Relays in the Hot Box

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***Abstract*—Protective relays, by their very nature, are called upon to operate under both ideal and unfavorable physical conditions. While many relays are installed in environmentally controlled buildings, others are installed in enclosures that may range from free-standing boxes to control cabinets mounted on primary equipment to door mounts in outdoor metal-clad switchgear cubicles.**

While recognized standards, such as IEEE C37.94, establish a range of operating conditions that relays are expected to function correctly in, the actual conditions may be beyond the standards in some respect. Temperature ranges in uncontrolled cabinets can go beyond those in standards. Even where the temperature is within the range specified in standards, the duration of a relatively high temperature may cause a relay to experience either a permanent or temporary failure.

This paper presents a series of temperature records collected at electric utility stations. The records are continuous for a summer season, and they include values in different cabinets and different locations within and around the cabinets. This paper makes a comparison between these different locations and an evaluation based on equipment in the cabinets. An analysis is performed to compare upper and lower cabinet temperatures and inside versus ambient temperatures.

Using the measured temperature profile, researchers put a number of different manufacturer's relays into a thermal chamber and took internal measures at critical locations, such as microprocessors and power supplies. These internal measures contribute to an estimate of relay life or degradation caused by high operating temperatures. Recommendations for relay installation are given based on these results.

I. Introduction

A number of factors make it attractive to install intelligent electronic devices (IEDs) such as relays in outdoor cabinets. These factors include simplification of wiring, reduced space required for installation, ease of installation, and placing the control device close to the primary gear it controls. IEEE C37.94 provides for ambient operating temperatures of –20 to +55°C (ANSI C37.90-1989). This standard recognizes that internal components of the relay will have temperature rise above this value—it lists a table with allowable coil rise for different coil ratings and measurement methods. The question that arises, and that this paper starts to address, is how these standards relate to the installation of modern microprocessor relays in harsh environments.

The combination of high ambient temperatures, limited ventilation in small control cabinets, and solar radiation has, anecdotally at least, caused relay failures. This paper does not cover enough locations to build a statistical sample, but it does provide a basis for looking at the relationship between cabinet and outside temperatures and how the temperature around the relay affects the temperature of critical components within the relay.

The Arrhenius equation gives the relationship between temperature and the rate of chemical reaction, or component aging, as a function of temperature [1]. The equation is:

$$K = Ae^{-\left(\frac{E_A}{RT}\right)} \tag{1}$$

Where

K = rate constant
A = frequency factor
E_A = activation energy
R = gas constant
T = temperature

Using temperatures measured and from tested values we can make calculations using this formula to predict life reduction as a result of elevated temperatures.

While the temperatures recorded, especially at Imperial Irrigation District, are fairly hot, the record high temperatures in many states exceed even the hottest measured in this research (see Appendix). The high temperature in every state, including Alaska, is 100°F or higher. Because heavy electrical loads are very likely to occur on high temperature days, it can perhaps be considered especially important that relays function properly on these days.

II. Data Collection

Two utilities conducted research at two locations where high temperatures were regularly experienced. Even though these utilities have regular temperatures that are above normal for the U.S., high summer temperatures are experienced at least on occasion in most areas. Alabama Electric Cooperative (AEC) and Imperial Irrigation District (IID) in Southern California are both in the southern part of the United States and regularly experience ambient temperatures well above 90ºF (32ºC). Both locations have the temperature probes installed in conjunction with outdoor circuit breakers.

The unit at AEC was installed at Gantt substation, in a circuit breaker where the cabinet is being hit by direct sunlight all day. The outside probe is hanging from the bottom of the cabinet, which puts it in the shade the majority of the day, and the inside probe is hanging about two inches from a protective relay that is in the cabinet.

At IID, the probes were also installed in an outdoor breaker at Euclid substation (see Fig. 1 below). The only shade at Euclid substation is from the busbars above the breakers and late afternoon shade from other substation equipment. The temperature probes at this location are installed at the very bottom of the cabinet and the top of the control compartment, where protective relays are typically mounted. While AEC can be considered typical of southern locations, IID is certainly at the end of any bell curve of temperature. At roughly 50 feet below sea level and in the Southern California desert, the El Centro, California area has recorded temperatures regularly among the hottest in the nation.

