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NightCool: Nocturnal Radiation Cooling Concept

Long Term Performance Evaluation

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NightCool: Nocturnal Radiation Cooling Concept Long Term Performance Evaluation

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Executive Summary

This report describes the experimentally evaluated potential of a novel residential night cooling concept. *NightCool* uses a home's metal roof under a sealed attic as a large radiator to the night sky to provide nocturnal cooling. Data are provided for two full cooling seasons.

Measured cooling energy savings between the control and *NightCool* building averaged 15% over an eight month test period in 2007 – somewhat lower than the previous simulation analysis. Several measures have been taken over the past year to get a closer match between the theoretical and practical outcome of the *NightCool* concept as well as to improve the rigor of the experimental test.

In 2008, the brown shingle roof of the control building was altered to a white reflective roof- identical with that of the experimental building. While this could be expected to reduce savings, improvements were made to the attic air distribution system such that a 12% cooling energy reduction was achieved in the cooling season of 2008 with identical roofs. Moreover, the *NightCool* system provided cooler nighttime temperatures as seen in Figure E-1.

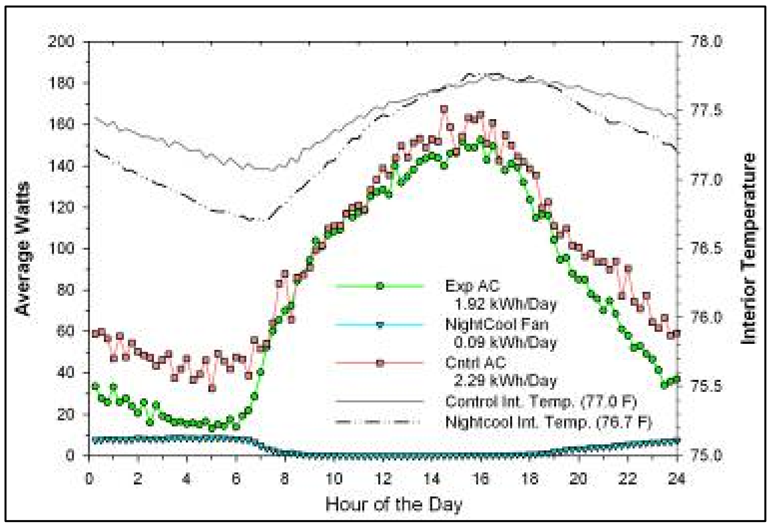

Figure E-1. Comparative cooling performance of the Control and *NightCool* building air conditioning system and system fans over the daily cycle for April – November 2008.

Also in 2008, an integrated enthalpy-based attic ventilation system with solar drying of low-temperature regenerated desiccants was incorporated into the *NightCool* building. This resulted in a significant reduction in interior relative humidity during periods of minimal space conditioning. Many buildings in Florida experience moisture problems in months such as March and November when little space cooling is needed. With the new solar dehumidification system in the second season the *NightCool* building had significantly lower humidity during periods of low space conditioning. For instance in November of 2009, the average relative humidity was only 52% in the *NightCool* interior versus 59% in the control building.

The favorable experimental results indicate that *NightCool* can be a promising technology for very low energy homes. It also appears possible to mate the concept with Building Integrated Photovoltaics (BIPV) to provide combined solar electric power, nighttime cooling and winter afternoon heating. A priority for future experimentation would be to examine realistic performance in more temperate and drier climates with the objective of completely eliminating the vapor compression cooling system. Combining *NightCool* with ductless mini-split heat pumps appears to be the most practical system configuration for full scale implementation of the concept.

NightCool: Nocturnal Radiation Cooling Concept Long Term Performance Evaluation

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ABSTRACT

An experimental evaluation has been conducted on a building-integrated night sky cooling system designed to substantially reduce space cooling needs in homes in North American climates. The system uses a sealed attic covered by a highly conductive metal roof (a roof integrated radiator) which is selectively linked by air flow to the main zone with the attic zone to provide cooling – largely during nighttime hours. Available house mass is used to store sensible cooling. The system's capability for solar dehumidification with minimal electricity input is demonstrated with long-term performance data taken over 2007 - 2009. A year-long study period , with identical white roofs, showed a cooling energy reduction of 12% in Central Florida with superior dehumidification. An opportunity experiment in the second year of monitoring also found that the simple measure of implementing reflective walls can produce a further measured 9% cooling energy reduction.

Introduction

Radiative cooling to the night sky is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower temperature (Martin and Berdahl, 1984). In many North American locations, the available night cooling exceeds the residential nighttime cooling loads and in arid desert climates may be considerably in excess of total daily cooling requirements.

Careful examination of air conditioner operation in many homes in Florida (Parker, 2002) shows that night sky radiation could substantially reduce cooling needs. Over a 10 hour night, theoretically night sky radiation amounts to about 250 - 450 Wh/m^2 if all could be effectively utilized. However, that is not easily achieved. Various physical limitations (e.g. air flow pattern under the radiator, fan power, convection and roof conductance) limit what can be utilized, so that perhaps half of the potential rate of cooling can be practically obtained. However, passive systems with very little air velocity under the radiator (i.e. with free convection) still will achieve net cooling rates of 1 - 5 W/m^2. With 200 m^2 of roof in a typical home that adds up to a nearly free cooling rate of 200 - 1,000 Watts (700 - 3,400 Btu/hr).

In addition, the system offers enticing potential for low energy dehumidification. Materials with high humidity absorption placed in the attic, may absorb humidity from the interior during night cooling while exhausting moisture during daytime solar heating.

Description of the *NightCool* Concept

We devised an innovative night cooling system consisting of a metal roof serving as a large area, low mass highly-conductive radiator (see Figure 1). The metal roof is used at night during spring, autumn and acceptable summer periods to perform sensible cooling. Various exotic night sky radiation cooling concepts have been tested in the past. These have included very expensive “roof ponds” or, complex cycles or, movable roof insulation with massive roofs so that heat is not gained during daytime hours (Hay, 1978; Fairey et.al., 1990; Givoni, 1994). The key element of the *NightCool* configuration is that the insulation is installed conventionally on the ceiling. The operation of the system is detailed in Figure 1.

