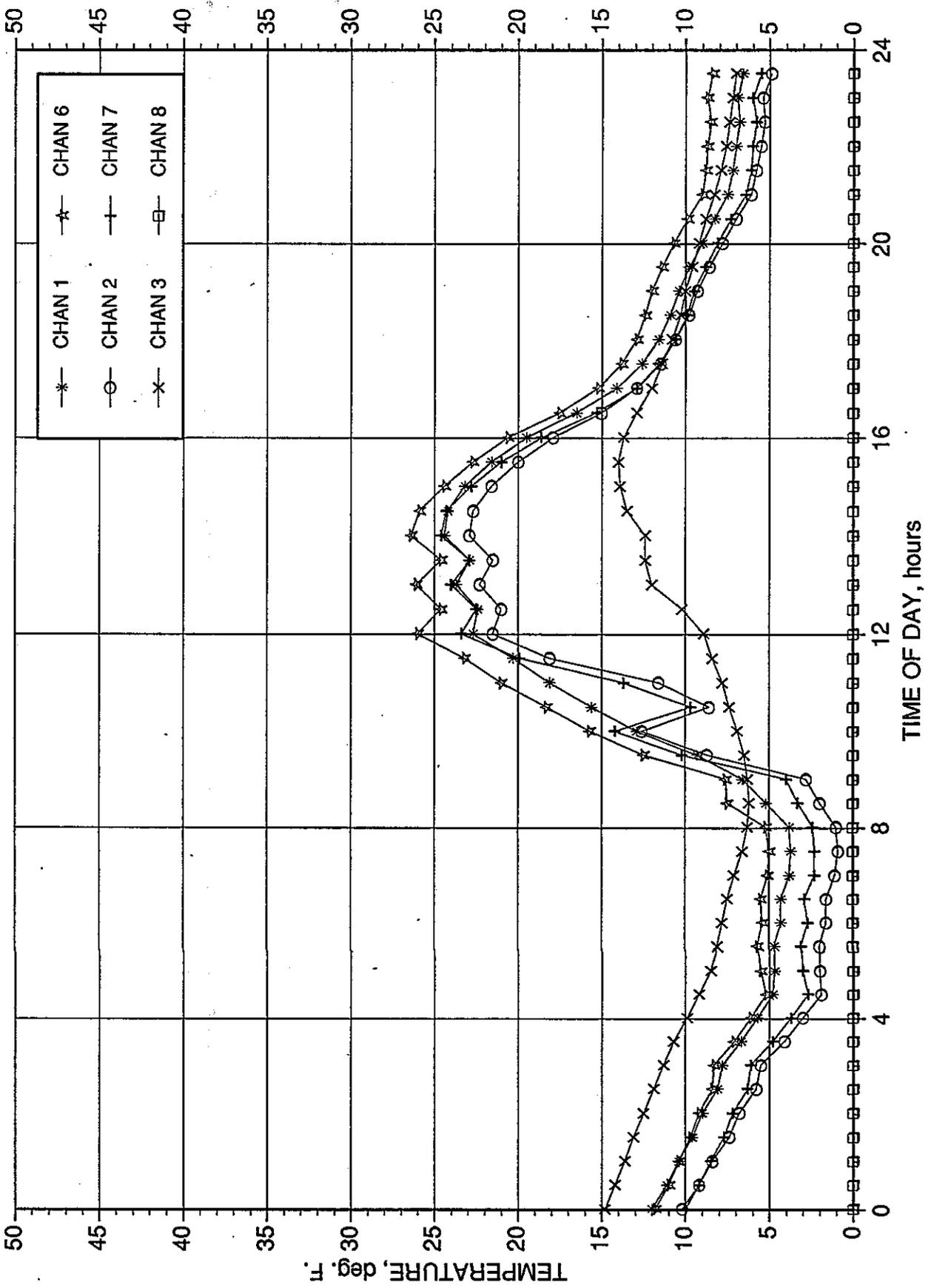
**DECEMBER 28, 1990 - JANUARY 10, 1991**

**COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY**

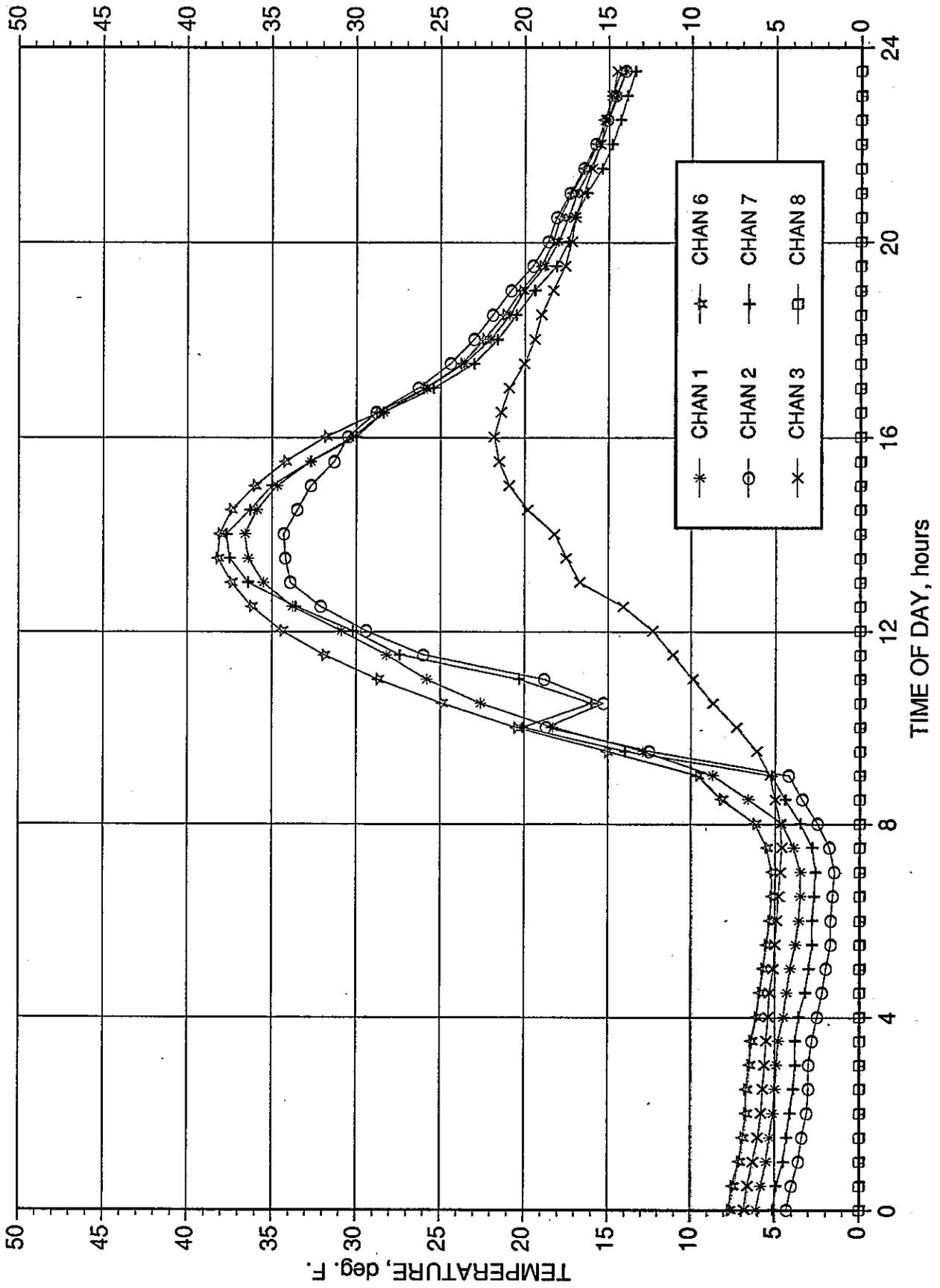
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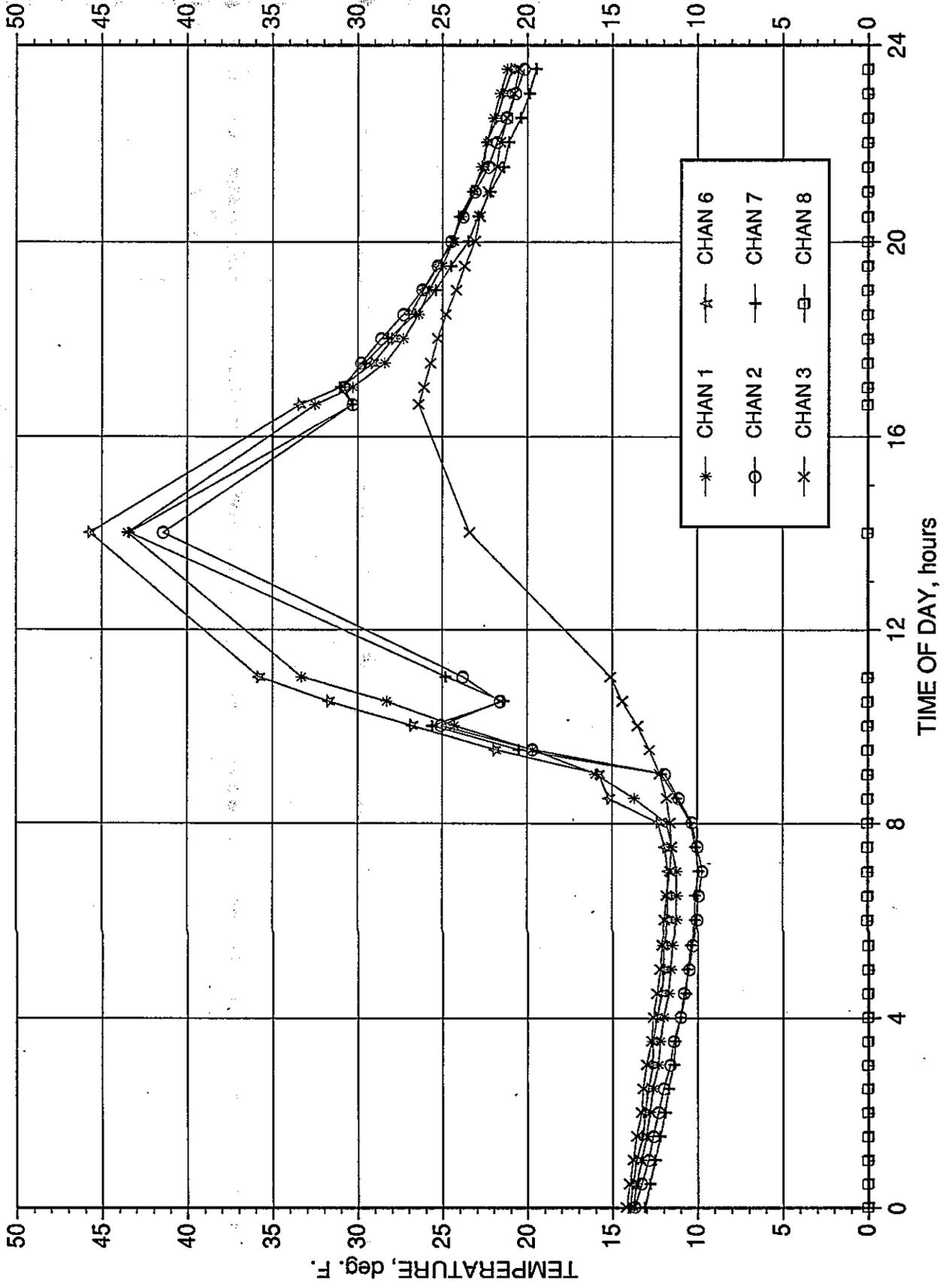
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 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



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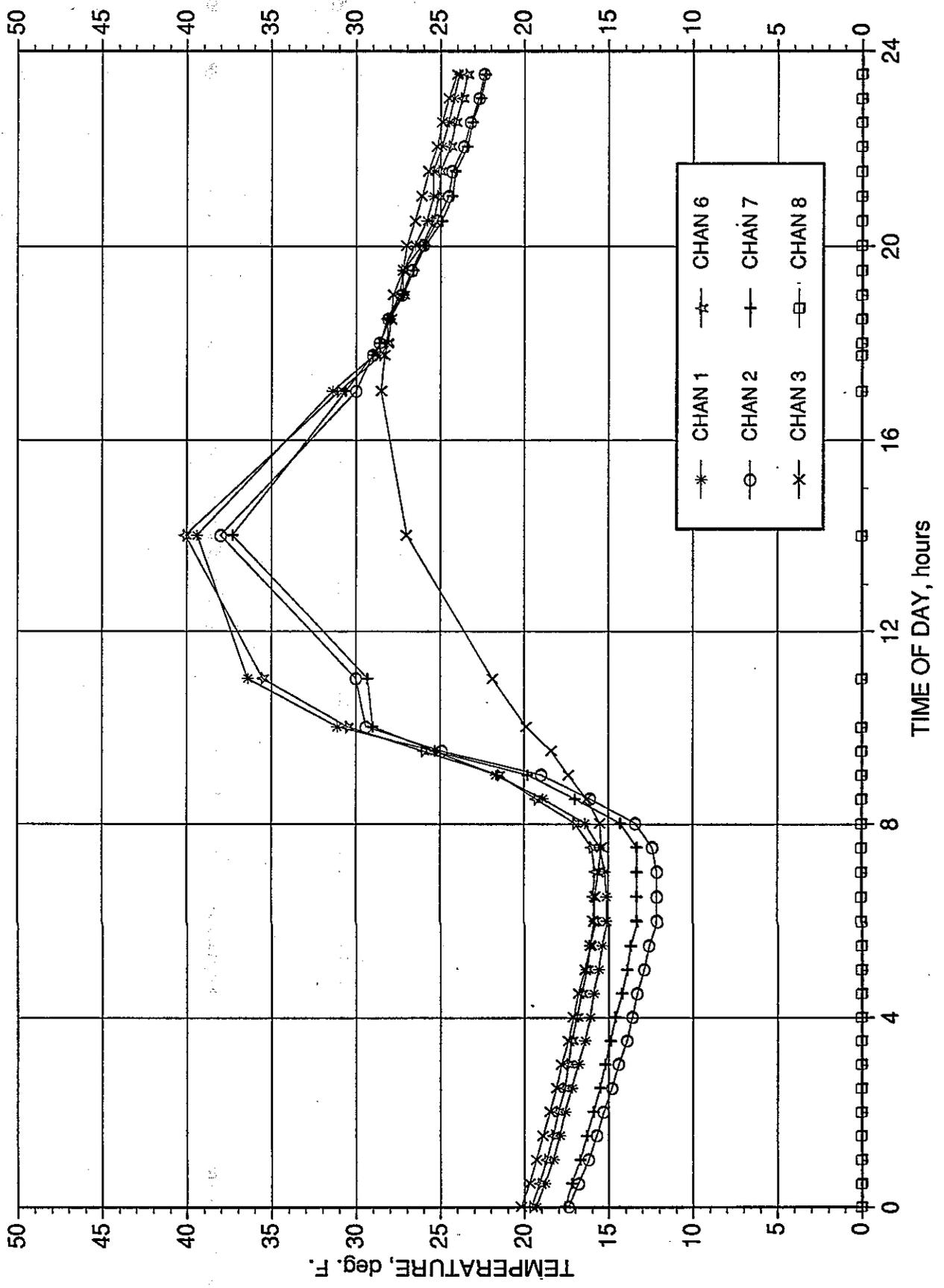


CASTLE PEAK HEATING OVERLAY DEC. 31, 1990  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY

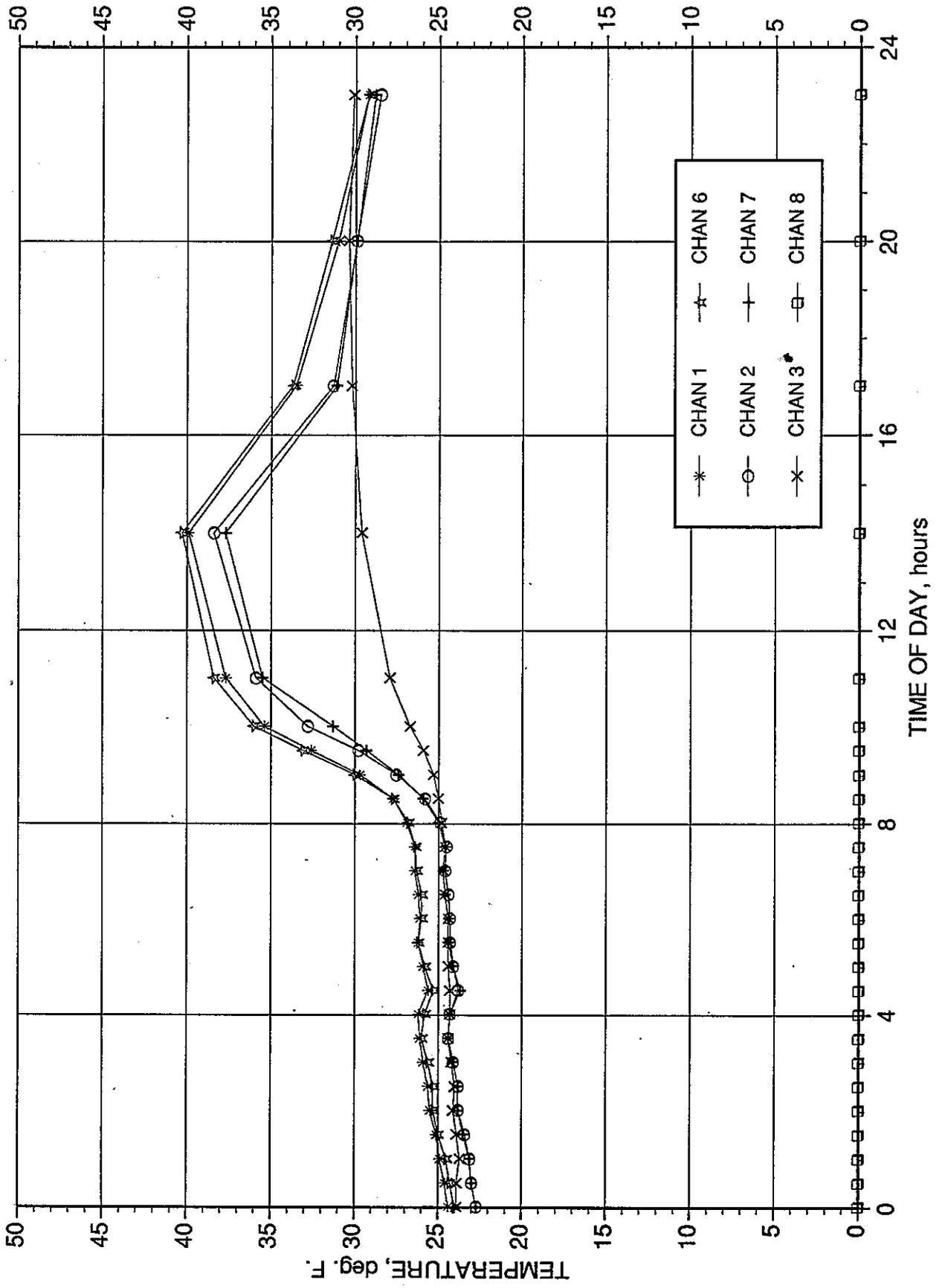




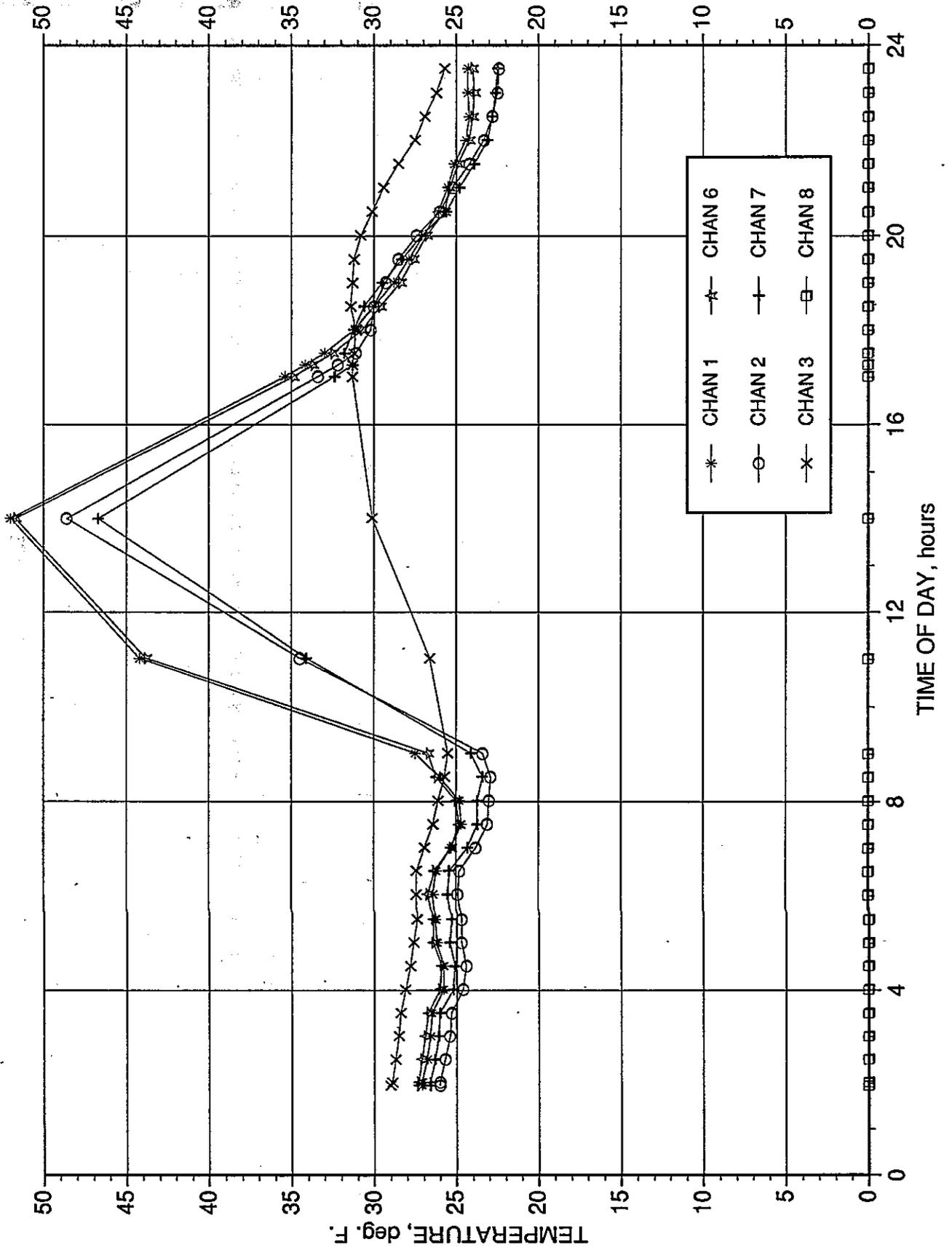
CASTLE PEAK HEATING OVERLAY JAN. 2, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



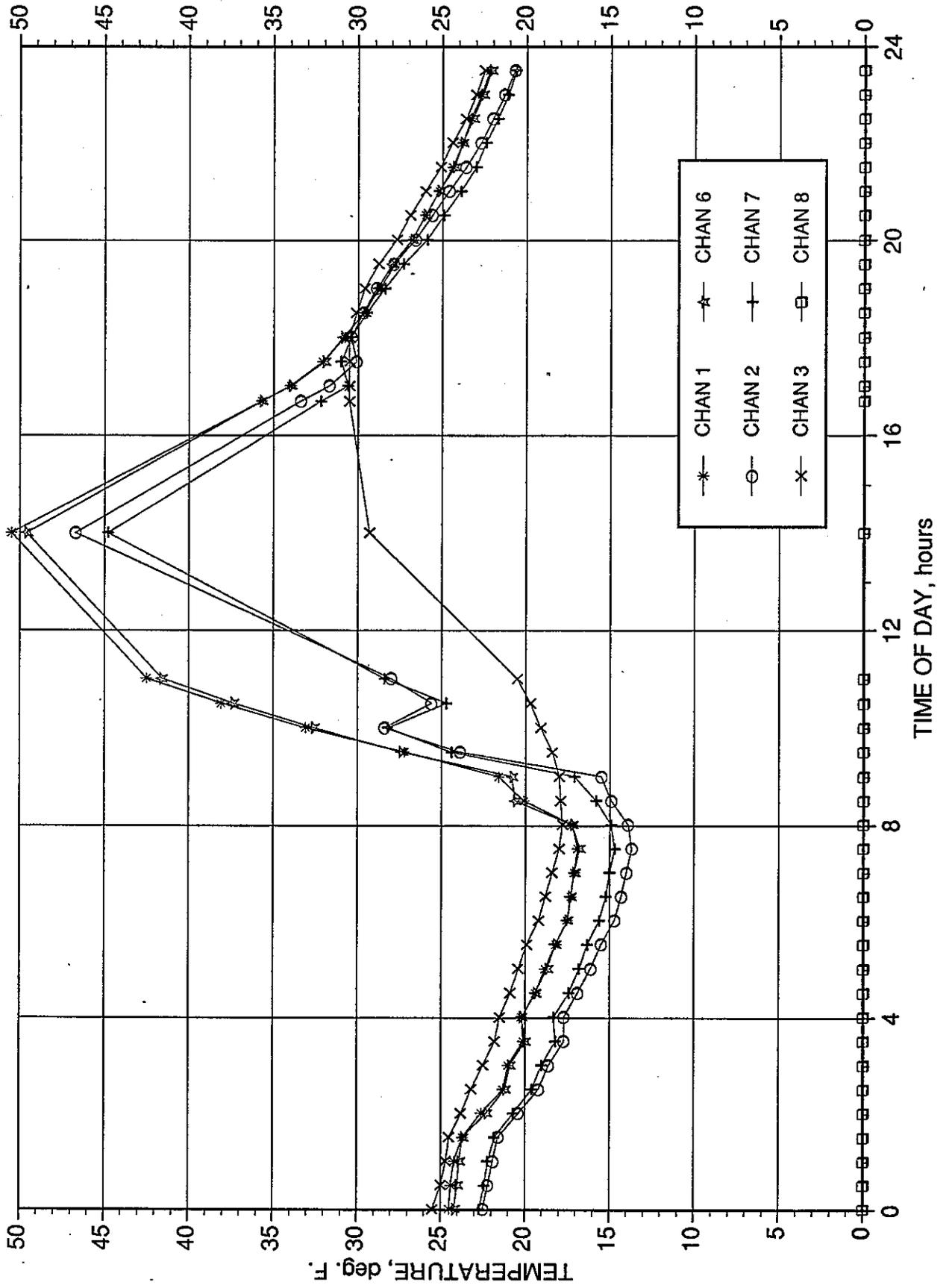
CASTLE PEAK HEATING OVERLAY JAN. 3, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



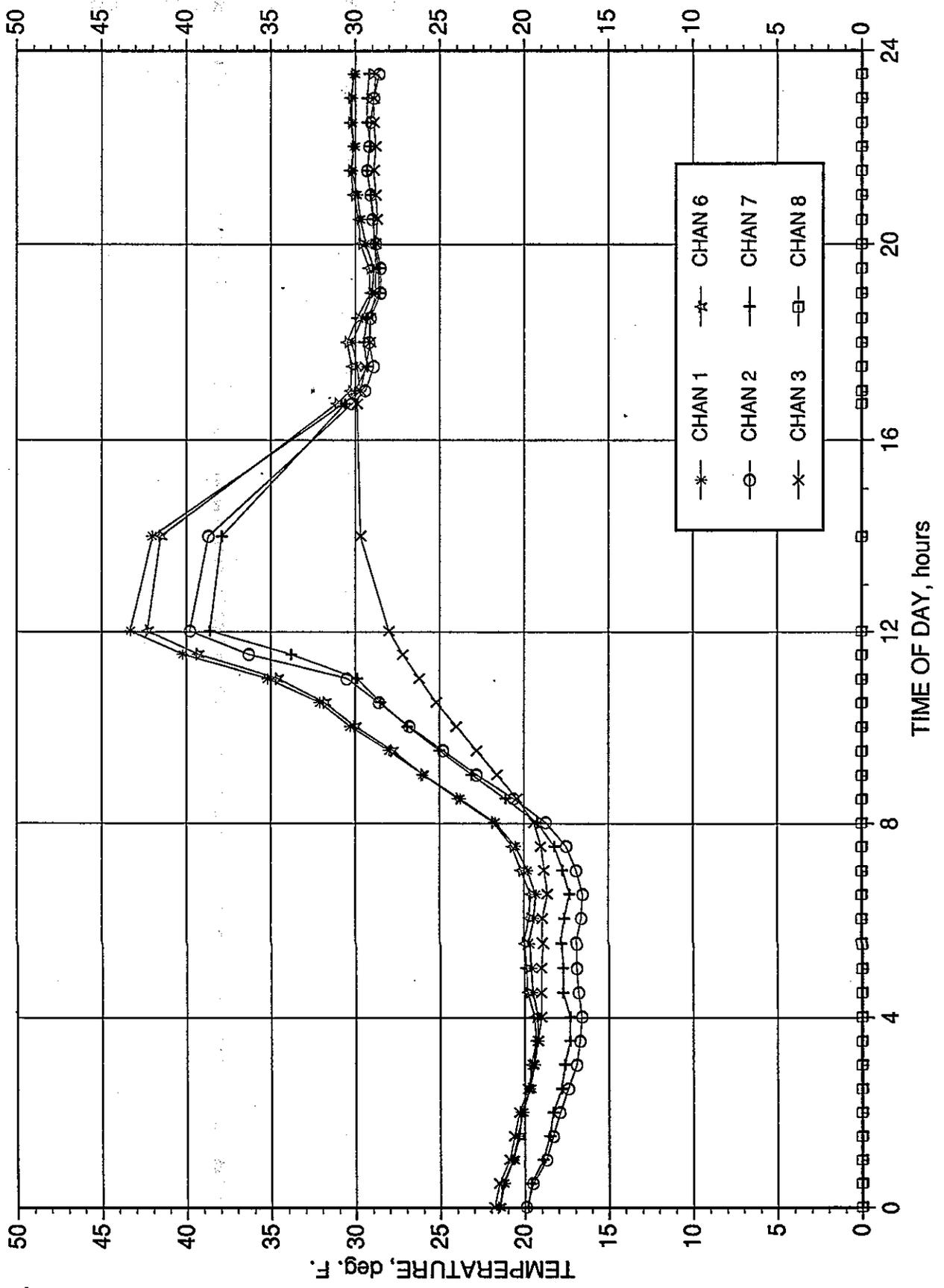
CASTLE PEAK HEATING OVERLAY JAN. 4, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



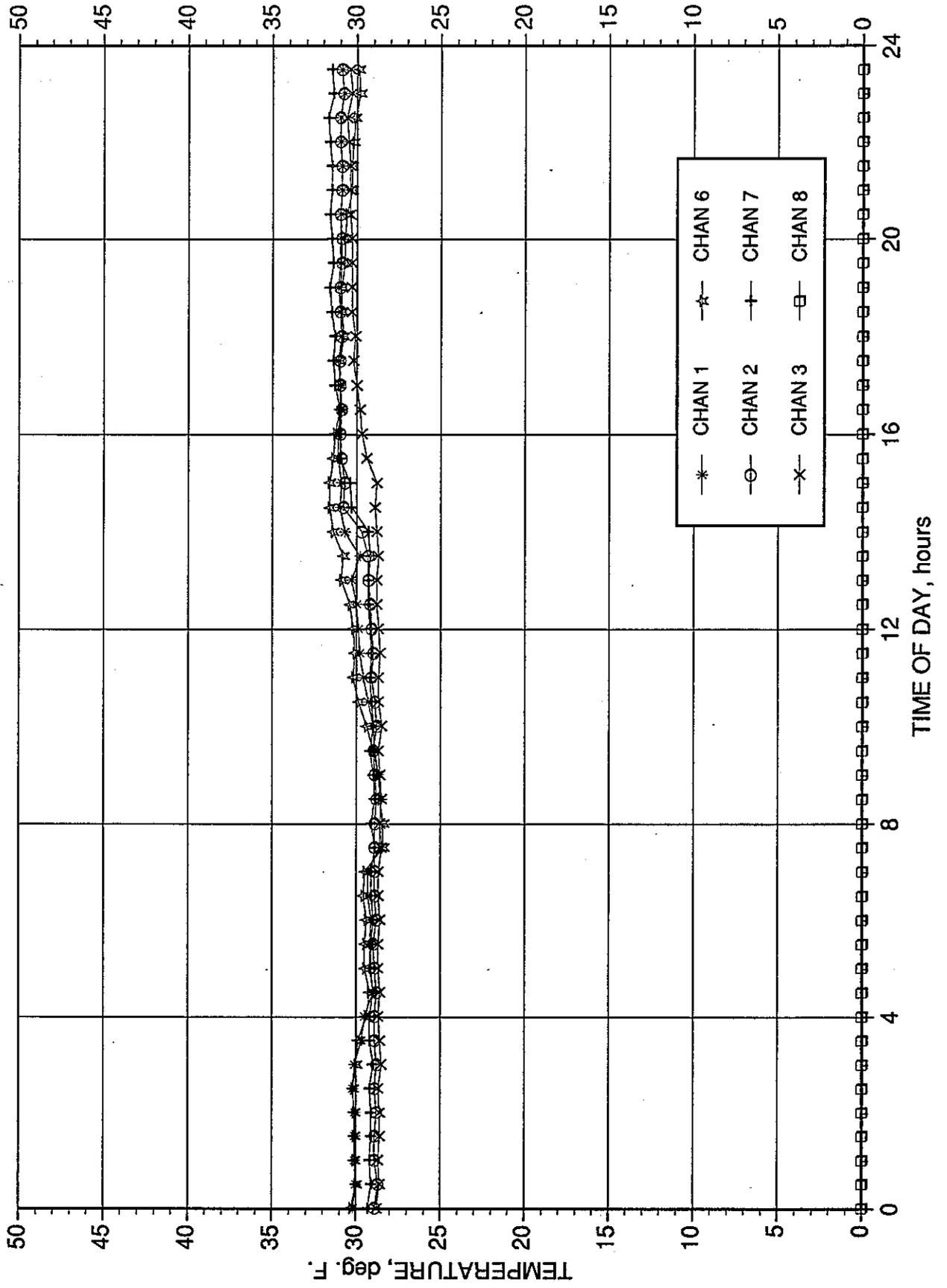
CASTLE PEAK HEATING OVERLAY JAN. 5, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY



CASTLE PEAK HEATING OVERLAY JAN. 6, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY

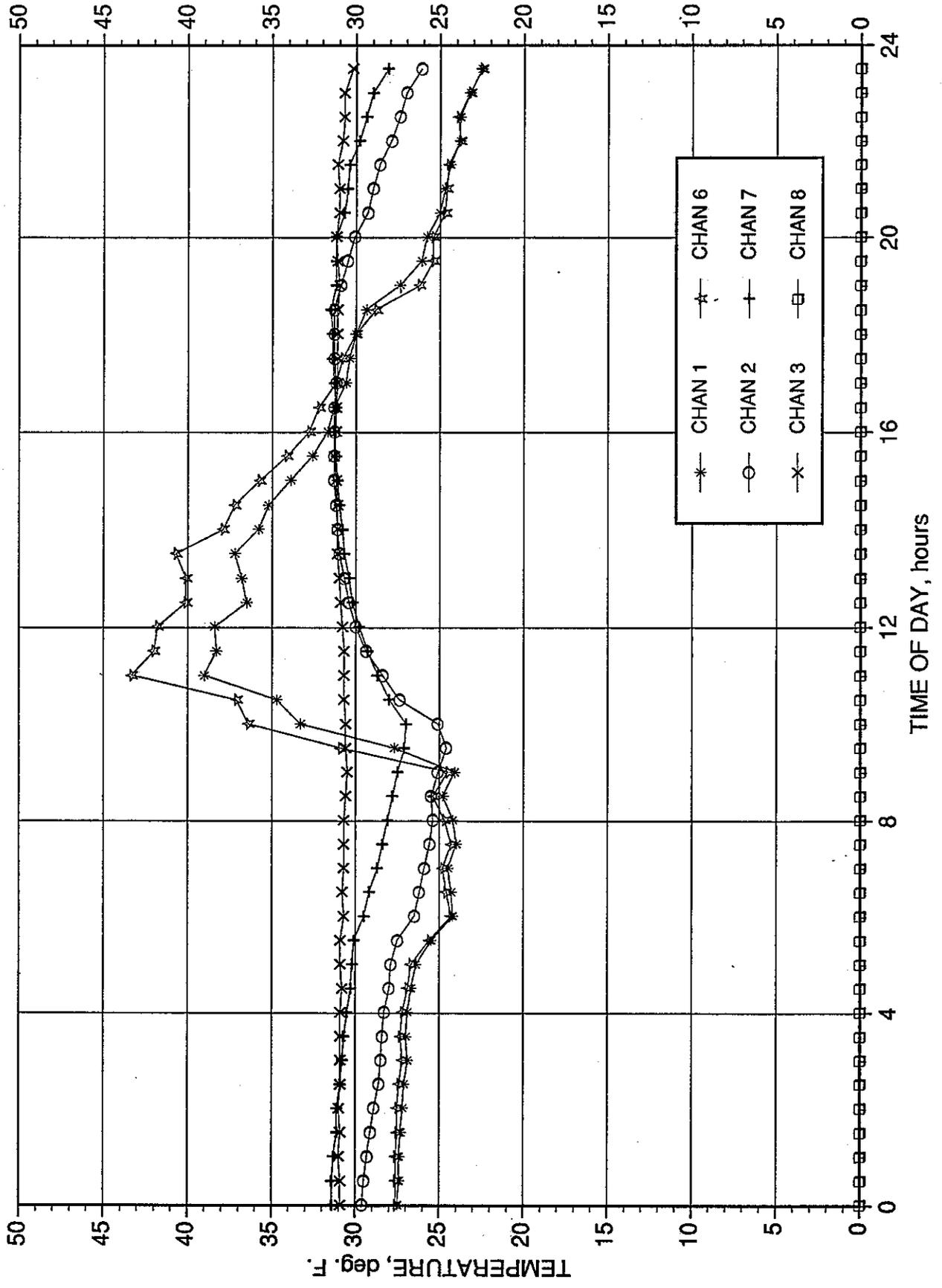


CASTLE PEAK HEATING OVERLAY JAN. 7, 1991  
COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY





CASTLE PEAK HEATING OVERLAY JAN. 9, 1991  
 COMPARISON OF TEMPERATURES OUTSIDE OVERLAY BOUNDARY





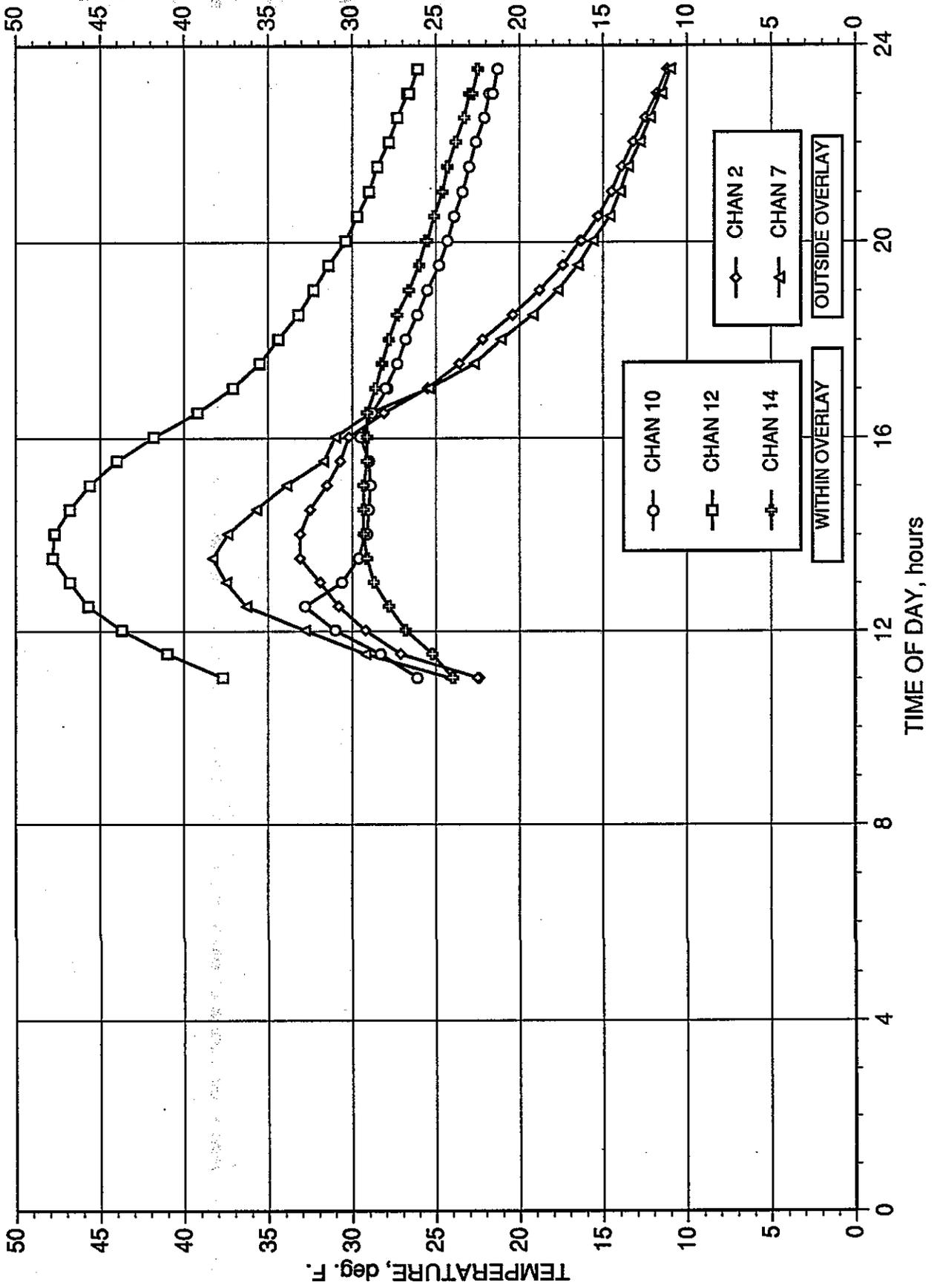
# **APPENDIX G**

**DECEMBER 28, 1990 - JANUARY 10, 1991**

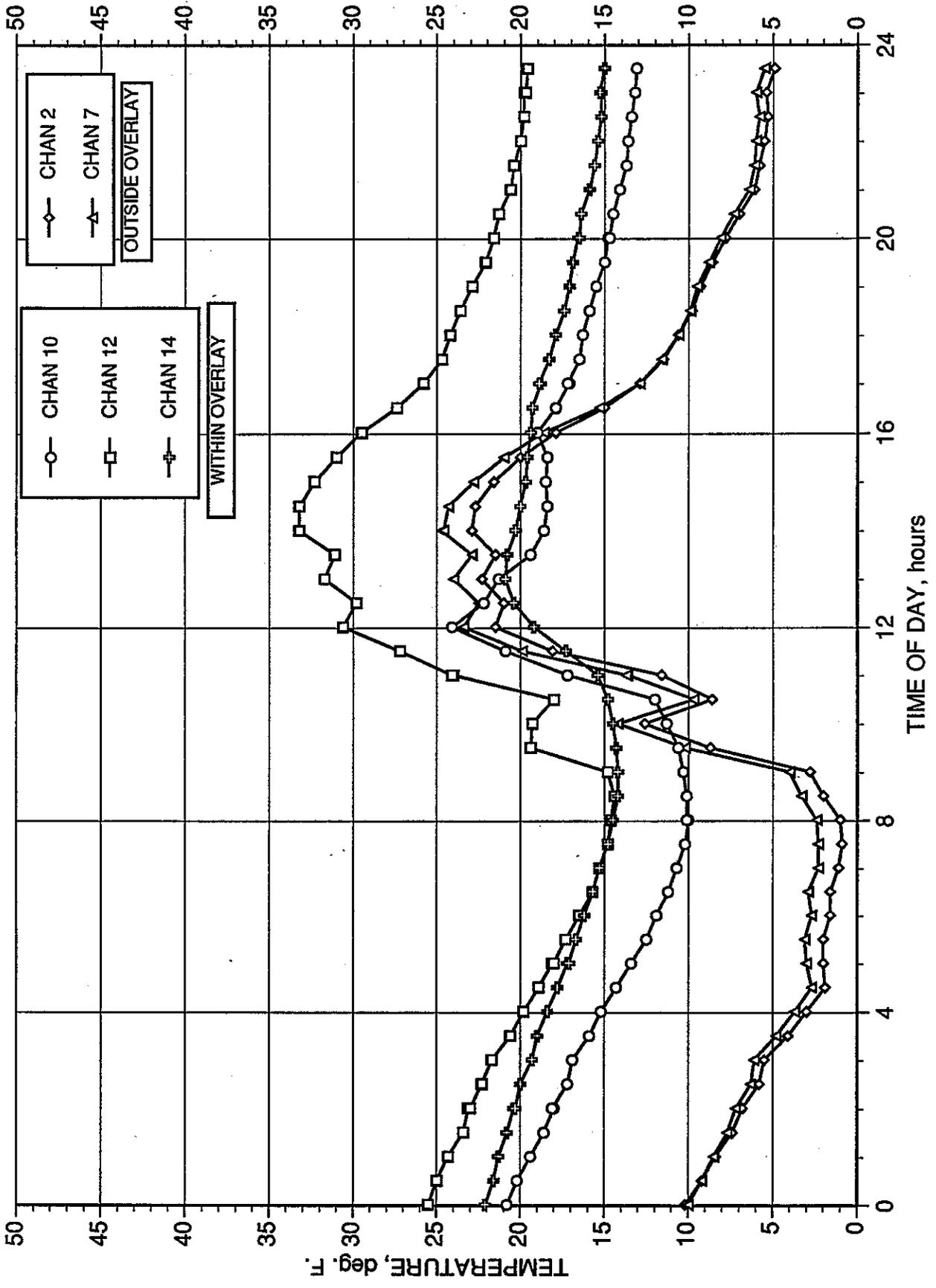
**COMPARISON OF CENTER ROW TEMPERATURES -**

**(MIDWAY BETWEEN LANE AND RAIL)**

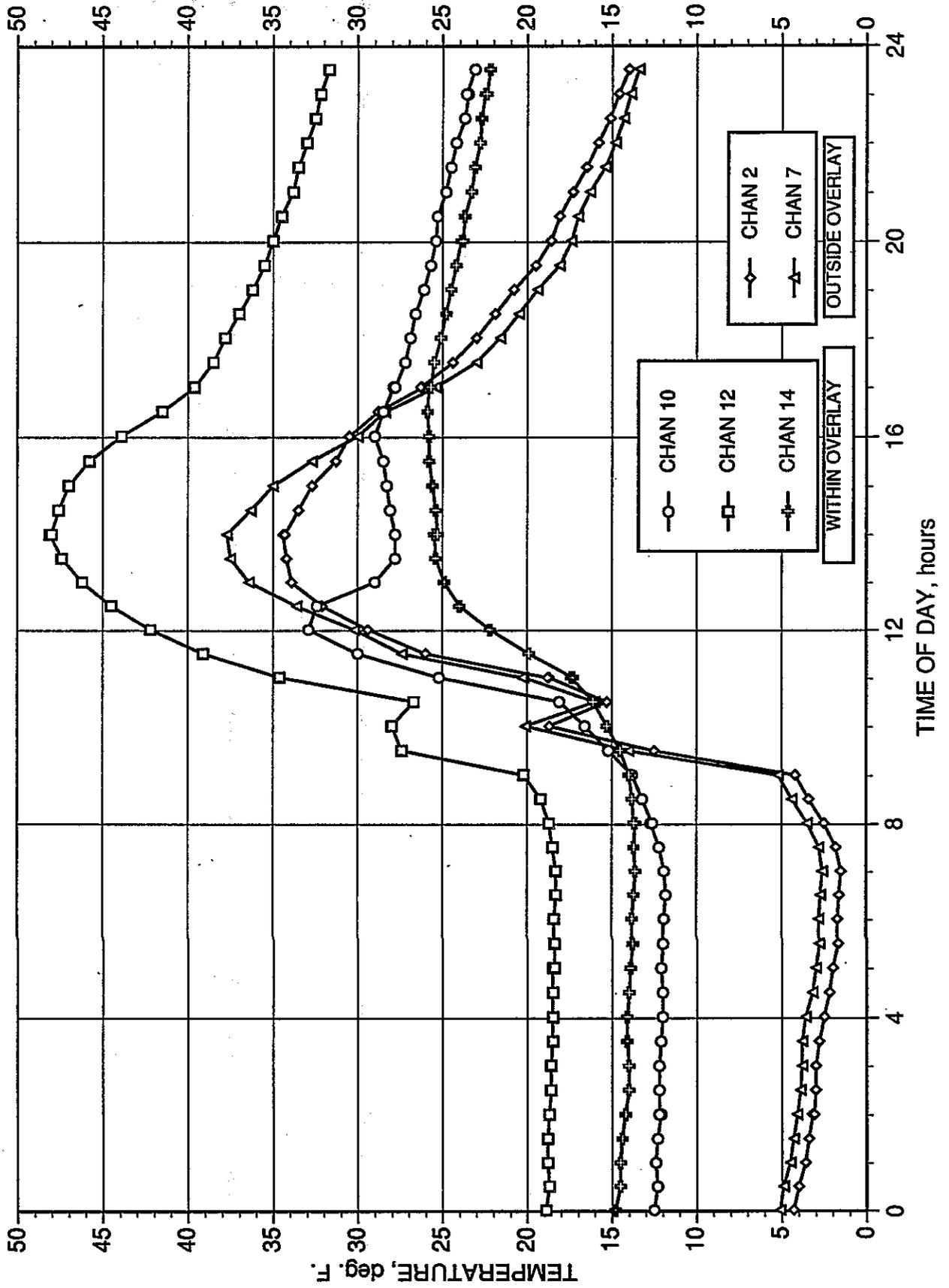
CASTLE PEAK HEATING OVERLAY DEC. 28, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



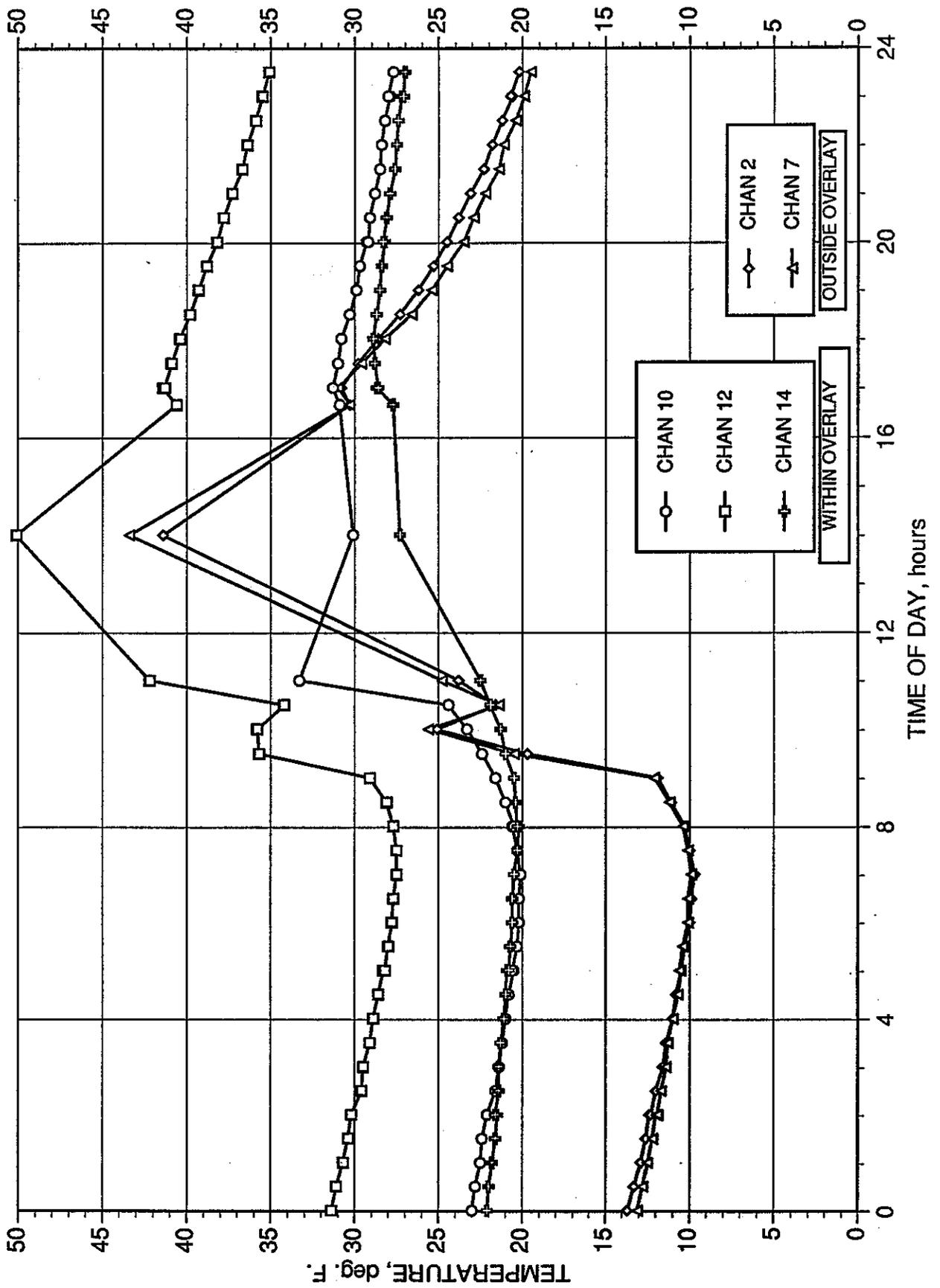
CASTLE PEAK HEATING OVERLAY DEC. 29, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