Fig. 1. Euclid Substation in Imperial Irrigation District

The only shade at Euclid substation is from the busbars above the breakers and late afternoon shade from other substation equipment. The temperature probes at this location are installed at the very bottom of the cabinet and the top of the control compartment, where protective relays are typically mounted. While AEC can be considered typical of southern locations, IID is certainly at the end of any bell curve of temperature. At roughly 50 feet below sea level and in the Southern California desert, the El Centro, California area has recorded temperatures regularly among the hottest in the nation.

The temperatures were recorded using a monitoring device that uses microprocessor relay construction. It records the temperature every 15 minutes. Because the monitor has an active power supply, it could be argued that its maximum of 15 W power consumption contributed to the heating inside the cabinet. Because this is exactly the same effect as having another relay in the cabinet, this does not compromise the data collected.

The monitor has a "universal" power supply, so it can be powered from either an ac outlet in the breaker cabinet or the dc used to power the breaker itself. The monitor is rated up to 85°C, so it had no problems with the high temperatures experienced.

The monitor collects data in either Fahrenheit or Celsius. Because we were collecting integer data, we used Fahrenheit to get slightly more resolution. We estimate that the accuracy is better than the resolution because of the short lead length. The temperature probes used were 100 ohm platinum.

III. Temperature Profiles

For two months, from each of the two locations, temperature was recorded from two temperature probes. By obtaining a 15-minute profile for a period this long, we can look at details of not only the peak temperature during a hot day, but also how long that temperature lasted and the typical cooling time. While this will vary with the thermal mass of the cabinet and its enclosed equipment, these data give a reasonable representation of outdoor circuit breaker control cabinets. Some heating can also be caused by current flow in the circuit breaker, but this has to be figured into the temperature rating of the relays as well.

It is interesting to look at an entire month of data (see Fig. 2), although it is difficult to draw information from the raw collection.

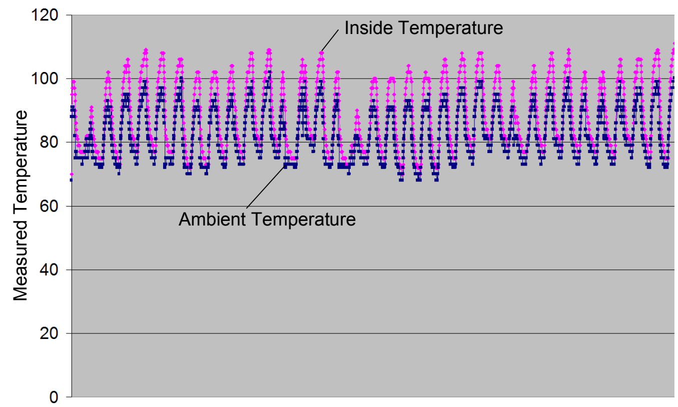

Fig. 2. Raw Data From One Month of Collection

It is difficult to see the relationship between ambient temperature and cabinet temperature at this scale. In addition, there is no direct, functional correlation between a specific ambient and cabinet temperature. One day an ambient of 99°F will produce a cabinet temperature of 104°F, while another day it will produce a cabinet temperature of 108°F, and another day, 109°F. This illustrates that a number of unobserved factors, such as sunlight and breaker loading, contribute to the cabinet temperature.

While a specific correlation between temperatures cannot be obtained, there is certainly a general relationship. The following figures (Figs. 3–8) compare temperatures at Gantt station in Alabama to Euclid station. The figures on the left (Figs. 3, 5, and 7) show the temperature profile, temperature rise, and difference between ambient and cabinet temperatures at Gantt station. The figures on the right (Figs. 4, 6, and 8) show the same temperature measurements at Euclid station.

A typical, moderately hot day at Gantt station in Alabama had a profile as shown in Fig. 3. This is compared to the temperature profile of the hottest day at Euclid station (Fig. 4).

In Fig. 5 and Fig. 6, the bottom line is the outside temperature, while the top line is the inside temperature, at Gantt station and Euclid station, respectively. We can see the cabinet temperature rising after 12:00, even though the ambient temperature is basically flat.

Fig. 7 and Fig. 8 show the difference between the ambient and cabinet temperatures on the respective days at Gantt station and Euclid station.

Comparing these graphs, we see that some quantities are different, but the curves are very similar.

While there was a minor difference between the rise of 17 degrees in the hot environment and 15 degrees in the slightly cooler environment, this could have resulted from variations in measurement points or random variations, as previously mentioned. Both of these locations validate the IEEE switchgear temperature rise of 10°C over ambient.