1. White metal roof on metal battens (no decking). Both sides are surfaced for high emissivity. A temperature probe measures roof underside temperature.
2. Small capacity dehumidifer (such as *Whirlpool AD40DBK*); operates only during evening hours when thermostat and roof temperature monitor calls for cooling and attic relative humidity is greater than 55%.
3. Baffled inlet frill from attic for nighttime operation.
4. Room return inlet (for daytime operation). Closed by damper at night when temperature conditions are met.
5. Thermostat (compares roof surface temperature and setting to determine vapor compression vs. nighttime cooling operation).
6. Variable speed air handler fan with electronically commutated motor.
7. Vapor compression air conditioner cooling coil.
8. Interior duct system with supply outlet.
9. Interior room air return to attic during evening hours when Night Cool is activated.
10. Roofline drip collection system with drain.
11. Ceiling return for *NightCool* operation mode.
12. Attic air connects to cool roof for nocturnal cooling.
13. R-30 ceiling insulation.
14. Sealed attic construction with top plate baffles (tested and sealed system).
15. Air conditioner outdoor unit (condenser).
16. Concrete interior walls (thermal mass for sensible cool storage).
17. Tile floor (add thermal mass).

Figure 1. Schematic of full scale *NightCool* concept.

During the day, the main zone is de-coupled from the attic, i.e. there is no air exchange and, due to the thick ceiling insulation, there is minimal heat transmission as well. Currently heat gain to the attic space is minimized by the white reflective metal roof. At this time the main zone is conventionally cooled with an appropriately sized air conditioner. However, at night as the interior surface of the metal roof in the attic space falls two degrees below the desired interior thermostat set point, the return air for the air conditioner is channeled through the attic space by way of electrically controlled louvers with the variable speed fan. The warm air from the interior cools off at the interior side of the metal roof which then radiates the heat away to the night sky.

As increased cooling is required, the air handler fan speed or runtime is increased. If the interior air temperature does not cool sufficiently, the air conditioner supplements *NightCool*. Also, if temperature conditions are satisfied, but relative humidity is not, a dehumidifier (note 2 on Figure 1) or other dehumidification system may be energized. The massive construction of the home interior (tile floor and concrete interior walls) stores sensible cooling to reduce space conditioning needs during the following day.

A 225 square meter metal roof structure was modeled for Tampa, Florida (Parker, 2005). The model predicts a cooling rate of about 2,140 Watts (7,300 Btu/hr), an average summer cooling benefit of about 15 kWh per day for 1.4 kWh of fan power and a system seasonal energy efficiency ratio (SEER) of about 37 Btu/Wh (COP = 10.8). Performance in less humid climates with more diurnal temperature swing is predicted to be substantially better. The major weather-related influences on achieved cooling performance are outdoor air temperature, dewpoint temperature, cloudiness and wind speed. Physical factors with a large influence are the system return air temperature (and hence radiator temperature) air flow rate and fan and motor efficiency.

The performance of the system has been detailed in three previous reports covering the theoretical performance (Parker, 2006), the early experimental testing (Parker et al, 2007), full scale testing with concept refinement (Parker et al., 2008). This final report describes performance of the final test configuration over a one year period as well as some follow-on experiments to examine how various experimental changes are shown to influence the savings of the final system. Below, we briefly summarize a description of the test facilities and earlier collected data. Please see previous project report for additional details.

Small Scale Test Buildings

To verify the potential of the *NightCool* concept, it is being tested in two 12 x 16' (3.7 x 4.9 m) test structures (192 ft^2 or 17.8 m^2) of conditioned area. These highly instrumented buildings are located at the Florida Solar Energy Center (FSEC) in Cocoa, Florida. Figure 2 shows the completed side by side test buildings.

Figure 2. Completed side-by-side test buildings at Florida Solar Energy Center, 2007 test season.

The control building has dark brown asphalt shingles with a solar reflectance of 8% over a standard ½" (1.2 cm) plywood decking on rafters. The vented attic in the control building has 1:300 soffit ventilation. The ceiling is insulated with ten-inch R-30 $ft^2 \cdot h \cdot {}^oF/Btu$ (RSI 5.3 $m^2 \cdot K/W$) fiberglass batts over ½" (1.2 cm) dry wall.

The experimental unit has a white metal 5-vee roof on metal battens and a sealed attic, which can be convectively linked to the main zone by a powered circulation fan. The white metal roof had an initial solar reflectance of 65% (see Figure 2). Figure 3 shows an interior view of the experimental *NightCool* facility's roof. Note the sealing of the soffit vents with insulation inserts and sealant foam. The white metal roofing is installed on metal battens so that it is directly exposed to the attic below. This produces strong radiation and convective linkage between the fully exposed roof and the sealed attic interior.

Figure 3. Interior detail of experimental *NightCool* sealed attic with exposed metal roofing on metal. Note metal arm holding wood sample which is weighed on a precision scale to establish changes in moisture content.

Both units have uninsulated 6" (15 cm) concrete slab floors with an area of 192 square feet (17.8 m^2). The frame walls in both are insulated with R-13 (RSI 2.3) fiberglass batt insulation, covered with R-6 (RSI 1.1) exterior isocyanurate sheathing, and protected by beige concrete board lapped siding.

Each test building has four 32" x 32" (0.81 x 0.81 m) double-glazed solar control windows. The single-hung windows have air leakage rating of 0.1. These have a NFRC rated overall U-factor of 0.35 Btu/(hr·ft^2·^{o}F) (1.99 W/m^2 · K) a solar heat gain coefficient of 0.35 and a visible transmittance of 60%. The windows are covered with white interior blinds. To approximate typical internal mass in residential buildings, twenty hollow core concrete blocks were located on the north side of both buildings.