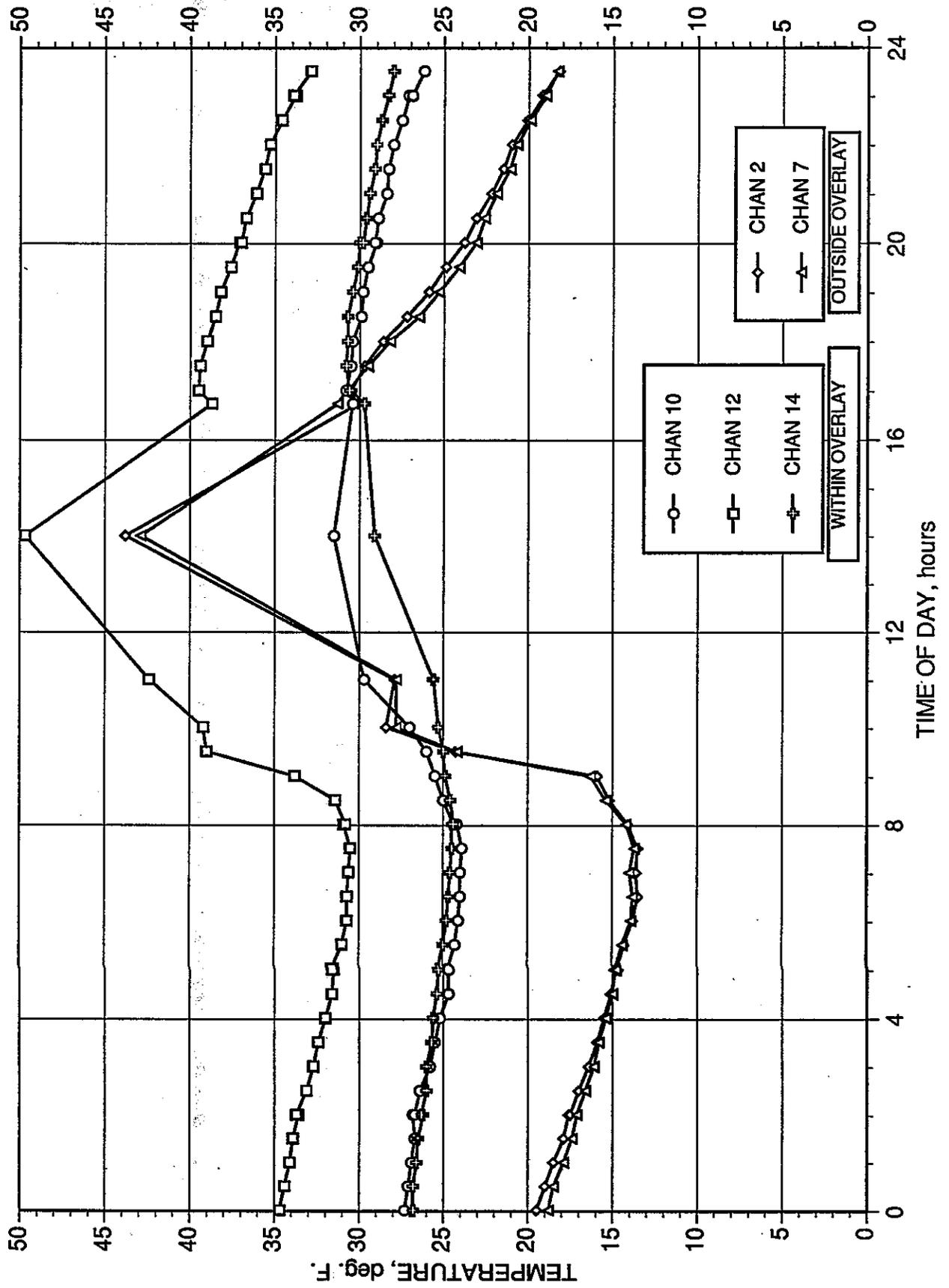
CASTLE PEAK HEATING OVERLAY DEC. 30, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



CASTLE PEAK HEATING OVERLAY DEC. 31, 1990  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)

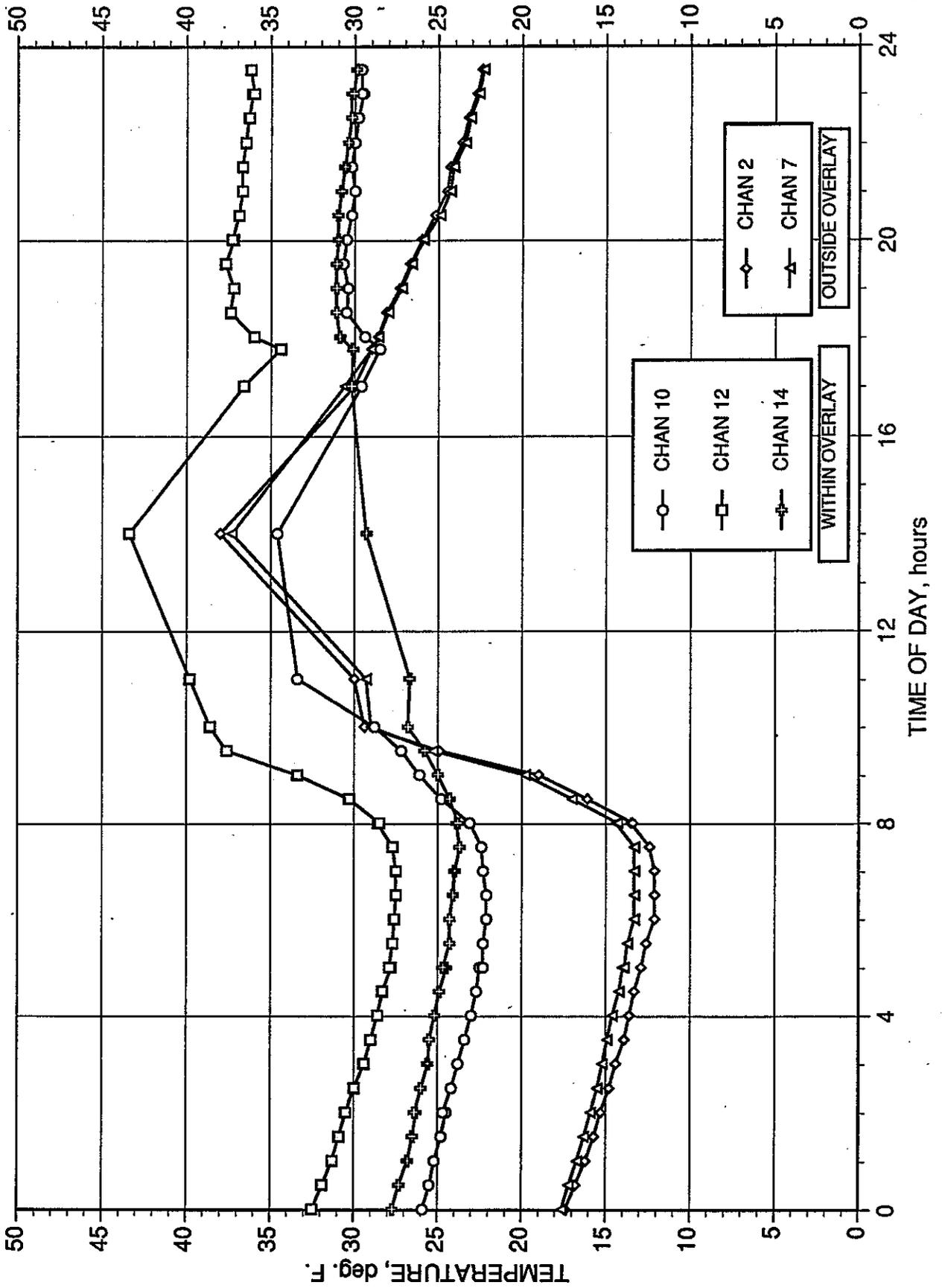


CASTLE PEAK HEATING OVERLAY JAN. 1, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)

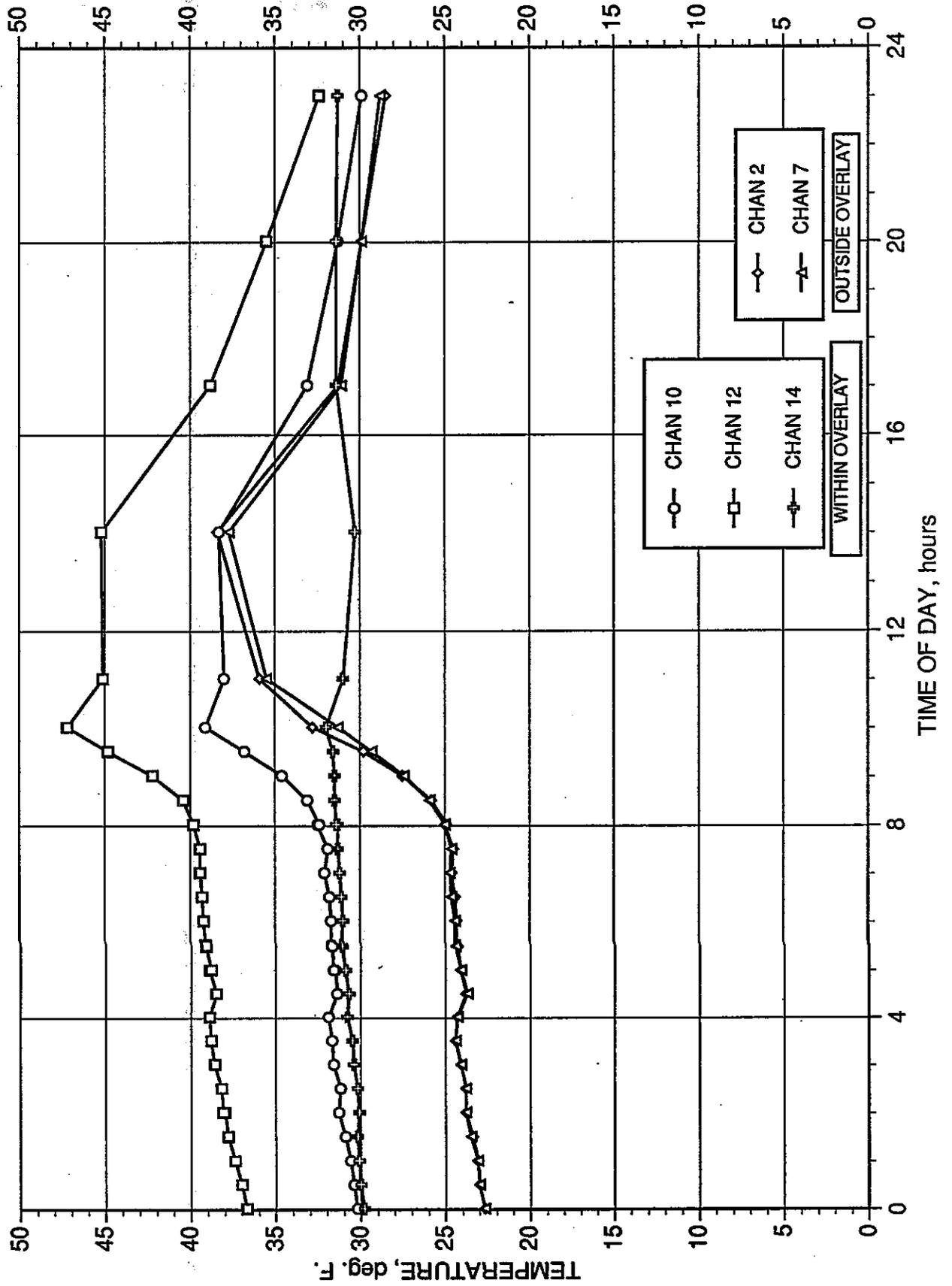


# CASTLE PEAK HEATING OVERLAY JAN. 2, 1991

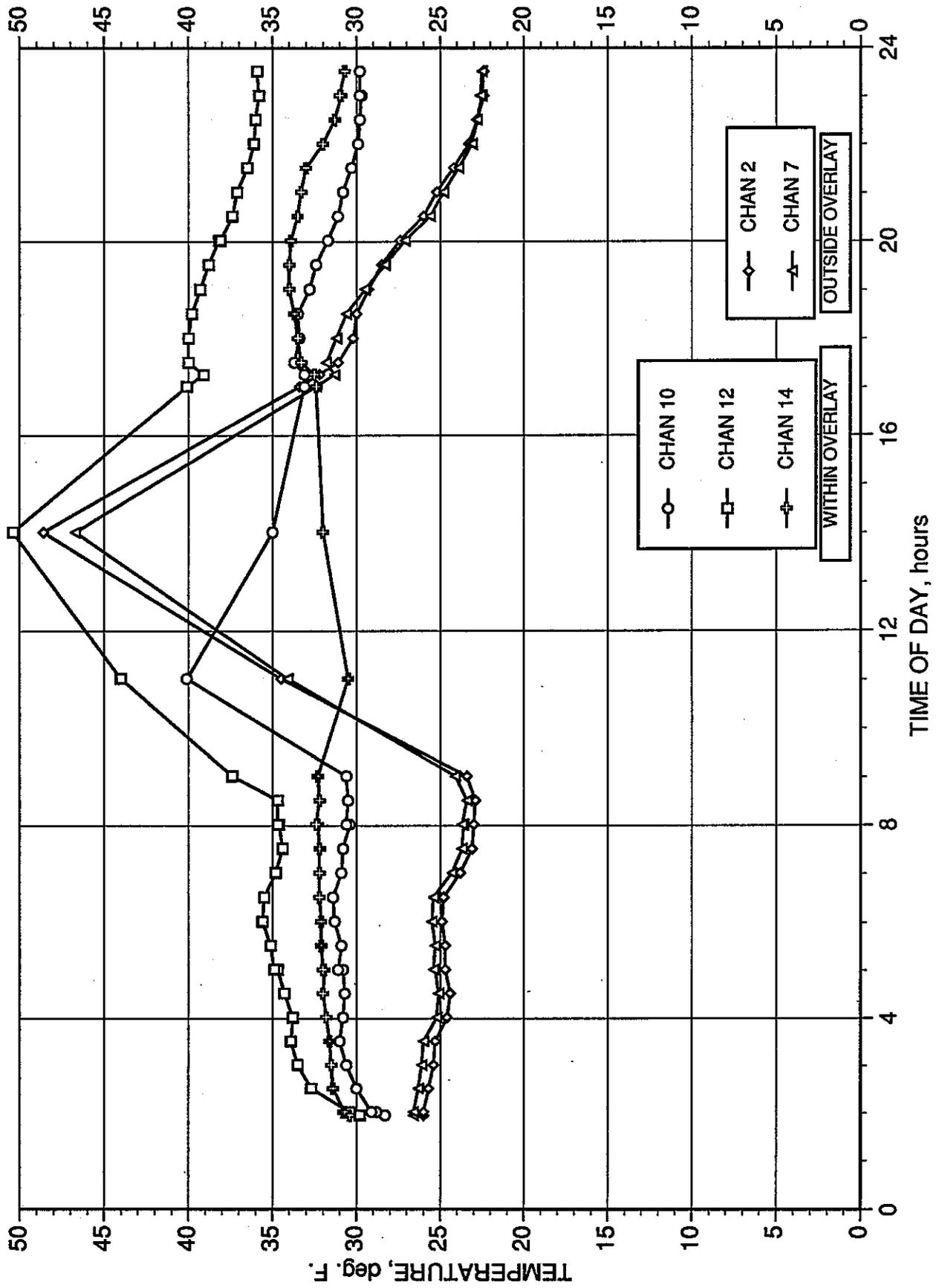
## COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