The duration of temperature peaks is interesting to note. In the "cooler" example, the temperature inside of the box exceeded 100°F (38°C) for 11 hours and exceeded 110°F (44°C) for 1.25 hours. This is all on a day when the ambient air temperature exceeded 95°F (35°C) for only 6.5 hours.

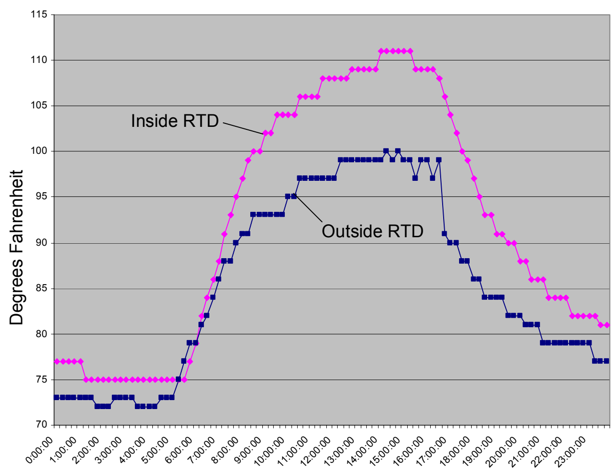

Fig. 3. Temperature Data From Typical Moderately Hot Day at Gantt Station

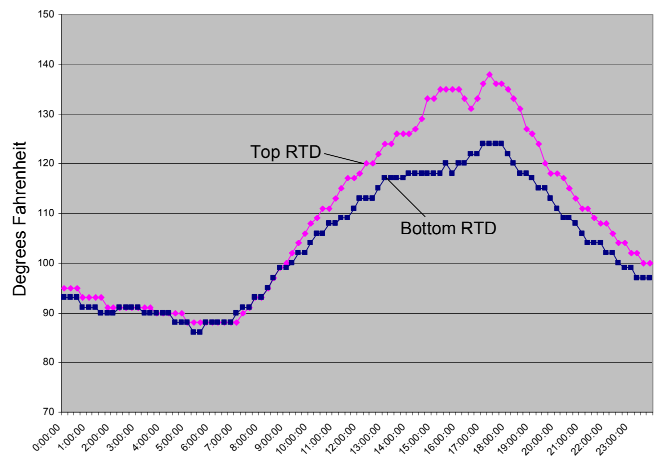

Fig. 4. Temperature Data From Hottest Day at Euclid Station

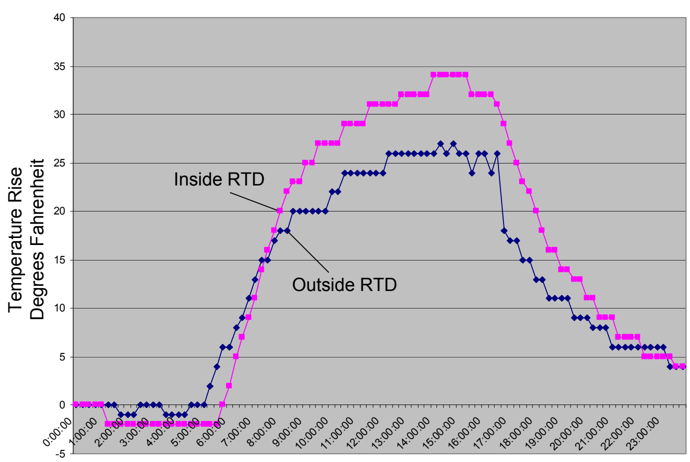

Fig. 5. Temperature Rise of Inside and Outside Temperature From Typical Moderately Hot Day at Gantt Station

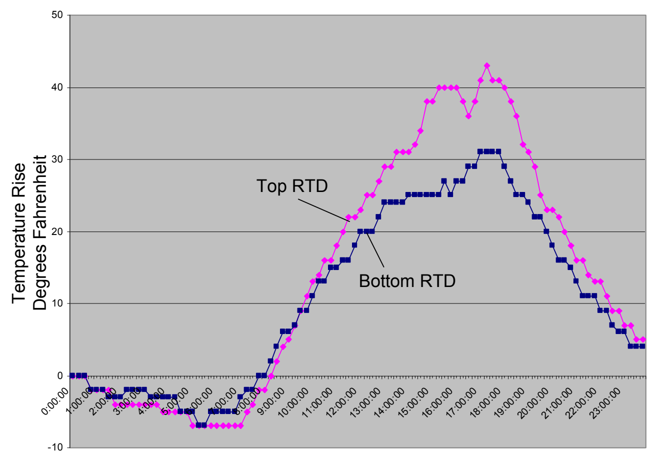

Fig. 6. Temperature Rise of Top and Bottom Temperature From Hottest Day at Euclid Station