On October 20, 2006, we used SF_6 tracer gas to test the *in situ* infiltration rate of the control and *NightCool* buildings with the air conditioning off, but with the *NightCool* air circulation grills open. The measured infiltration rates were 0.27 ACH in the control and 0.34 ACH in the *NightCool* test building – a fairly similar result.

Instrumentation and Monitoring

An extensive monitoring protocol was developed for the project as shown in the full project report (Parker et al., 2007). Room temperature and humidity conditions are measured in each building. Also, a key measurement in the *NightCool* building involves measuring air mass flow with the return and supply temperatures from the sealed attic space under the radiatively coupled roof. Weather parameters include temperature, humidity, insolation, wind-speed and a pyrgeometer are used to determine potential night cooling along with nighttime heat dissipated to the integral night sky radiator system.

Small 5,000 Btu/hr (1.46 kW) room air conditioners are installed to supply supplemental cooling. Internal loads are simulated by switching on and off interior lamps using wall timers and a calibrated room humidifier. Electricity consumption data is collected for air conditioner, internal loads and *NightCool* fan power.

Components and Control of *NightCool* Circulation System

Two ceiling mounted registers were cut out from the R-30 SIPs panel ceiling of the experimental building. A *Fantech FR125* centrifugal fan (148 cfm or 70 L/s, 18 Watts) was installed on one side to circulate air from the main zone to the attic space when temperature conditions are met. Generally the *NightCool* system is activated when the attic air temperature falls below 74°F (23.3°C). To maintain the main interior zone under a positive pressure, the fan drew air from the sealed attic with return air entering from a passive register on the opposite side of the room.

Prior to the long term monitoring, two motorized 16-inch (0.4 m) dampers were added to the supply and return air respectively so that the air from the main zone to the attic is closed when the attic is at a higher temperature than the main zone or when the attic is being ventilated.

The dampers are open for passive cooling when the attic is cooler than the main zone (warm air rises to the *NightCool* attic and then falls as it is cooled to the main zone). Always, when the attic temperature drops below 75°F (23.9°C) the dampers are open for cooled air to circulate to the main zone.

Both the experimental and control buildings are cooled by two small window unit air conditioners. These AC systems are operated by the data acquisition system to obtain very fine temperature control of the interior space which is set to 78°F (25.6°C). These have a nominal capacity of 5,000 Btu/hr (1.46 kW) and an EER of 9.7 Btu/Wh (COP = 2.84). Based on measurements we determined that they draw about 520 Watts when running at 85°F (29.4°C) outdoor condition.

NightCool Controls

The monitoring in 2007 evaluated the fully operational *NightCool* system with supplemental air conditioning used when interior temperatures rose above 78°F (25.6°C). The *NightCool* activation conditions are:

- Attic Temperature < 75.5°F (24.2°C)
- Attic Temperature < Interior air temperature
- Interior Air Temperature > 74°F (23.3°C)

Conditions are evaluated every 10 seconds with a decision made every five minutes in terms of whether air conditioning or *NightCool* is activated. When *NightCool* is on, the air conditioning system is turned off. Conversely, if the indoor air temperature is above 78°F (25.6°C), the room air conditioner is activated and *NightCool* fans cannot be activated. As set up, the *NightCool* system will cool the interior space down to 74°F (23.3°C), prior to being turned off. The cut off prevents overcooling of the conditioned interior.

Typical Daily Performance

The two figures below illustrate the performance of the *NightCool*. The data show performance on 12 April 2007 under good performance conditions for the *NightCool* concept. Figure 4 shows the recorded weather temperature conditions on this relatively clear spring day. There was very warm weather in the afternoon with a good amount of cooling necessary in both buildings. The air temperature reaches a maximum of 85.5°F (29.7°C), with relatively high moisture (dewpoint averages 69°F or 20.6°C). However, with a clear sky the measured sky temperature drops below 50°F (10°C) after sunset – ideal for nocturnal cooling.

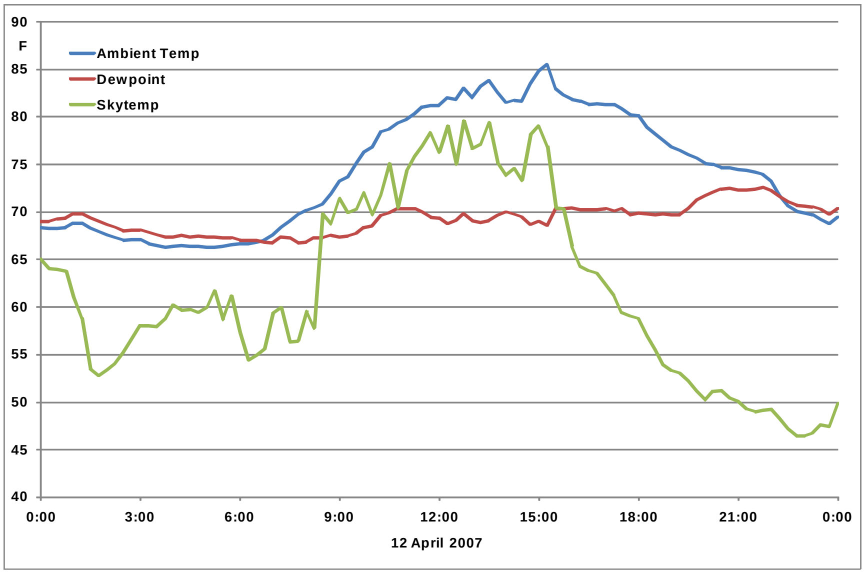

Figure 4. Outdoor temperature conditions on 12 April 2007.