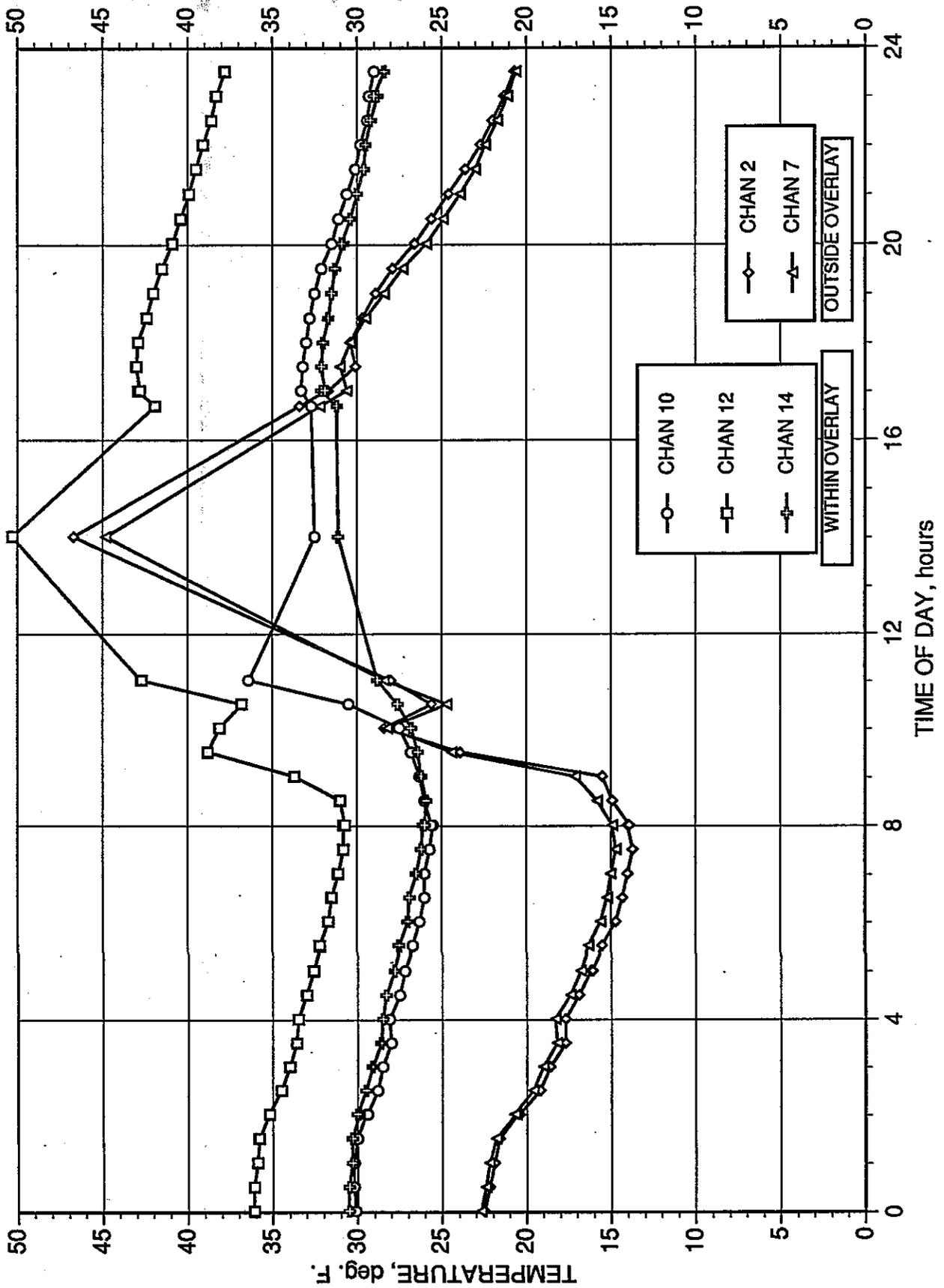
CASTLE PEAK HEATING OVERLAY JAN. 3, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



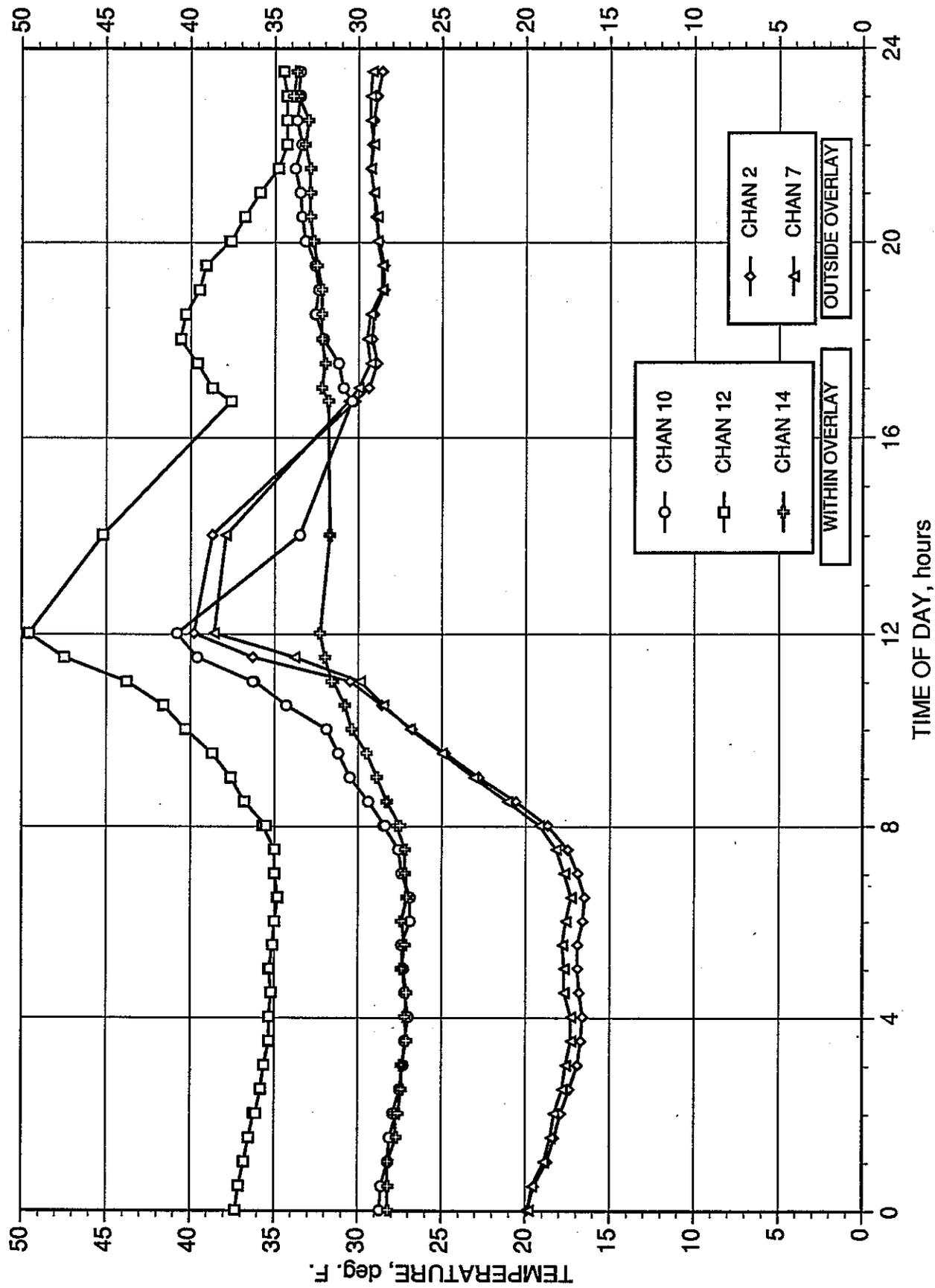
CASTLE PEAK HEATING OVERLAY JAN. 4, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



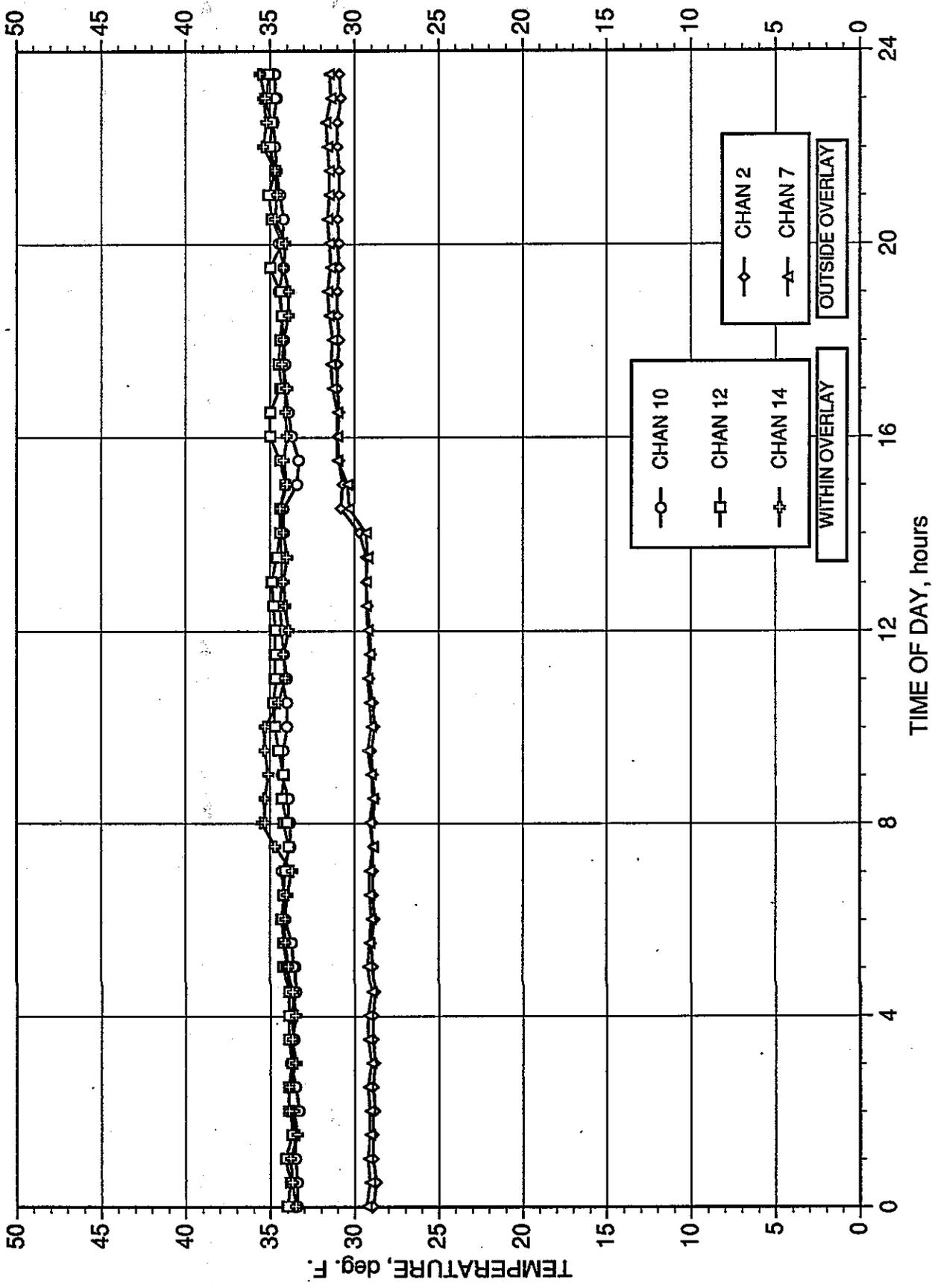
CASTLE PEAK HEATING OVERLAY JAN. 5, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



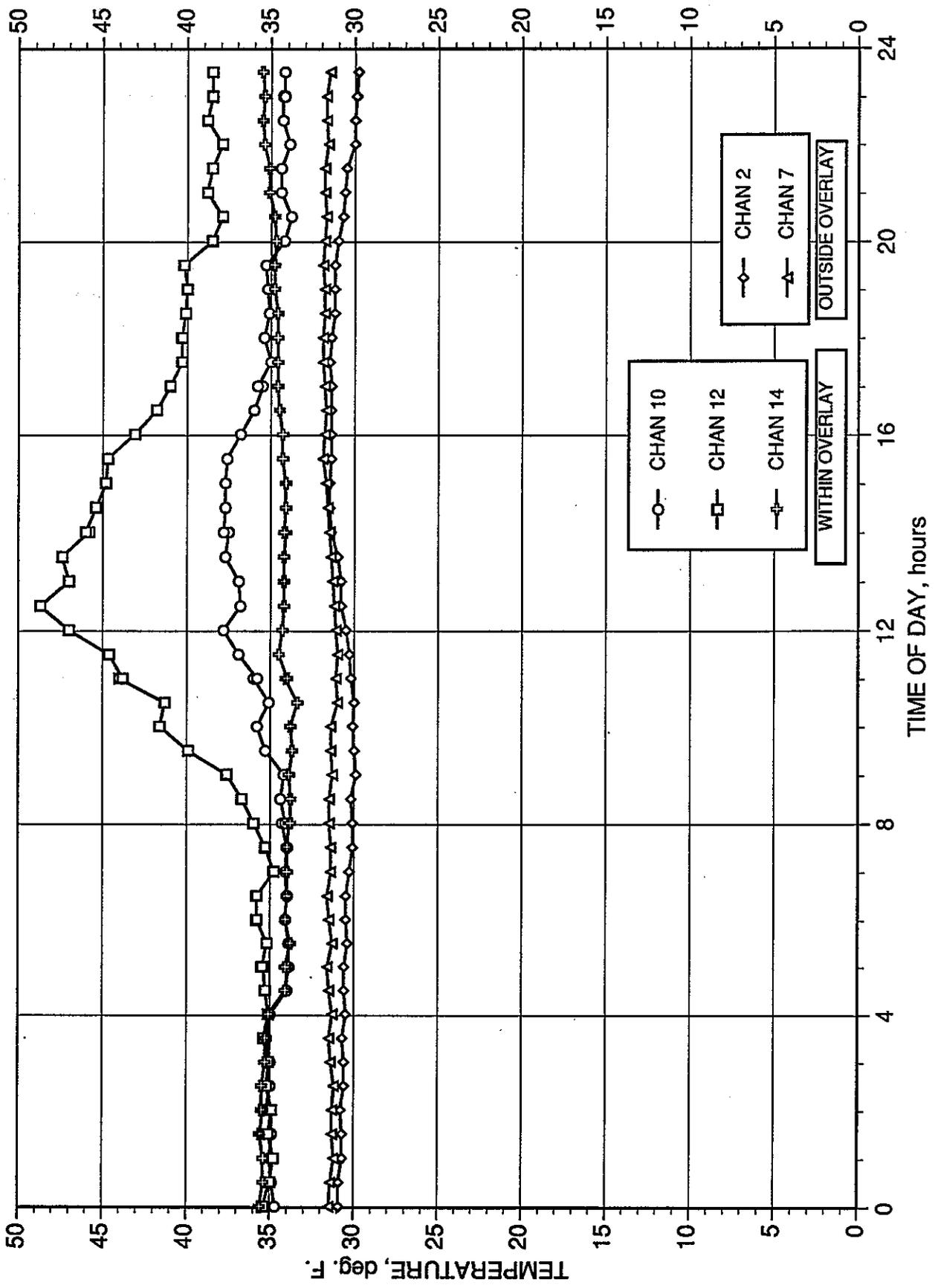
CASTLE PEAK HEATING OVERLAY JAN. 6, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



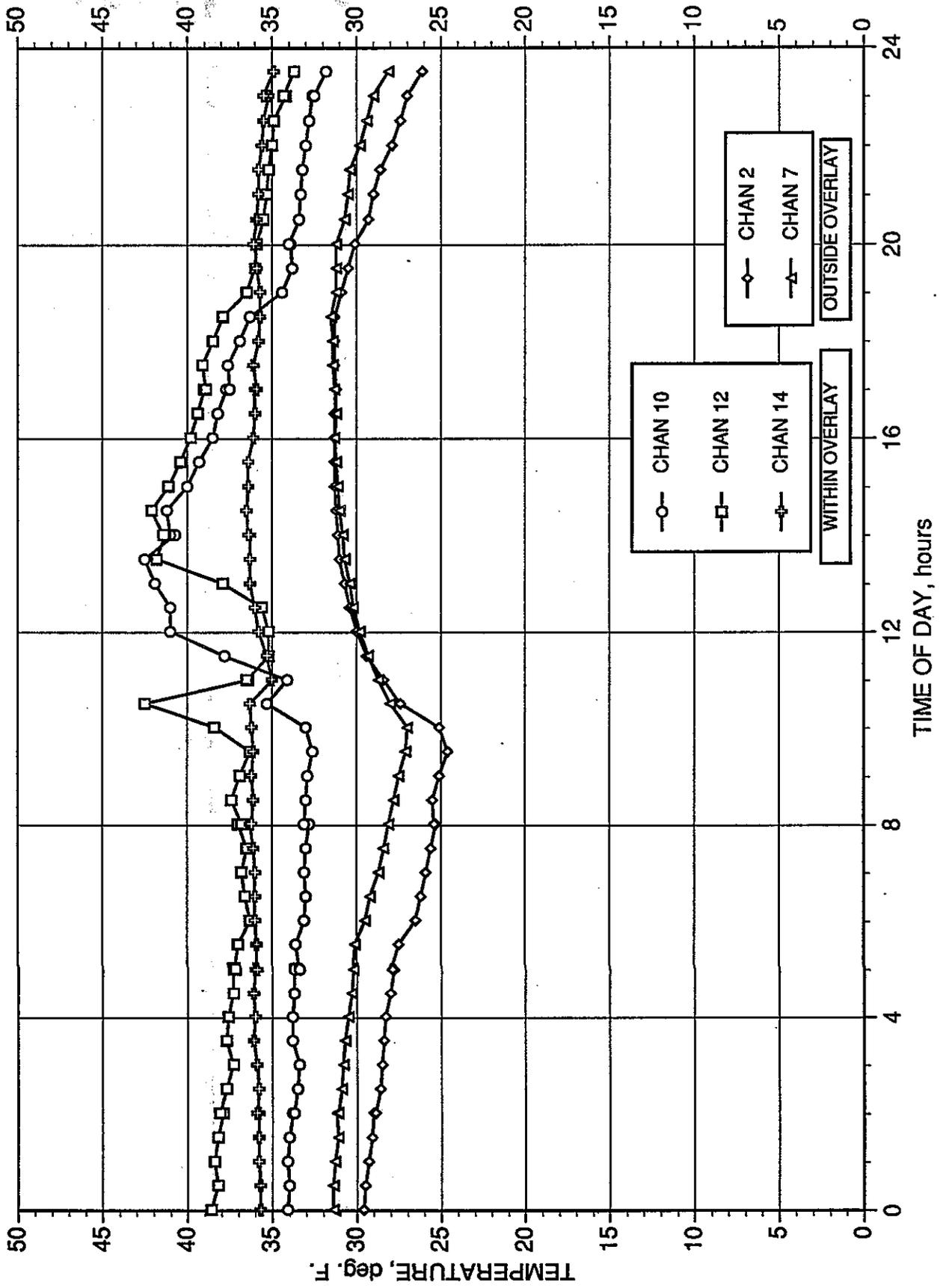
CASTLE PEAK HEATING OVERLAY JAN. 7, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