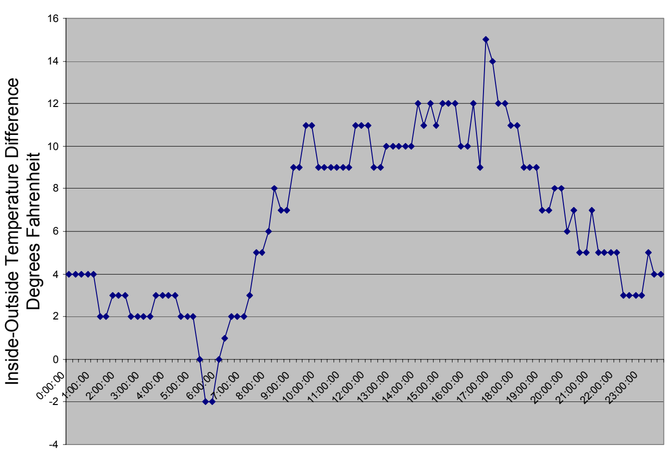

Fig. 7. Difference Between Ambient and Cabinet Temperatures From Typical Moderately Hot Day at Gantt Station

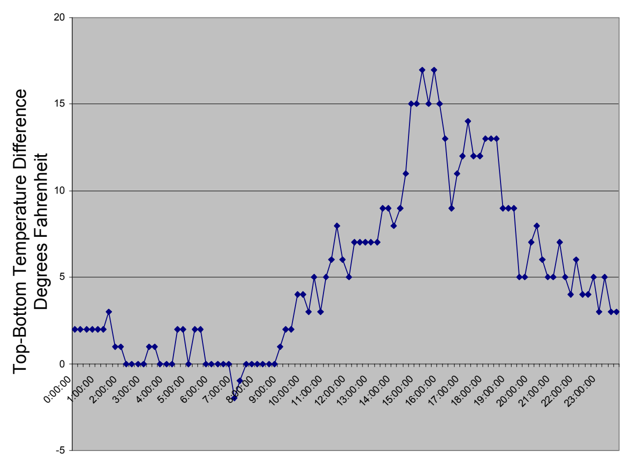

Fig. 8. Difference Between Top and Bottom Cabinet Temperatures From Hottest Day at Euclid Station

IV. Laboratory Testing

After establishing a temperature profile from actual field measurements, we then measured internal relay temperature and relay performance during temperatures actually experienced and at generally elevated temperatures.

A. Apparatus

We used the following equipment to complete our tests:

- Two different manufacturer's distribution protection systems with functionally identical settings
- Communications processor
- Secondary injection test set
- Test set software
- Laptop with Windows® 2000 operating system.
- Industrial testing oven
- Omega HH509 thermocouple unit
- Assorted cords, connectors, and cables

Inside the oven, the relays were connected to operating current and voltages similar to what they would experience in the field under operating conditions. Thermocouples were connected to the main processing unit and on the analog-to-digital processing units within the two relays. Operating time was measured using the relay test set.

B. Pickup Time Deviations

The first test followed the IID temperature data for the highest temperature day. The standard time (at room temperature) was established for instantaneous elements for the two relays. The operating time was then measured with the time at the hottest point compared with the standard time (see Table I).

Table I
Relay Response to Hot Day Temperature Profile

Element	Relay X Standard	Relay X Pickup	Relay X Deviation	Relay Y Standard	Relay Y Pickup	Relay Y Deviation
Phase 50	33 ms	37.6 ms	4.6 ms	25 ms	20.7 ms	–4.3 ms
Ground 50	33 ms	42.1 ms	9.1 ms	25 ms	29.6 ms	4.6 ms

While both relays had a change in operating time that was within the published tolerances of the relay, the increase in time for Relay X was certainly more significant. An increase in operating time of 21 percent, or over half a cycle, for a high-speed element could show a relay under "stress." Based on this, we decided to increase the temperature some more and see what effect a hotter ambient temperature would have on the IED performance.