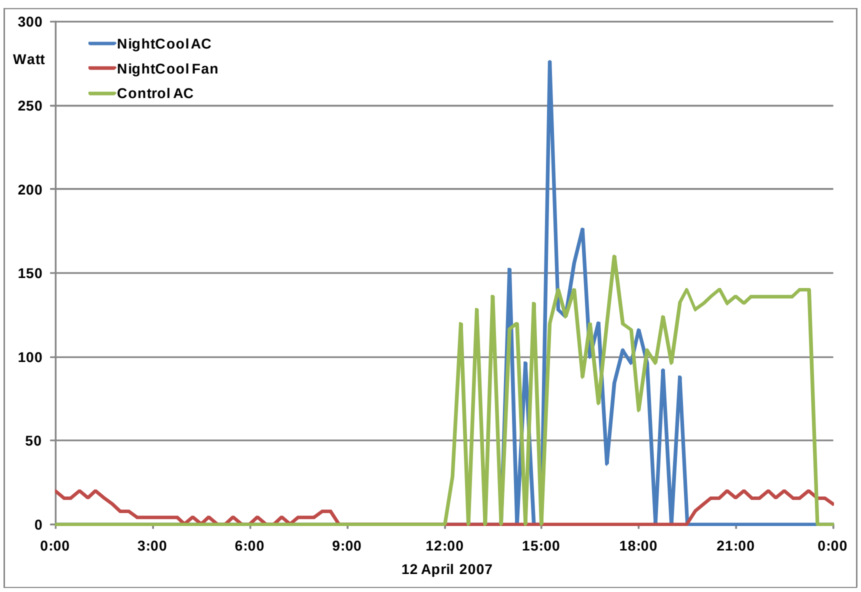

Figure 5. Control vs. *NightCool* HVAC power on 12 April 2007.

The second plot, Figure 5, plots the measured air conditioner and *NightCool* fan power. Over the course of the day, *NightCool* reduced cooling use by 48% including the energy use of the circulating fans. The control building used 1.22 kWh for cooling over the day while the air conditioner in *NightCool* used 0.51 kWh and the fans another 0.12 kWh. Also, the experimental system produced better comfort with lower and more even interior air temperatures.

Measured Long-Term Performance: 2007

Below, we summarize the collected data for a full year for the cooling season in Central Florida, which stretches from April to November of 2007. Within the monitoring, mechanical air conditioning used in the control and the experimental unit during daytime, and with the *NightCool* fan circulation system used during evenings. A daytime temperature of 78°F (25.6°C) was maintained in both test buildings. Air conditioner cooling energy use averaged 4.6 kWh/day in the control building against 3.6 kWh in the experimental building, which also used 0.2 kWh/day for the circulation fans. Measured cooling energy savings between the control and *NightCool* building averaged 15% over those 8 months. The comparative profiles of measured performance over the 24-daily cycle from April to November are shown in Figure 6. Note that a 15% energy savings is seen regardless of the fact that the *NightCool* system averages an interior air temperature about half a degree cooler than in the control.

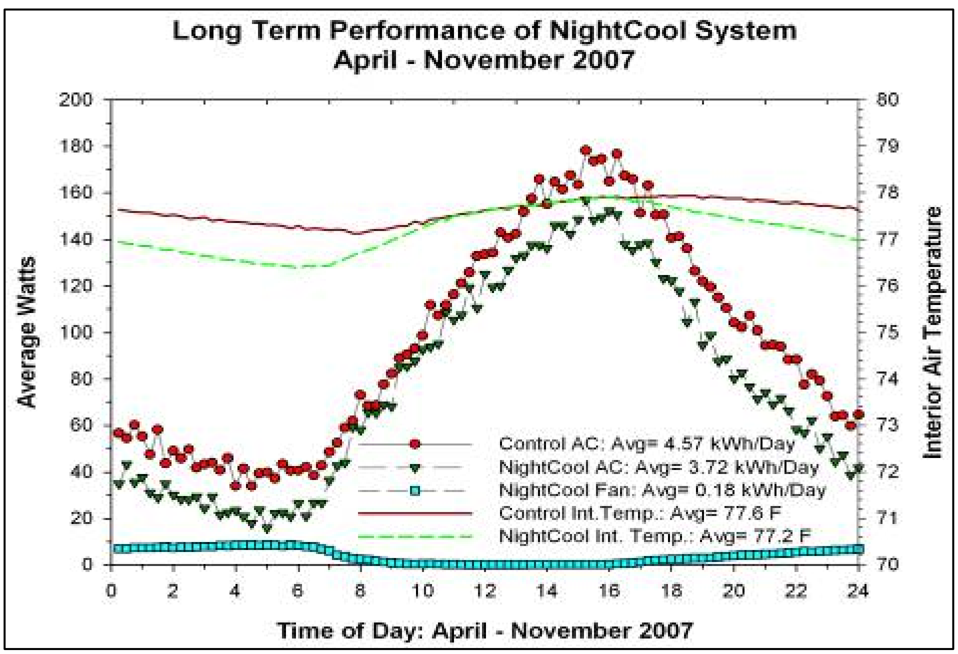

Figure 6. Comparative cooling performance of the Control and *NightCool* building air conditioning system and system fans over the daily cycle.

The delivered seasonal cooling rate averaged about 1.5 - 3.0 Btu/hr/ft^2 (5 - 10 W/m^2) of roof surface on the average evening, implying that *NightCool* in a full scale 2,000 square foot (186 m^2) home would cool at a rate of 4,000 - 8,000 Btu/hr (1170-2340 W) depending on the season. Over a typical 6 hour operating period, this would produce about 0.2 ton-hours of sensible cooling or 2 ton-hours (7.0 kWh) in a full scale home.

Monthly performance indices were also produced. Average long-term monthly energy efficiency ratios (EERs) ranged from 16 - 32 Btu/Wh (COP = 9.7 - 9.4) with a mean of 25 Btu/Wh (COP = 7.3) over the cooling season – somewhat lower than simulations conducted earlier. Figure 7 shows the monthly performance indices in terms of monthly energy savings in absolute and percentage terms as well as the *NightCool* system EER. Table 1 numerically summarizes the detailed performance in terms of energy, efficiency, thermal and comfort related performance.