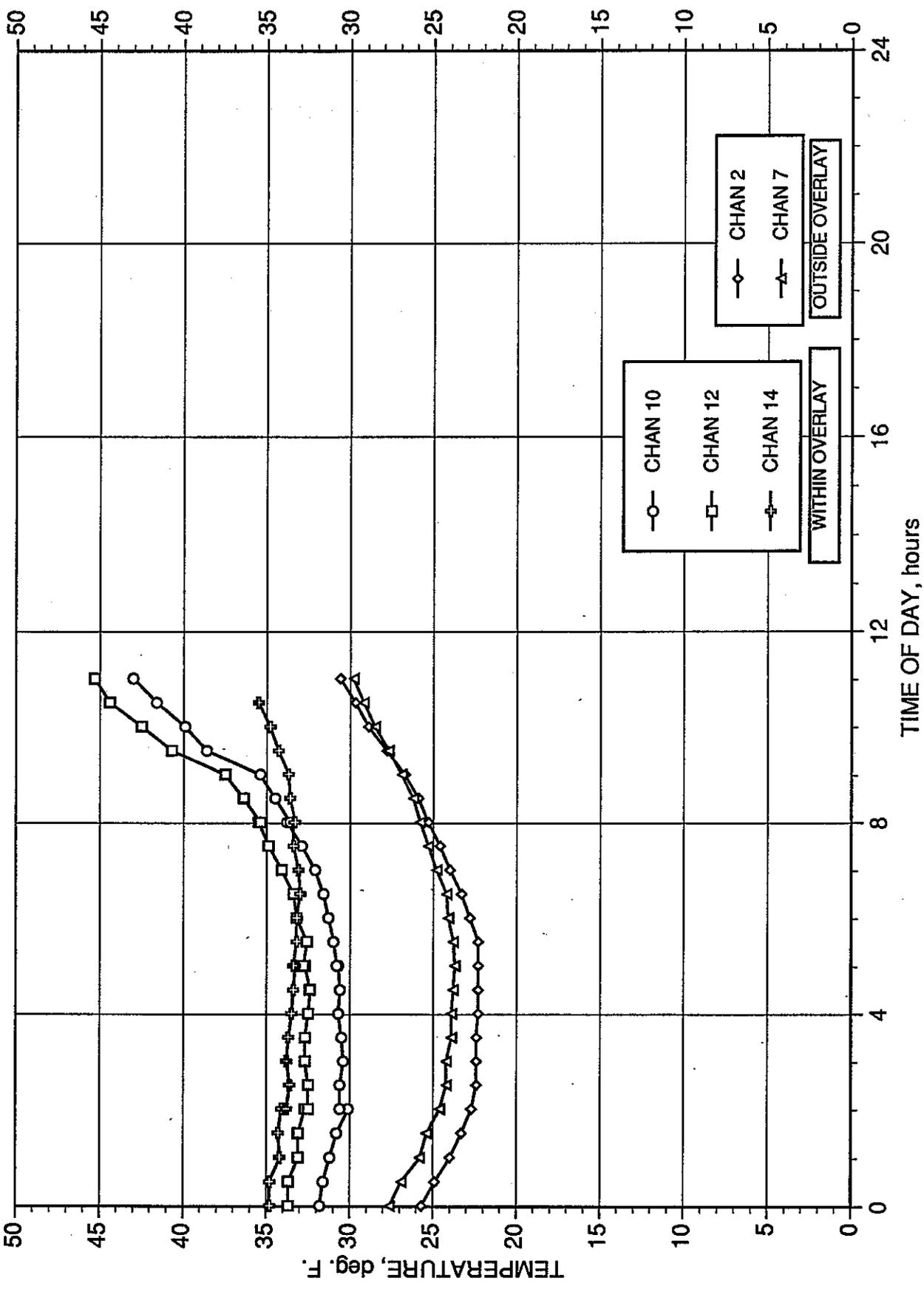
CASTLE PEAK HEATING OVERLAY JAN. 8, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



CASTLE PEAK HEATING OVERLAY JAN. 9, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



CASTLE PEAK HEATING OVERLAY JAN. 10, 1991  
 COMPARISON OF CENTER ROW TEMPERATURES - (MIDWAY BETWEEN LANE AND RAIL)



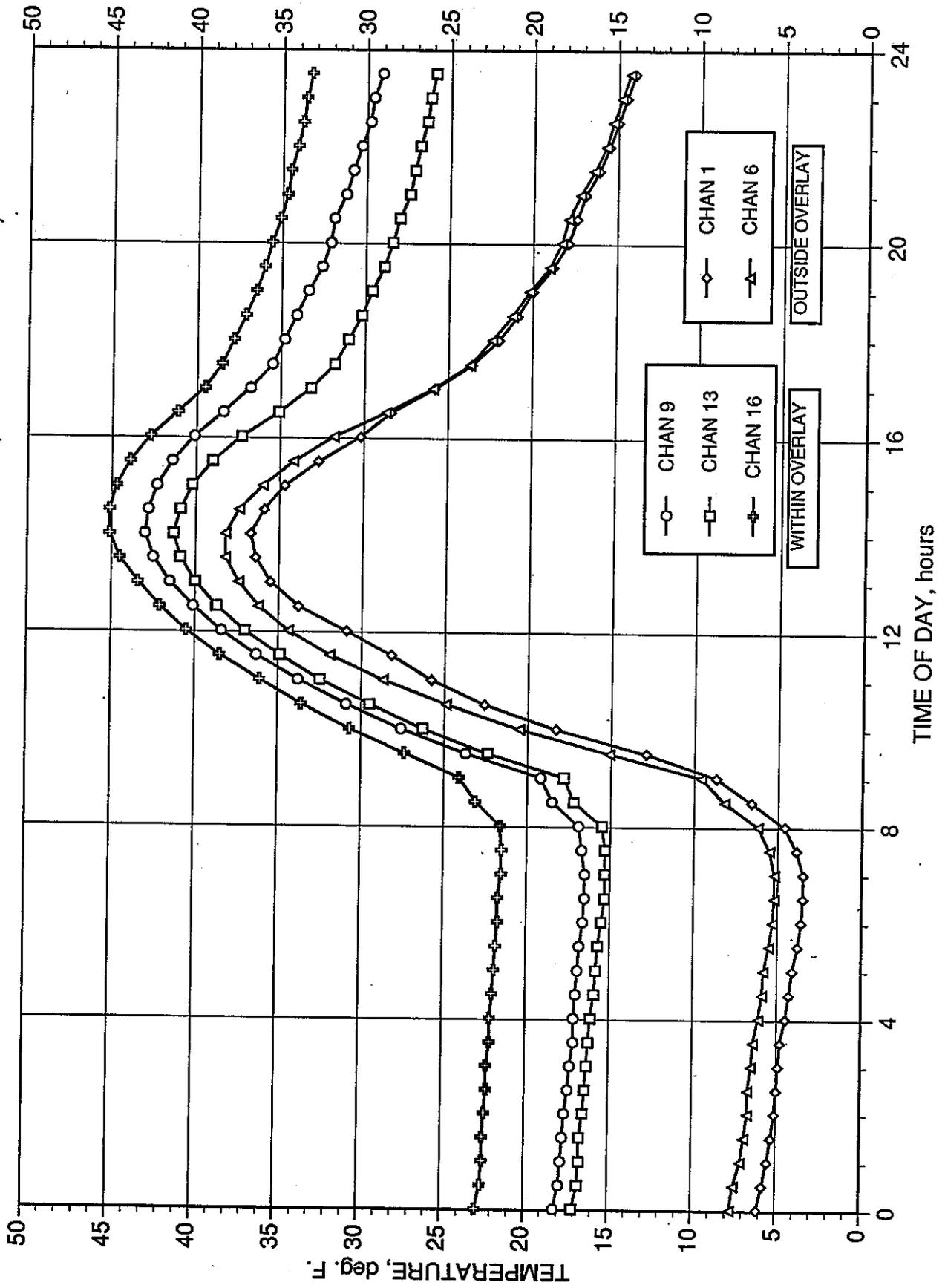
# **APPENDIX H**

**DECEMBER 30, 1990 - JANUARY 6, 1991**

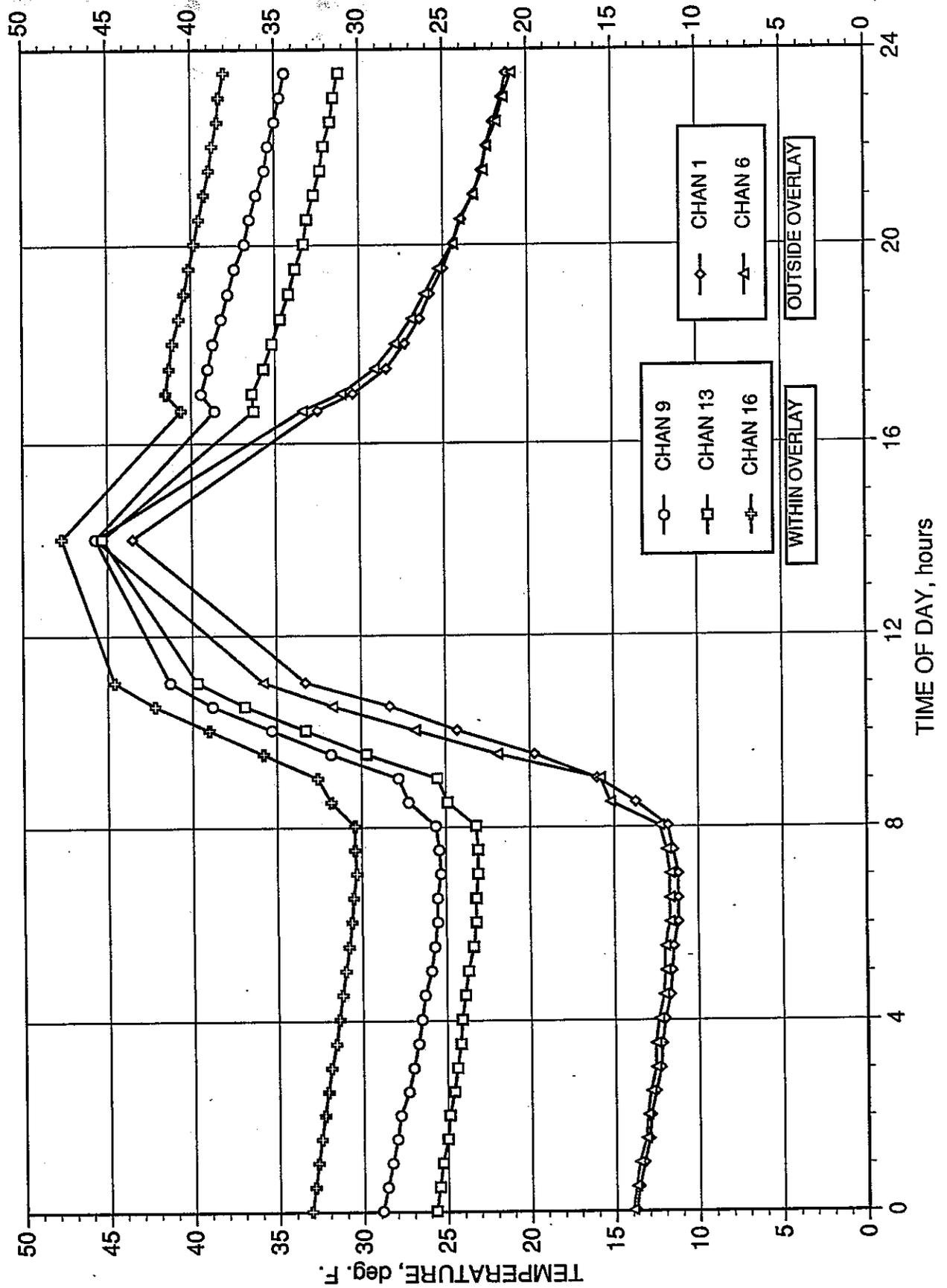
**COMPARISON OF INNER ROW TEMPERATURES -**

**(CLOSEST TO LANE)**

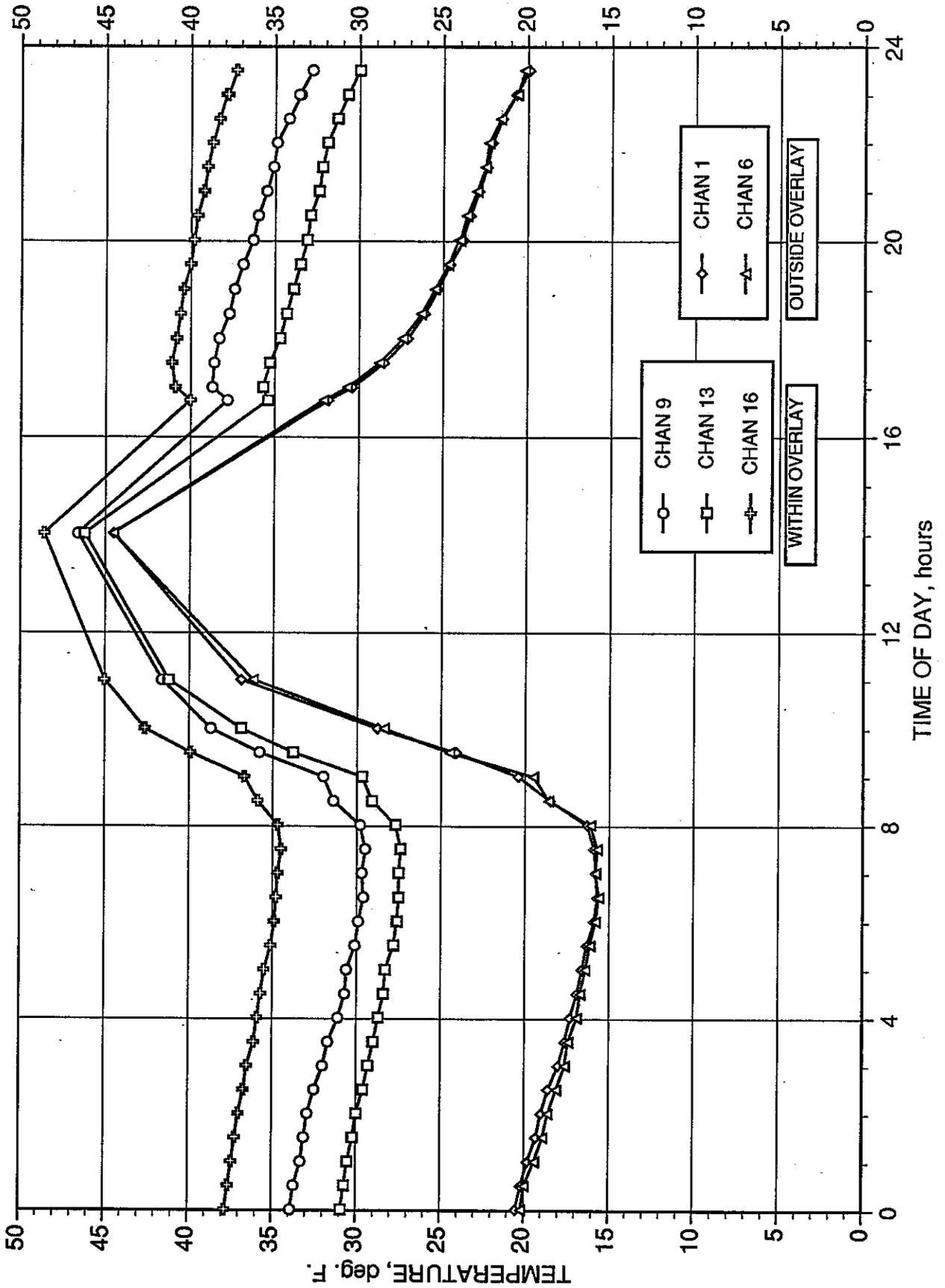
CASTLE PEAK HEATING OVERLAY DEC. 30, 1990  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