In the second test, we did a two-hour increase from 50°C to 70°C, one-hour stable at 70°C and two-hour decrease to 50°C (see Table II).

Table II
Relay Response to One Hour High Temperature

Element	Relay X Standard	Relay X Pickup	Relay X Deviation	Relay Y Standard	Relay Y Pickup	Relay Y Deviation
Phase 50	33 ms	42.6 ms	9.6 ms	25 ms	19.8 ms	–5.2 ms
Ground 50	33 ms	42.9 ms	9.9 ms	25 ms	28.9 ms	3.9 ms

In this case, we can see that the operating time of Relay X continued to increase, although it was still within the published limits. Relay Y operating time appears to be either independent of temperature or speeding up slightly as the temperature increased. To verify this, we performed a final test.

In the third test, we performed a six-hour burn steady-state test at 70°C.

Table III
Relay Response to Six Hour High Temperature

Element	Relay X Standard	Relay X Pickup	Relay X Deviation	Relay Y Standard	Relay Y Pickup	Relay Y Deviation
Phase 50	33 ms	42.8 ms	9.8 ms	25 ms	18.2 ms	–6.8 ms
Ground 50	33 ms	43 ms	10 ms	25 ms	29.5 ms	4.5 ms

Here we see the trends for Relay X and Y continuing. Relay X continues to get slightly slower for both phase and ground elements. Relay Y actually gets slightly faster on the phase elements, although not to the degree of variance of Relay X, and continues slightly slower for the ground elements.

To get down to the component level, thermocouples were placed directly on components within the two different relays.

Table IV
Relay Component Temperature During Temperature Test

Temperature Celsius (K couple)	Relay X Processor	Relay X Analog Processor	Relay Y Processor	Relay Y Analog to Digital
30°C (86°F)	40.1	45.6	39.2	40.4
35°C (95°F)	45.9	50.8	44.9	46.5
40°C (104°F)	47.8	52.8	47.1	48.7
45°C (113°F)	56	61.3	55.7	54.5
50°C (122°F)	58.3	63.4	58.1	58.5
55°C (131°F)	64.9	70.1	65.1	61.5
60°C (140°F)	68.3	73.6	68.7	68.4
65°C (149°F)	72.5	77.7	72.8	72.6
70°C (158°F)	77	82.3	77.2	76.4
2 hours	79	86.6	80.6	79.5
3 hours	82	86.8	82	78.7
4 hours	82.1	87	82.1	79

While there are practically no differences in temperature between the two relay's main processors, it is interesting to note that the analog processors in the two relays differ by up to 8°C. This may also be significant considering the change in the performance of Relay X as temperature changed. Temperature ratings for different modern microprocessor components vary considerably, but generally speaking, the Arrhenius equation predicts an exponentially shorter life for electrical components as the temperature of the component increases.

If we assume a nominal life expectancy for a relay of 30 years, then the K factor from Equation (1) would be 0.033. The amount this factor is increased with increased temperature depends on the activation energy. The specific activation energy used depends on which component is the "weakest link" leading to failure. In insulation structures, for example, an increase in temperature of 6–8°C above 90°C causes a doubling of the aging, or half the life [2]. Of course, this does not apply exactly the same to all components, but the principle certainly applies. This validates the experience of relay technicians who note that failures of relays in outdoor cabinets increases with temperature.

V. Conclusions

1. Relays mounted in outdoor enclosures can be expected to experience temperatures above those stated in IEEE 37.94. These relays need to be designed and rated to achieve a long life in this environment.
2. The design and components of relays may change the relay's performance at extreme temperatures. Products should be chosen that are tested and validated to be within the requirements of each application.
3. The application of the Arrhenius equation to the temperature rise measured inside the relays demonstrates that relays designed for greater temperature extremes will generally have a longer life, even at more moderate temperatures.
4. Relay life should be evaluated, based on experience at similar installations, when choosing a relay.

VI. References

[1] Rate Constants and the Arrhenius Equation. Available http://www.chemguide.co.uk/physical/basicrates/arrhenius.html

[2] H. J. Sim and S. H. Digby, "The Making of a Transformer," presented at Doble The Life of a Transformer Seminar, 2004.