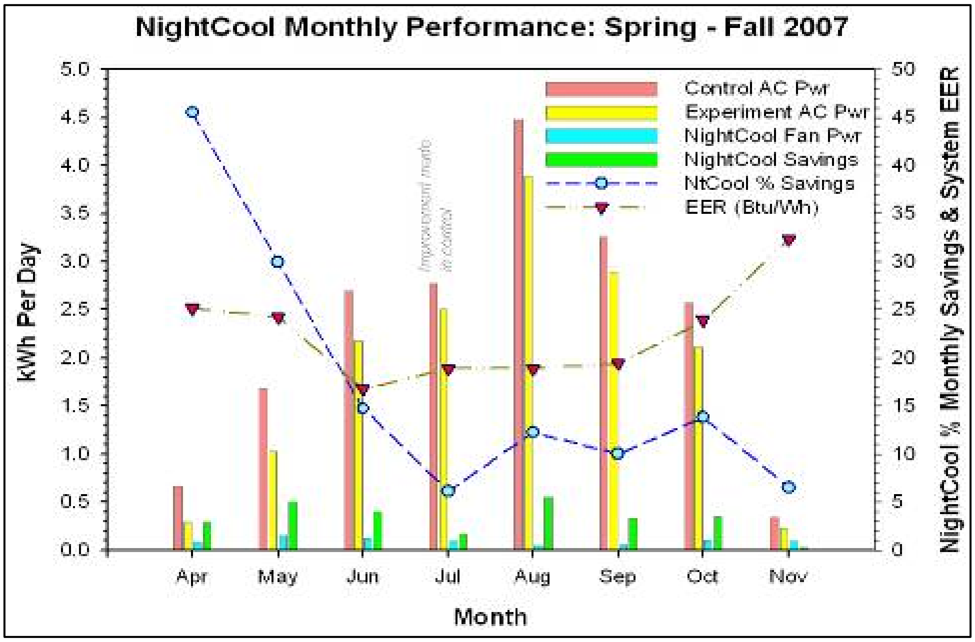

Figure 7. Monthly average performance of *NightCool* system in 2007.

Table 1. Annual *NightCool* Performance 2007

Power & Efficiency								
	April	***May***	***June***	***July***	***August***	***September***	***October***	***November***
Experiment AC (kWh)	8.759	31.825	65.269	69.391	119.948	84.334	65.369	6.720
Experiment Fans (kWh)	2.411	4.692	3.644	2.468	1.432	1.474	3.210	2.846
Control AC (kWh)	20.502	52.111	80.820	76.535	138.335	97.702	79.563	10.253
Experiment Lights (kWh)	81.60	83.14	79.80	79.83	81.87	80.94	83.48	80.82
EER (Btu/Wh)	24.6	23.9	16.5	18.6	18.6	19.3	23.6	31.8
RTF (run-time-fraction)	0.185	0.358	0.291	0.216	0.120	0.118	0.250	0.227
T (°F) (T_{return} - T_{supply})	2.73E	0.65E	1.83E	2.07E	2.07E	2.14E	2.62E	3.53E
Percent *NightCool* Savings	45.5%	30%	14.7%	6.0%	12.3%	10.0%	13.8%	6.5%
Building Conditions								
Experiment Attic Temp. (°F)	73	79.9	83.8	85.2	86.2	83.5	80.8	68.5
Control Attic Temp (°F)	81.0	85.7	90.0	91.8	94.9	89.2	85.6	74.7
Experiment Room Temp. (°F)	77.3	78.9	80.1	79.9	74.6	79.2	79.1	76.5
Control Attic Temp. (°F)	77.9	79.1	79.2	79.0	78.7	78.6	78.6	77.0
Experiment Room RH (%)	47.5	45.4	44.0	43.9	39.5	41.8	46.7	53.0
Control Room RH (%)	45.1	40.5	40.3	41.9	39.2	42.7	44.4	54.8
Weather Conditions								
Ambient Temp. (°F)	69.6	74.5	78.5	79.9	82.9	80.2	78.3	67.5
Ambient RH (%)	67.3	68.5	77.7	82.9	6.3	79.7	79.4	76.3
Solar (w/m^2)	250.0	253.5	235.0	210.9	235.5	181.6	150.5	151.6
Dewpoint (°F)	57.9	64.0	71.6	74.9	75.0	73.6	71.7	59.8
Sky Temp. (°F)	50.1	58.6	66.8	70.5	70.8	69.6	67.7	49.0

NightCool Fan run-time fraction

Measured space cooling in the *NightCool* building from April - October 2007 was 464 kWh (19 kWh used for *NightCool* fan). During the same time period, the control building used. 546 kWh in the Control (15% savings). Given the 1:10 scale of the buildings, this would suggest a consumption of for a full scale *NightCool* building against 5460 kWh for a similar control. These values are similar, although somewhat lower given the higher efficiency construction, than typical cooling energy measured in real homes in Central Florida (Parker, 2002).

Enthalpy-Controlled Solar Attic Ventilation

As the original *NightCool* concept provided only sensible cooling, we saw higher interior relative humidity in mid-summer strongly suggesting the need for supplemental dehumidification. However, using even a small amount of standard dehumidifier power would adversely impact the system efficiency since that process is inherently energy intensive. Thus, we conceived use of the solar daytime attic heat to dry attic wood and a clay desiccant with enthalpy controlled ventilation to exhaust the moisture. This approach is similar to the solar dehumidification scheme described by Areemit and Sakamoto (2005), which utilized a plywood attic to achieve effective dehumidification with COPs exceeding 15 – three times as great as the best standard electric dehumidifiers.