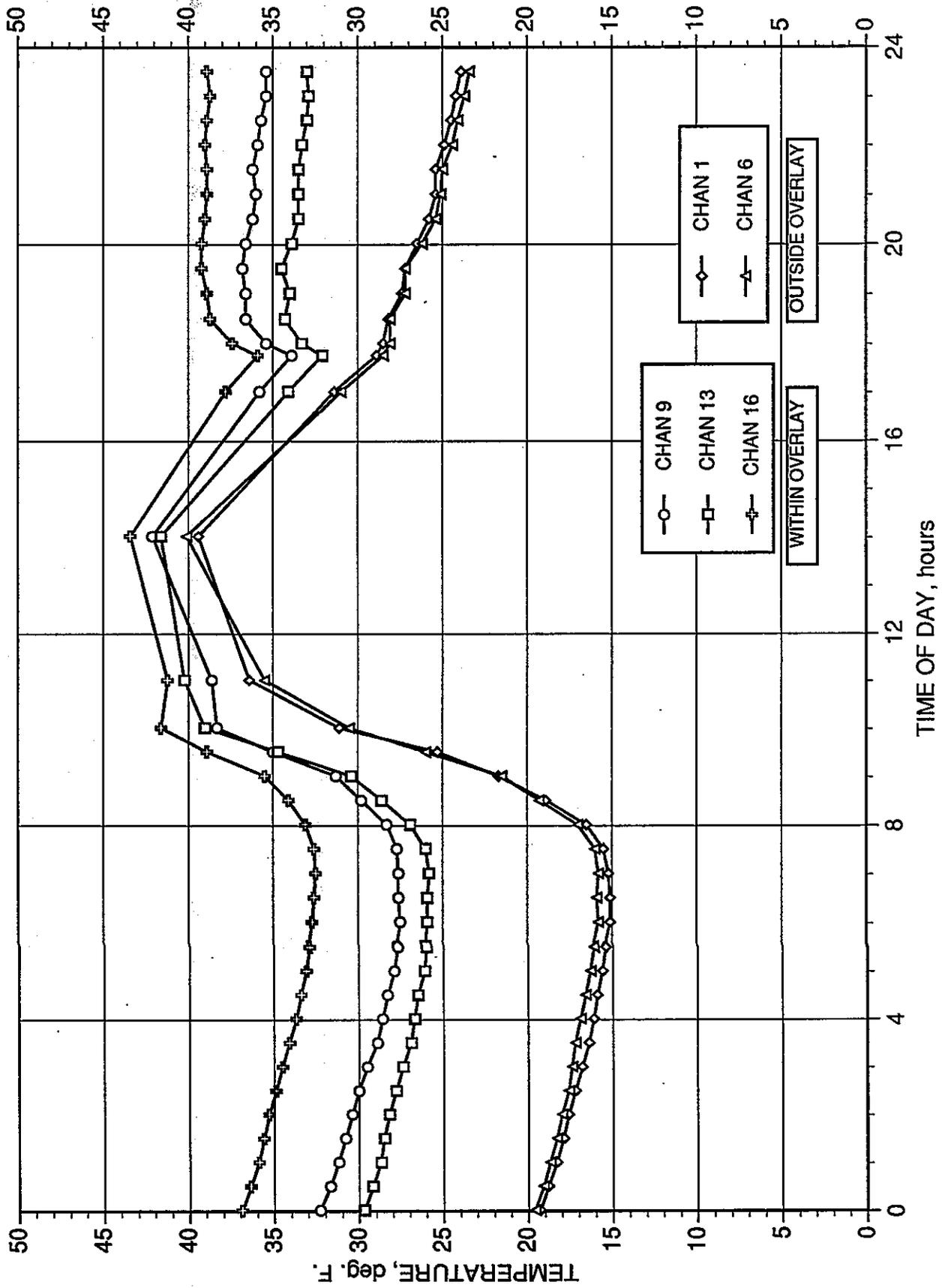
CASTLE PEAK HEATING OVERLAY DEC. 31, 1990  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



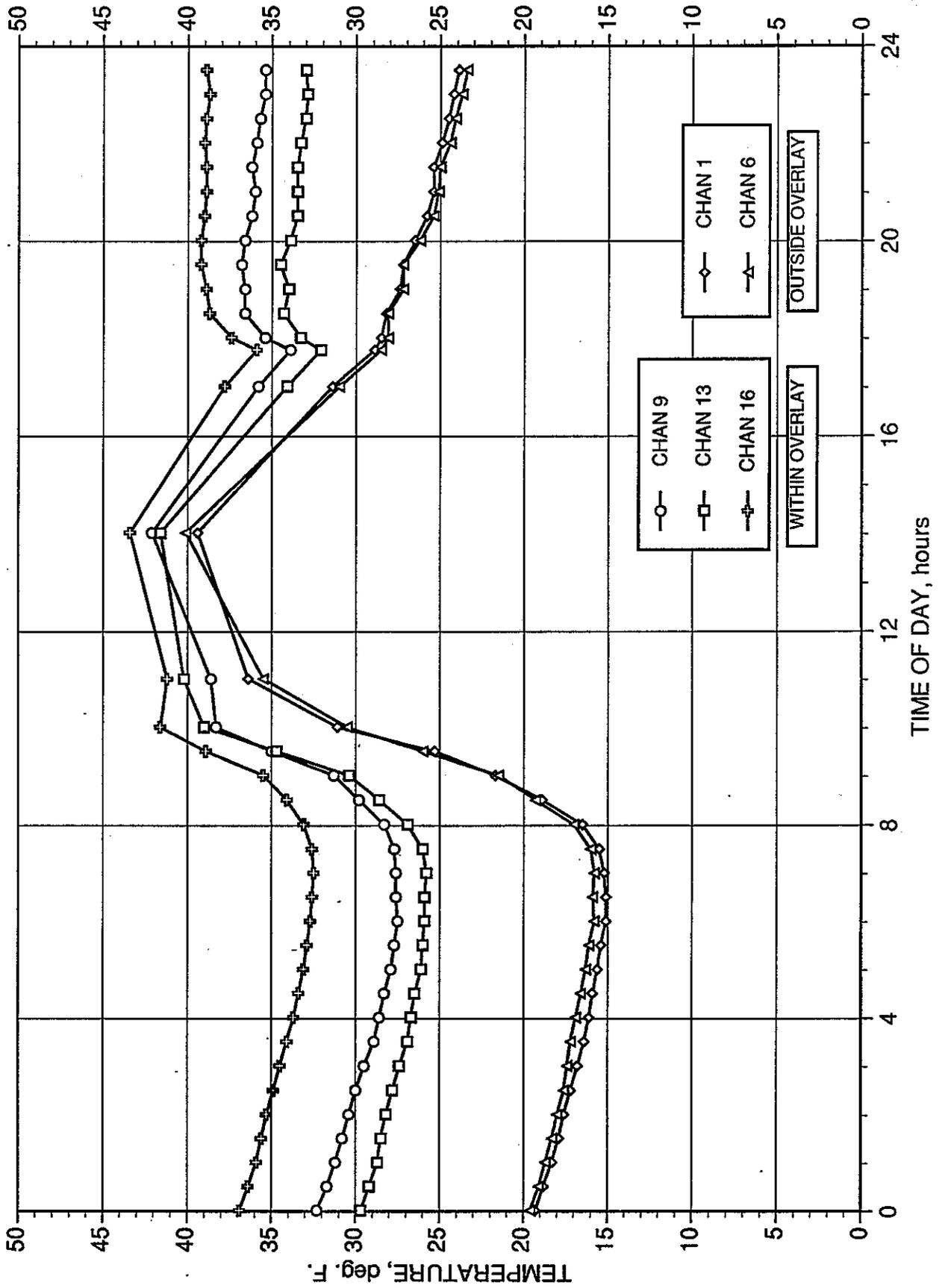
CASTLE PEAK HEATING OVERLAY JAN. 1, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



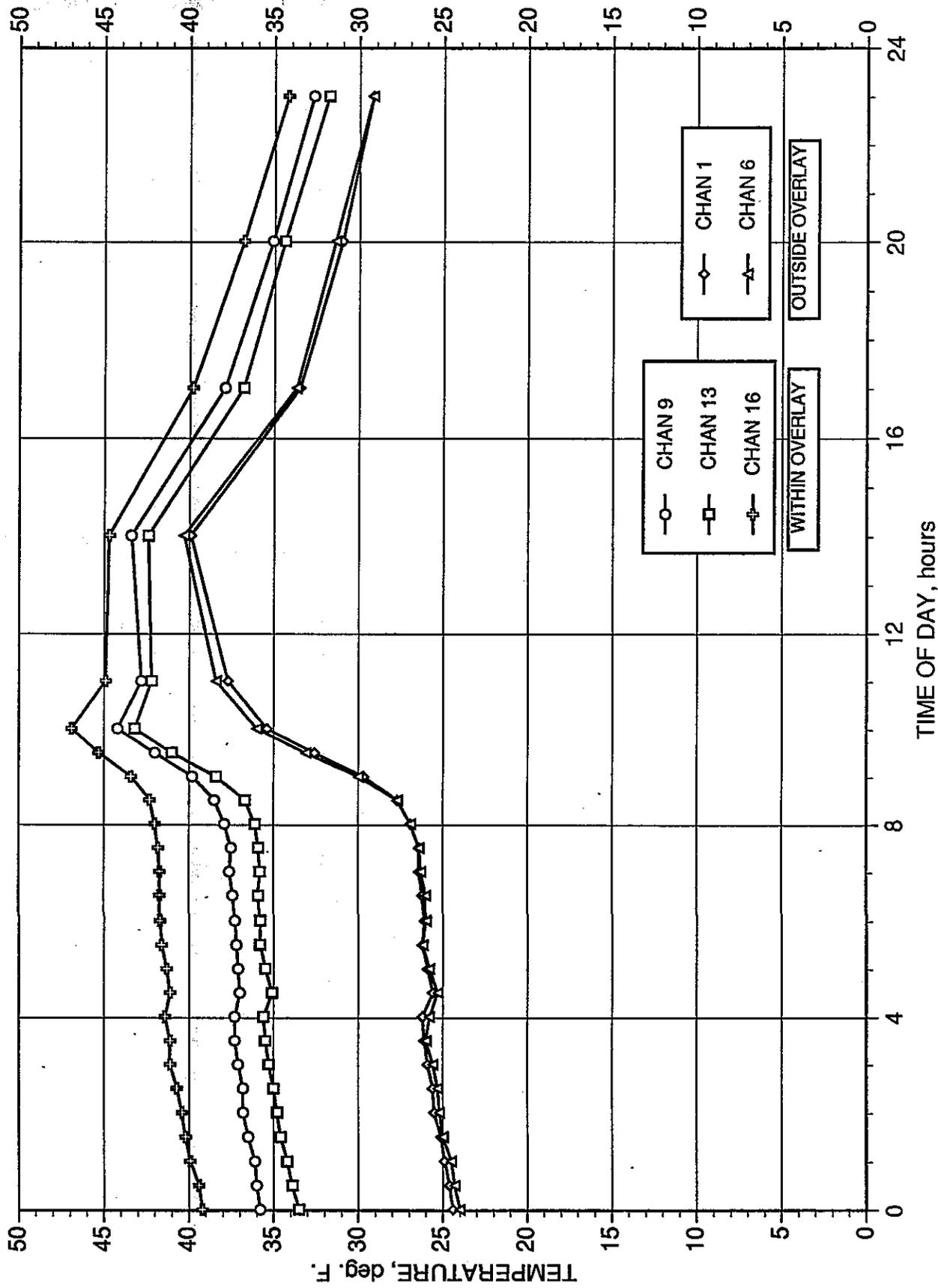
CASTLE PEAK HEATING OVERLAY JAN. 2, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



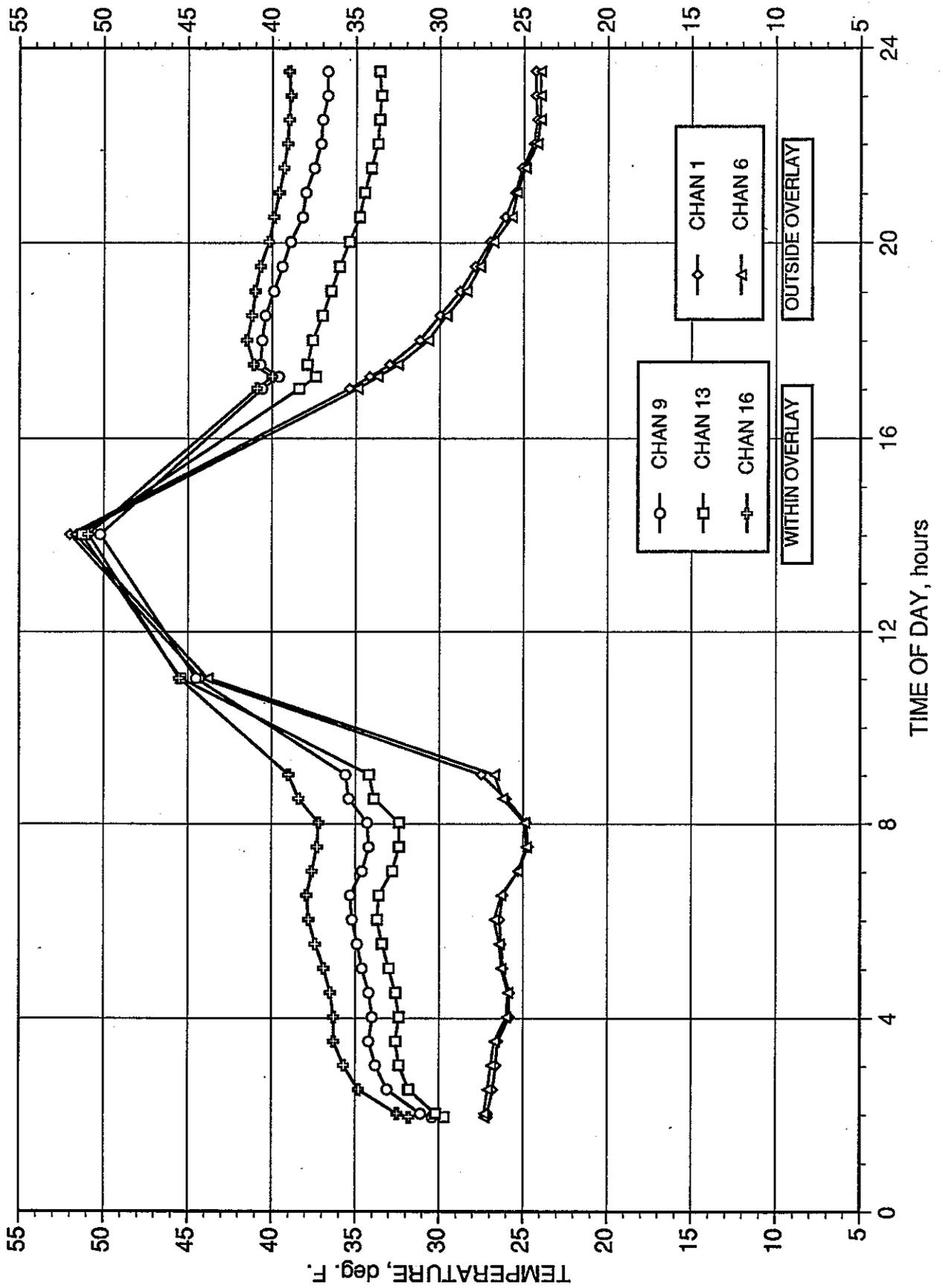
CASTLE PEAK HEATING OVERLAY JAN. 2, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