VII. Biographies

Fernando "Nando" Gutierrez holds two Associate Degrees: AA in Business Administration/Management and an AS in Electronics Engineering. He is currently Imperial Irrigation District's Substation Construction & Maintenance Superintendent. Since 1990, he has been a part of Substation C&M and is currently leading their efforts in substation integration and automation. He has been responsible for the construction, installation, commissioning, and acceptance testing of over ten new substations and numerous substation retrofits to incorporate microprocessor-based relay protection and communication. Mr. Gutierrez has been a major player in the implementation of IID's Apprenticeship Program for Substation Personnel. He also holds his state certified teaching credential for the purpose of instructing within this program.

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as market manager for transmission system products. He is now a senior product manager. Prior to joining SEL, he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the State of Pennsylvania.

David Kopczynski will graduate from Washington State University in 2006 with a B.S. in Electrical Engineering. Dave is an engineering marketing intern with SEL and also serves as president of the Alpha Tau Omega Fraternity.

Dan Holmes has a B.S. in Electrical Engineering from the University of Idaho. Dan joined SEL as an associate product manager after graduation in 2005.

VIII. Appendix

Table V
State High Temperature Records

State	Temp	Date	Station	Elevation (feet)
Ala.	112	Sept. 5, 1925	Centerville	345
Alaska	100	June 27, 1915	Ft. Yukon	420*
Ariz.	128	June 29, 1994	Lake Havasu	505
Ark.	120	Aug. 10, 1936	Ozark	396
Calif.	134	July 10, 1913	Death Valley	N/A
Colo.	118	July 11, 1888	Bennett	5,484
Conn.	106	July 15, 1995	Danbury	450
Del.	110	July 21, 1930	Millsboro	20
Fla.	109	June 29, 1931	Monticello	207
Ga.	112	July 24, 1952	Louisville	132
Hawaii	100	April 27,1931	Pahala	850
Idaho	118	July 28, 1934	Orofino	1,027
Ill.	117	July 14, 1954	E. St Louis	410
Ind.	116	July 14, 1936	Collegeville	672
Iowa	118	July 20, 1934	Keokuk	614
Kansas	121	July 24, 1936	Alton	1,651
Ky.	114	July 28, 1930	Greensburg	581
La.	114	Aug. 10, 1936	Plain Dealing	268
Maine	105	July 10, 1911	N. Bridgton	450
Md.	109	July 10, 1936	Cumberland and Frederick	623, 325
Mass.	107	Aug. 2, 1975	New Bedford and Chester	120, 640
Mich.	112	July 13, 1936	Mio	963
Minn.	114	July 6, 1936	Moorhead	904
Miss.	115	July 29, 1930	Holly Springs	600
Mo	118	July 14, 1954	Warsaw and Union	705, 560
Mont.	117	July 5, 1937	Medicine Lake	1,950
Neb.	118	July 24, 1936	Minden	2,169
Nev.	125	June 29, 1994	Laughlin	605
N.H.	106	July 4, 1911	Nashua	125
N.J.	110	July 10, 1936	Runyon	18
N.M.	122	June 27, 1994	Lakewood	N/A
N.Y.	108	July 22, 1926	Troy	35
N.C.	110	Aug. 21, 1983	Fayetteville	213
N.D.	121	July 6, 1936	Steele	1,857
Ohio	113	July 21, 1934	Gallipolis	673
Okla.	120	June 27, 1994	Tipton	1,350
Ore.	119	Aug. 10, 1898	Pendleton	1,074

State	Temp	Date	Station	Elevation (feet)
Pa.	111	July 10, 1936	Phoenixville	100
R.I.	104	Aug. 2, 1975	Providence	51
S.C.	111	June 28, 1954	Camden	170
S.D.	120	July 5, 1936	Gannvalley	1,750
Tenn.	113	Aug. 9, 1930	Perryville	377
Texas	120	Aug. 12, 1936	Seymour	1,291
Utah	117	July 5, 1985	Saint George	2,880
Vt.	105	July 4, 1911	Vernon	310
Va.	110	July 15, 1954	Balcony Falls	725
Wash.	118	Aug. 5, 1961	Ice Harbor Dam	475
W. Va.	112	July 10, 1936	Martinsburg	435
Wis.	114	July 13, 1936	Wisconsin Dells	900
Wyo.	116	Aug. 8, 1983	Basin	3,500

Source: U.S. National Climatic Data Center (last updated December 2000)
By Jack Williams, USATODAY.com
06/21/2005 - Updated 09:38 PM ET