Over the project monitoring period, we installed a drying system used in conjunction with *NightCool*. We added 300 clay desiccant packs between the roof and the wood rafter in the attic (see Figure 3). The total net weight of clay desiccant total 900 ounces (56 lbs or 25.6 kg). The desiccant absorb moisture at night when attic temperatures are low and thus relative humidity (RH) is high and desorb moisture during day when attic temperatures are high and RH is low. It is noteworthy, however, that with no way for the moisture to be removed from the building there is only a temporary benefit from adding the desiccant packs unless the attic is ventilated. Therefore four watt DC ventilation fans were added to the otherwise sealed *NightCool* attic – one for supply ventilation feeding in 40 cfm (19 L/s) of outside air from the south east side soffit and the other exhausting warm moist air from the attic western side ridge and exhausting that air out of the north soffit.

In January 2008 we began controlling the experimental facility attic ventilation based on the difference in the attic to outdoor absolute humidity. In this mode of operation, the sun's heat warms the attic and dries the desiccants activating the attic ventilation fans and thereby removing moisture. The status of the fans is determined every five minutes. If the exterior humidity is lower than that inside, the ventilation fans are activated. Otherwise they remain unpowered. During the night the ventilation ends and the desiccant reabsorbs moisture from the space during *NightCool* operation.

Latent Moisture Capacitance

Even during autumn days, we saw attic temperature exceeding 90°F (32°C) for periods of time during high insolation. However, they do not go much above this temperature level. Thus, a key need is for a workable desiccant material that can be regenerated at low temperatures. Although silica gel is a versatile and proven desiccant, it does not regenerate until temperatures of over 240°F (116°C) are obtained. Consequently, its use is not feasible with the concept. However, available montmorillonite clay desiccants regenerate at temperatures between 90°F and 120°F (32-49°C), thus at first they were considered ideal. Desiccant clay can hold up to 20% of its dry weight as moisture with a three-hour exposure.

The lower *NightCool* attic temperatures would indicate that potentially a 5-10% usable moisture adsorption potential might be available over a daily cycle in the *NightCool* attic. Given that residential research suggests that a rate of 1.25 gallon per 1,000 ft^2 ($5L/100m^2$) of daily moisture removal capacity is needed in a typical home (Tenowolde and Walker, 2001), this would suggest the need for about one liter or about 2 pounds (0.9 kg) of moisture capacity in the 192 ft^2 (17.8 m^2) *NightCool* building. This would indicate about 20-40 pounds (9-18 kg) of desiccant clay for the application in the test building. Not only does the ventilation remove collected moisture, but it would also lower the temperature of the attic space to reduce daytime sensible cooling loads across the insulated ceiling.

Solar Dehumidification

Since the change to enthalpy-controlled attic ventilation, we have seen beneficial reduction in relative humidity. Figure 8 shows the measured interior relative humidity in the control and *NightCool* main zone interior after the implementation of enthalpy based attic ventilation in mid January 2008. The data is for 1 February to 2 March 2008.

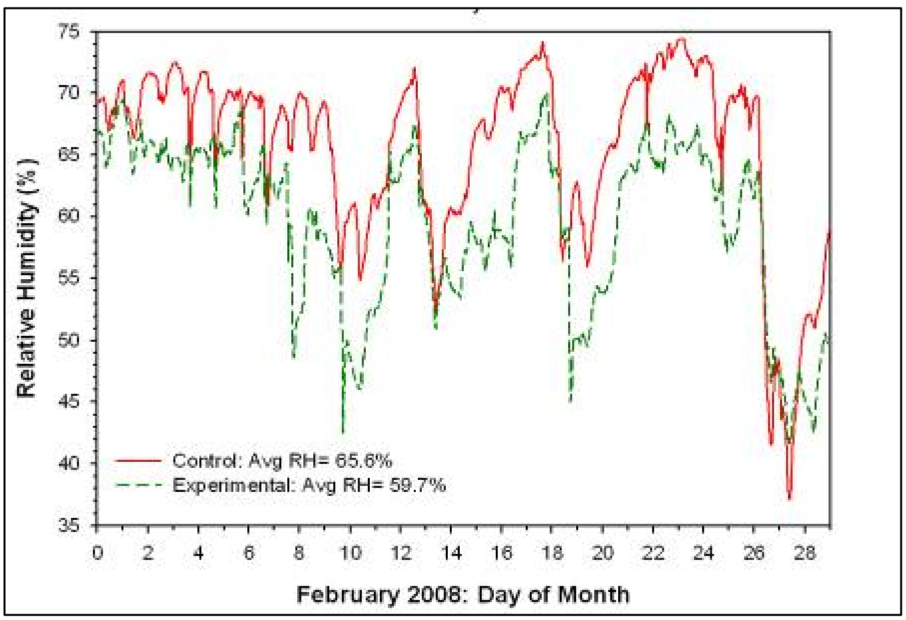

Figure 8. Comparative main zone RH with enthalpy controlled solar attic ventilation.

After the enthalpy based ventilation system was activated with the desiccant system, the average February interior main zone relative humidity averaged 65.6% in the control building against 59.7% in the *NightCool* building – a significant reduction in interior relative humidity during a seasonal period of minimal space conditioning. This is also a time where many buildings in Florida otherwise experience moisture problems. So during swing seasons *NightCool* may keep RH below 60% RH without backup dehumidification, which is desirable relative to mold, mildew, dust mites etc. Even during wintertime *NightCool*s additional moisture buffer may be utilized for staying within reasonable RH limits without consuming lots of energy.

Improved Dehumidification System

Research in early 2008 showed that even better dehumidification potential may be achieved by replacing the clay packs with wooden fiber boards, usually being used for floor underlayment and sound deadening. The use of this material water for building moisture adsorption has already been previously experimentally demonstrated in research at Germany's Fraunhofer Institute (Künzel et al., 2006). We found that fiber board responds faster to changes in RH than the clay desiccant, RH being the major climate parameter influencing the absorption-desorption process (see Figure 9). Used in the *NightCool* attic, the specific moisture absorption capacity of fiberboard is at least 50% higher compared to clay packs by weight and it is also higher than what can be achieved with standard plywood.