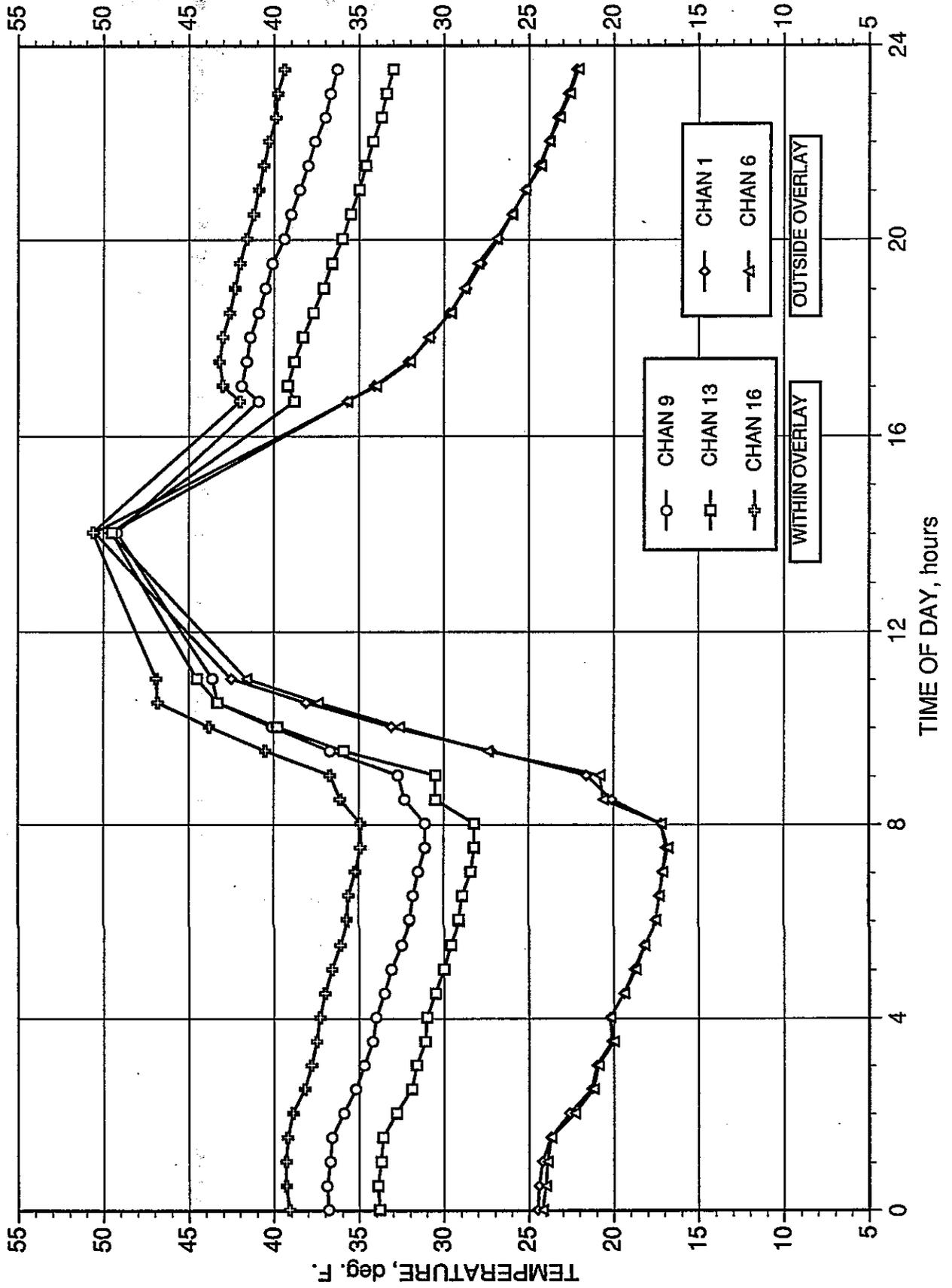
CASTLE PEAK HEATING OVERLAY JAN. 3, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



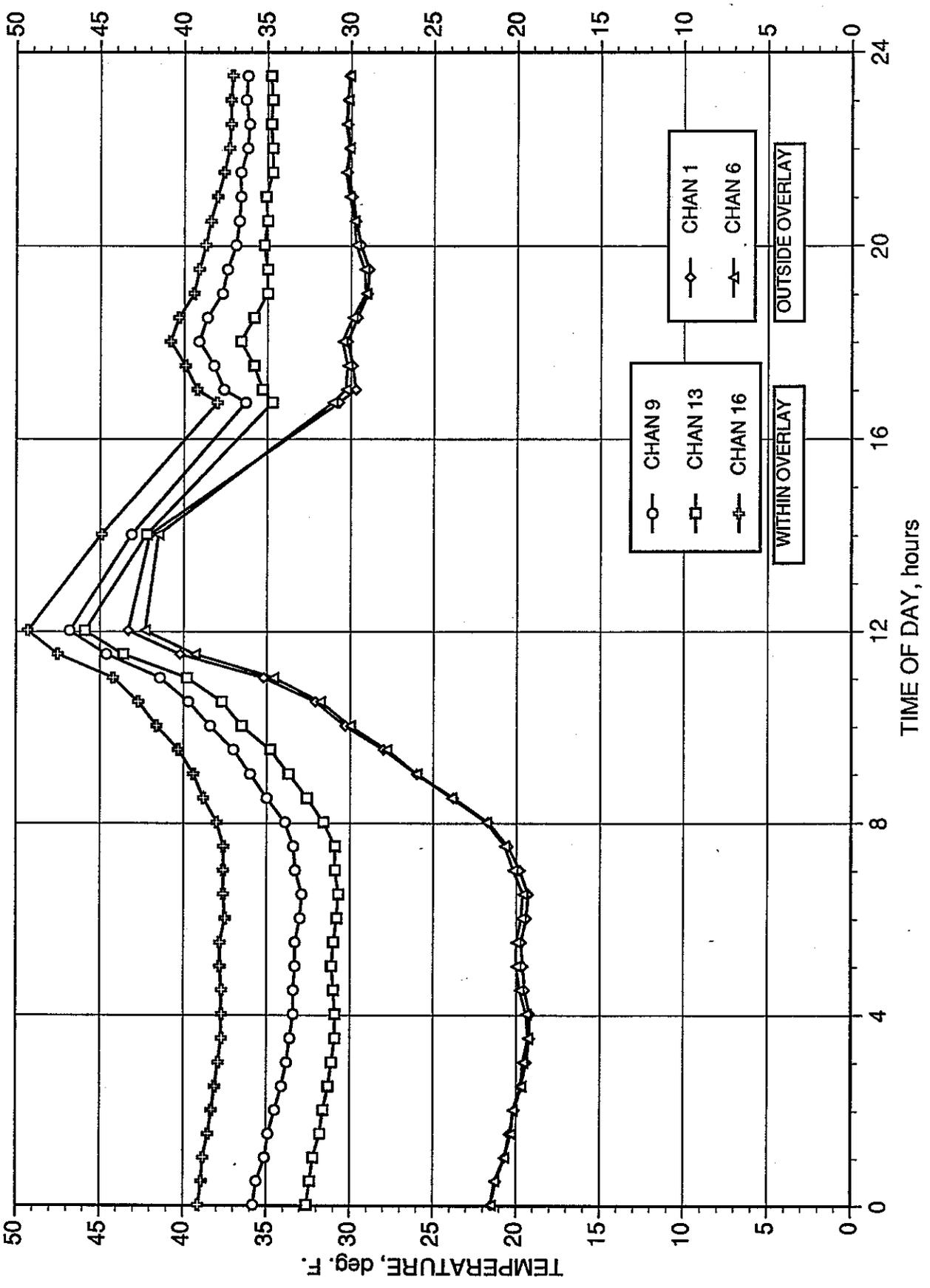
CASTLE PEAK HEATING OVERLAY JAN. 4, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



CASTLE PEAK HEATING OVERLAY JAN. 5, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



CASTLE PEAK HEATING OVERLAY JAN 6, 1991  
 COMPARISON OF INNER ROW TEMPERATURES - (CLOSEST TO LANE)



# **APPENDIX I**

**TEMPERATURE, VOLTAGE AND CURRENT DATA FOR DECEMBER 14 - 21**







CASTLE PEAK HEATING OVERLAY

DECEMBER 14-21, 1990

DATE	TIME	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25	26	27	28	30	41	42	43	44	45	46	47	48	49			
HRS	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	° F	
	Amp	Volt	Volt	Volt	Volt	Volt	Volt	Volt																																		
17 DEC 90	1:10	20.6	13.8	14.9	18.9	25.8	69.5	14.1	16.2	0	23.5	23.1	31.3	25.3	20.7	26.9	32.4	24.0	30.8	48.2	71.3	23.6	19.9	27.6	30.3	44.8	45.4	45.3	44.9	17.8	28.5	46.4	46.5	46.4	27.6	125.6	47.1	3	126.0			
17 DEC 90	1:60	20.3	13.7	14.7	18.6	25.7	70.4	14.0	16.0	0	23.3	22.9	31.0	25.2	20.6	26.6	32.3	23.9	29.9	49.3	72.1	23.6	19.9	27.6	30.3	44.8	45.3	45.3	44.8	17.7	29.8	46.4	46.4	46.4	27.6	125.6	47.0	3	125.6			
17 DEC 90	2:10	20.5	13.3	14.4	18.4	25.5	69.4	13.4	15.8	0	23.2	22.6	30.7	25.1	20.4	26.1	32.1	23.8	29.8	47.9	71.4	23.6	19.8	27.6	30.3	44.8	45.3	45.3	44.8	17.7	28.3	46.4	46.4	46.4	27.6	125.6	47.0	3	125.6			
17 DEC 90	2:60	20.2	12.9	14.0	18.1	25.4	68.1	13.0	15.4	0	23.0	22.4	30.4	25.0	20.2	25.8	31.9	23.7	29.8	46.6	70.0	23.6	19.8	27.6	30.2	44.7	45.3	45.3	44.8	17.7	28.2	46.4	46.4	46.4	27.5	125.5	47.0	3	125.5			
17 DEC 90	3:12	20.1	12.9	13.8	17.8	25.2	68.9	13.2	15.3	0	22.8	22.2	30.1	24.8	20.1	25.5	31.7	23.6	29.3	48.1	70.7	23.5	19.8	27.5	30.2	44.7	45.3	45.3	44.8	17.5	28.8	46.3	46.4	46.3	27.5	125.5	47.0	3	125.4			
17 DEC 90	3:60	20.3	19.0	13.8	17.5	25.1	69.4	13.4	15.3	0	22.7	21.9	29.8	24.7	20.1	25.2	31.5	23.5	27.9	48.7	71.2	23.7	19.9	27.6	30.3	44.6	45.5	45.5	45.0	17.6	28.3	46.5	46.6	46.5	27.6	126.0	47.2	3	126.1			
17 DEC 90	4:10	20.7	12.9	13.5	17.3	25.0	68.3	13.2	15.2	0	22.6	21.6	29.4	24.7	20.1	25.0	31.3	23.5	27.9	48.1	70.7	23.5	19.7	27.4	30.1	44.6	45.2	45.2	44.7	17.4	28.9	46.2	46.3	46.2	27.4	125.1	46.9	3	125.3			
17 DEC 90	5:10	20.8	13.4	13.7	17.1	24.8	69.8	13.9	15.4	0	22.5	21.5	28.7	24.8	20.2	24.8	30.9	23.5	26.9	49.0	71.0	23.6	19.7	27.5	30.2	44.8	45.3	45.3	44.8	17.6	28.9	46.3	46.4	46.3	27.5	125.5	47.0	3	125.9			
17 DEC 90	5:60	22.6	13.8	13.8	17.0	24.8	69.5	14.5	15.5	0	22.5	21.6	28.3	24.7	20.5	24.6	30.6	23.7	26.8	48.9	71.1	23.5	19.6	27.3	30.0	44.5	45.1	45.1	44.6	17.7	29.0	46.1	46.2	46.1	27.3	124.9	46.8	3	124.9			
17 DEC 90	6:10	23.5	14.7	14.3	17.1	25.1	70.7	15.5	16.0	0	23.0	22.2	28.0	25.5	21.5	24.9	30.5	24.6	27.1	50.3	72.3	23.8	19.8	27.6	30.3	44.9	45.5	45.5	45.4	17.9	29.4	46.5	46.6	46.5	27.5	126.2	47.2	3	126.2			
17 DEC 90	6:12	23.8	14.7	14.5	17.1	25.1	70.8	15.6	16.1	0	23.0	22.3	28.1	25.5	21.5	25.0	30.5	24.6	27.2	50.3	72.4	23.9	19.8	27.6	30.3	44.9	45.5	45.5	45.0	17.9	29.3	46.5	46.6	46.5	27.5	126.0	47.2	3	126.1			
17 DEC 90	6:60	25.1	15.5	14.8	17.2	25.4	71.8	16.5	16.5	0	23.5	22.7	27.8	26.0	22.1	25.2	30.3	25.3	27.5	51.0	73.4	24.1	20.0	27.7	30.4	45.1	45.7	45.7	45.2	18.0	28.4	46.7	46.8	46.7	27.6	126.5	47.4	3	126.5			
17 DEC 90	7:10	24.7	15.0	14.7	17.2	25.6	71.3	15.4	16.4	0	23.7	22.5	27.8	26.1	21.8	25.3	30.3	25.1	27.5	50.1	72.8	23.9	19.9	27.6	30.3	44.9	45.5	45.5	45.0	17.9	29.6	46.5	46.6	46.5	27.5	126.0	47.2	3	125.9			
17 DEC 90	7:60	25.1	15.2	14.7	17.2	25.7	72.3	15.8	16.3	0	23.8	22.5	27.6	26.1	21.9	25.2	30.1	25.1	27.6	51.5	74.0	23.9	19.9	27.5	30.3	44.9	45.5	45.5	45.4	17.9	29.0	46.5	46.6	46.5	27.5	125.7	47.2	3	126.0			
17 DEC 90	8:10	27.1	16.2	15.3	17.2	25.9	72.9	17.1	16.9	0	24.1	23.0	27.5	26.5	22.7	25.3	29.9	25.8	27.7	52.5	74.4	24.0	19.9	27.5	30.3	44.9	45.5	45.4	44.9	18.1	29.8	46.5	46.6	46.5	27.5	126.1	47.2	3	126.4			
17 DEC 90	8:60	29.3	17.6	15.6	17.3	26.3	67.3	19.6	17.2	0	24.8	23.4	27.4	26.9	24.9	25.5	29.6	27.5	26.0	54.0	71.3	24.4	20.2	27.8	30.6	45.4	46.0	46.0	45.5	18.0	29.8	47.0	47.1	47.0	27.7	127.5	47.7	3	127.6			
17 DEC 90	9:12	28.4	18.7	15.9	17.5	26.8	62.9	20.1	17.6	0	25.5	23.6	27.4	27.3	25.1	25.6	29.3	27.7	26.2	53.4	66.8	24.6	20.3	27.7	30.5	45.4	46.0	46.0	45.5	18.5	29.5	47.0	47.0	47.0	27.6	127.3	47.7	3	127.3			
17 DEC 90	9:60	29.3	21.7	17.8	18.0	27.8	57.6	20.0	19.3	0	26.5	24.3	27.4	29.2	28.0	26.1	29.2	30.5	26.4	48.9	59.1	24.5	20.2	27.4	30.2	45.0	45.5	45.5	45.0	18.1	29.5	46.5	46.6	46.5	27.2	126.0	47.2	3	125.9			
17 DEC 90	10:10	30.9	24.3	18.6	18.5	28.9	56.7	29.9	20.7	0	27.6	25.4	27.4	30.1	30.4	26.4	29.1	34.5	28.7	50.2	56.7	24.0	20.3	27.9	30.1	45.0	45.5	45.5	45.1	18.4	29.5	46.7	46.7	46.7	27.2	125.8	47.3	3	126.3			
17 DEC 90	10:60	32.0	26.3	19.8	18.8	29.6	54.3	32.9	20.8	0	28.6	25.4	27.5	30.2	34.2	26.7	28.9	36.9	29.0	47.4	54.3	25.2	20.5	26.9	29.7	44.7	45.3	45.3	44.8	18.3	28.2	46.3	46.4	46.3	26.6	125.8	47.0	3	125.7			
17 DEC 90	11:10	32.7	28.1	20.6	18.8	30.0	62.8	35.4	21.8	0	29.3	26.5	27.4	31.5	37.2	27.1	28.9	39.3	29.4	51.2	63.4	25.7	20.6	27.4	30.2	45.2	45.8	45.8	45.3	18.7	29.5	46.9	47.0	47.0	27.2	127.6	47.6	3	127.3			
17 DEC 90	11:60	33.6	29.0	22.3	19.3	31.0	57.4	37.6	25.9	0	30.5	29.1	27.6	35.5	39.2	27.4	28.9	41.3	29.8	48.8	57.2	25.6	20.2	27.8	30.5	45.0	45.6	45.6	45.1	18.5	29.0	46.7	46.7	46.8	27.4	128.5	47.3	3	126.7			
17 DEC 90	12:10	35.1	30.6	24.0	19.9	32.1	54.7	40.1	26.6	0	31.6	30.7	27.9	35.1	41.1	28.3	29.0	42.9	30.2	47.9	54.6	25.5	20.0	28.5	31.1	45.3	45.9	45.9	45.3	18.7	30.0	46.9	47.0	46.9	28.1	127.2	47.6	3	127.5			
17 DEC 90	12:10	35.1	30.6	24.0	19.9	32.1	54.7	40.1	26.6	0	31.6	30.7	27.9	35.1	41.1	28.4	29.0	42.9	30.2	47.9	54.6	25.5	20.0	28.5	31.1	45.3	45.9	45.9	45.3	18.7	30.5	47.0	47.1	47.0	28.2	127.5	47.7	3	127.4			
17 DEC 90	12:60	35.8	32.3	26.3	20.7	33.5	54.3	39.0	29.3	0	32.6	30.8	28.1	38.5	40.4	30.0	29.2	42.9	30.8	48.0	53.9	26.3	21.1	27.4	30.3	45.4	45.9	45.9	45.4	18.9	27.8	47.0	47.0	47.0	27.0	127.8	47.7	3	127.7			
17 DEC 90	15:10	38.5	32.7	29.7	23.4	36.9	71.1	37.0	31.3	0	34.0	30.5	28.1	36.3	36.4	30.2	30.2	36.3	29.9	52.9	72.6	3	3	3	3	3	3	3	3	0	1.8	3	3	3	3	3	3	3	3			
17 DEC 90	18:10	36.1	28.6	29.2	25.0	31.9	71.3	37.4	27.8	0	29.3	30.2	28.1	30.3	29.1	30.2	31.0	30.7	29.5	49.1	74.0	3	3	3	3	3	3	3	3	0	1.8	3	3	3	3	3	3	3	3			
17 DEC 90	21:10	35.3	24.1	27.1	25.4	29.4	77.2	24.9	25.5	0	27.5	28.2	29.0	26.0	27.0	29.5	31.2	28.4	26.2	50.2	79.9	3	3	3	3	3	3	3	3	0	1.8	3	3	3	3	3	3	3	3			
17 DEC 90	22:37	33.5	22.6	25.9	25.3	28.2	8																																			









# **APPENDIX J**

**TEMPERATURE, VOLTAGE AND CURRENT DATA FOR**

**DECEMBER 28 - JANUARY 12**

