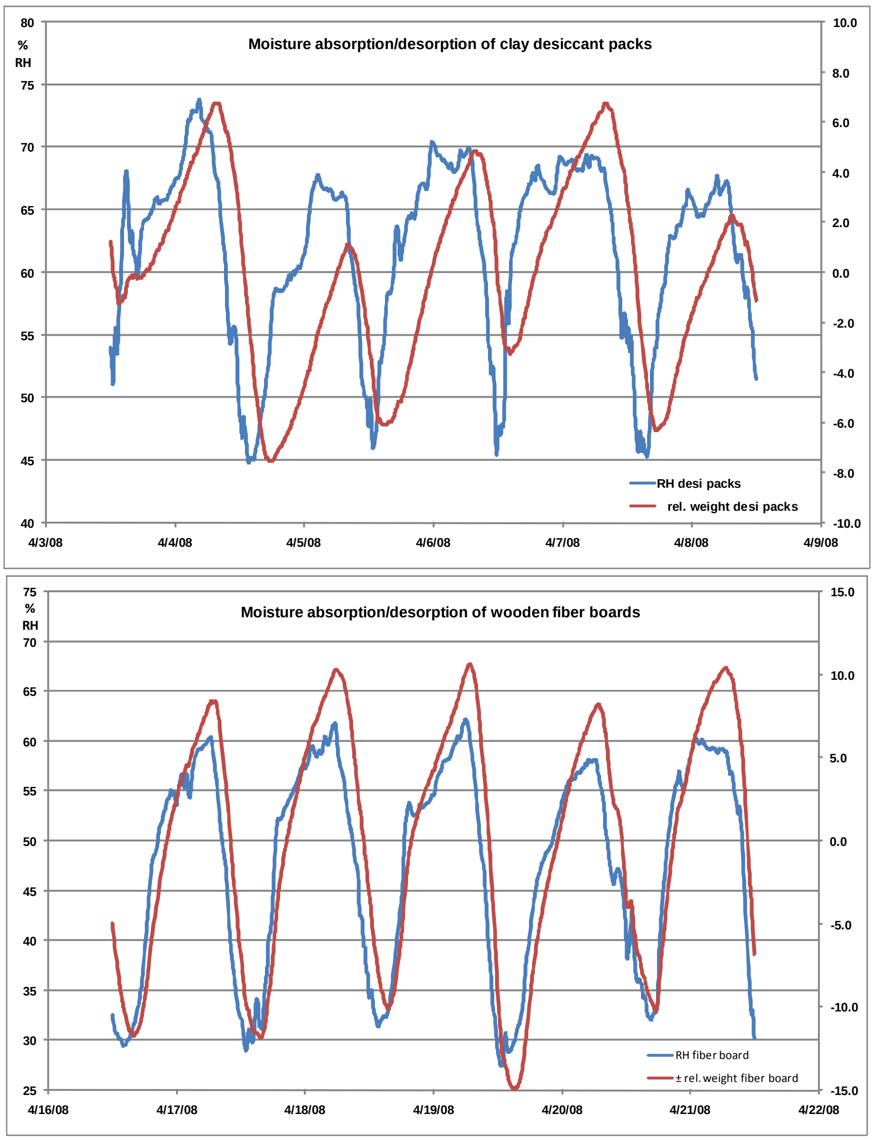

Figure 9. Comparative moisture absorption/desorption performance of clay desiccant packs versus wood fiber boards.

A precision digital scale in the attic of the *NightCool* building logged the weight of desiccant packs or fiber board respectively over several days. Figure 9 shows five day periods, starting and ending at noon. Both samples had an average weight of approximately 900 g. Note that RH range differs due to changing ambient conditions. Linear regression analysis for clay yielded a relative weight change of about 0.46% for each percent RH-change, against a 0.70 % change for the fiber board sample. Confining the comparison to the RH range of 45% to 70%, which occurred during both sampling periods, the advantage of the fiber board becomes even more pronounced. Finally, there is the faster response time of moisture adsorption with the fiberboards. Considering these results, we replaced the clay packs with fiber board by the beginning of May 2008 with immediately observed improvements to daily *NightCool* dehumidification performance.

Improving *NightCool* Radiator Performance

A major factor for achieving the theoretical night cooling potential is reaching as high as possible a temperature of the metal roof during nighttime. A recent change to pressurizing the attic by pushing the air from the main zone to the attic resulted in much better performance. First, by this change, the fan's heat is directed to the attic – where it helps heating up the radiator – rather than to the main zone and second by creating more turbulence in the attic the convective heat transfer is improved. We were able to isolate these problems by using infrared cameras on the *NightCool* building under test. In Appendix A, we show time lapsed interior IR images taken of the *Nightcool* attic in operation on March 12, 2007. These allowed us to graphically see the cooling of the roofing panels over time, and even to see the heat of moisture sorption in the wood roofing members. However, it was the exterior infrared images that allowed real improvements to the overall *NightCool* concept.

As shown in Figure 10, looking at the exterior south roof of the *NightCool* building during operation, the warm air from the interior is poorly distributed across the radiator, limiting its effectiveness as a nocturnal radiator. Note the hot spot above the fan with the cooler surrounding roof. In the image, color is proportional to temperature and the hot. Since radiational cooling is at the 4th power of the absolute temperature difference to the Stefan-Boltzmann constant, all efforts to increase the temperature of the radiator should produce better results.

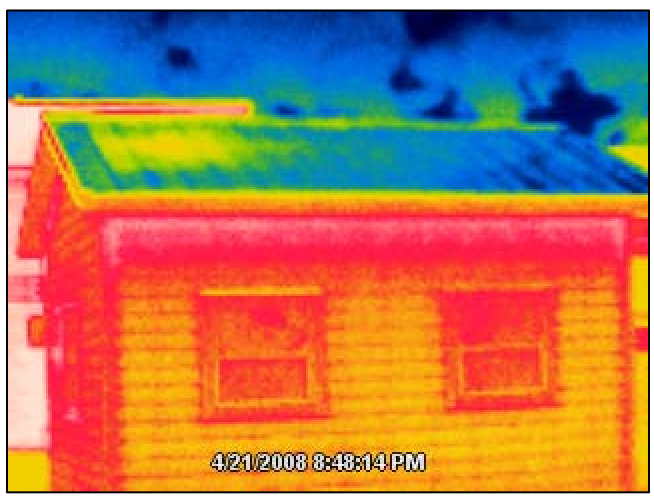

Figure 10. South exterior of the *NightCool* building during evening operation. Note the poor distribution of warmed air from the interior.

To address this limitation and optimize the configuration, we used a bucket truck with the infrared camera to take images of the roof of the *NightCool* building in operation when taken from above. Figure 11 shows the crane with camera suspended above the facility. Figure 12 shows the appearance of the original configuration where warm air from the interior is simply blown onto the interior roof from underneath.

Figure 11: ***NightCool*** **building with crane and suspended bucket with IR camera above the building.**

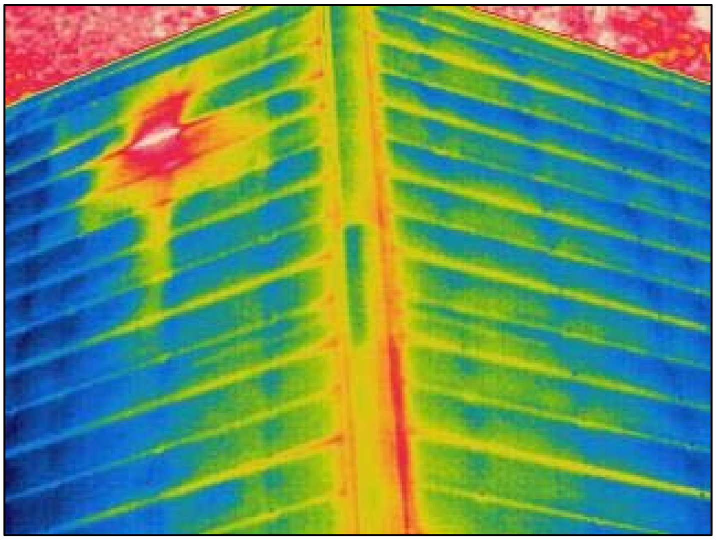

Figure 12. Image of the ***NightCool*** **roof in operation as seen by the overhead IR camera. Note hot spot directly above fran, but generally poor distribution of warm air across the roof radiator surface.**

After the original images were taken, FSEC staff tried three different air distribution configurations in an effort to achieve better results. One involved creating a narrow wood channel between the wood rafters and the air. Another involved opening the top of the channels near the roof peak and a final one involved using ducting to distribute the air along the length of the roof with open wooden channels along the top and bottom. The later configuration worked best as the other two created problems with passive cooling where no fans were operating. Each approach was tested and operated over a series of days in April of 2008 in which IR images and system performance test data were obtained.

We also installed a ducting system with increased wood latent capacitance as shown in Figure 13. Maximum EERs for this new mode ranged between 60-120 Btu/Wh (COP = 18-35) in April and early May 2008 – considerably better than that previously obtained. Figure 14 shows the image of the roof heat distribution as improved by the new configuration.

Figure 13. Ducted distribution of interior air to roof for cooling with added wood surfaces for latent storage.

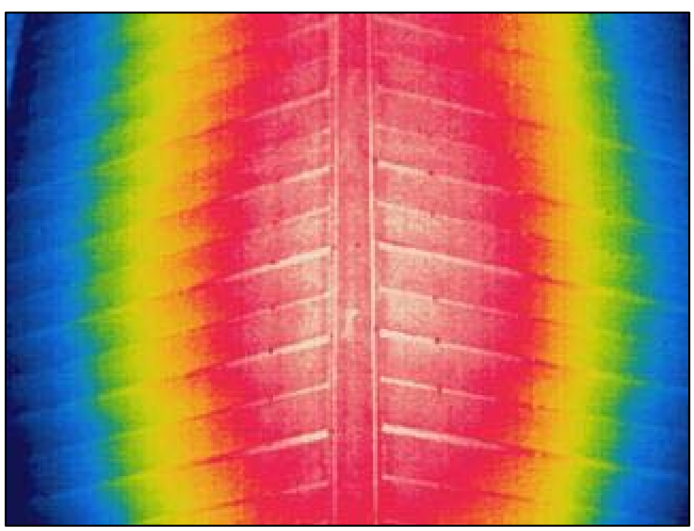

Figure 14. Image of the *NightCool* roof in operation with improved air distribution system and more even distribution of heat for radiation.

Identical Roof Reflectance for 2008 Monitoring Season

During early testing control test building had a brown shingle roof solar reflectance of about 8% compared with the 65% reflectance of the *NightCool* roof. Thus, the white roof is likely responsible for a portion of the savings seen from the *NightCool* experiment.

As there was uncertainty about which fraction of the *NightCool* savings is due to night time cooling and which is due to the white metal roof (resulting in lower attic temperatures during daytime), the control building's roof received the same white metal roof as the experiment in May 2008 (as shown in Figure 15).

Figure 15. Change of control building to a white metal roof in early May of 2008

Theoretical calculations assuming white roofs on both buildings and the disadvantageous depressurizing configuration of last year resulted in about 10% savings, compared to 15% measured in 2007. However, by continuing our measurements for another year into the future, we were able to evaluate the specific savings after both roofs were a reflective white metal.

Table 2 shows the measured performance from April – November of 2008 with identical white roofs in place. Note that the average savings showed a 12.3% reduction to cooling. Although lower due to the white roof maintained in the control, we also showed that the improved distribution configuration installed in April 2008 provided better nocturnal cooling reductions which is likely why savings were slightly higher than expected even after both building had a white roof.

Table 2. *NightCool* Performance 2008

	April	May*	June	July**	August	September	October	November
Power & Efficiency								
Experiment AC (kWh)	0.499	59.995	81.418	76.774	84.156	89.948	44.467	4.906
Experiment Fans (kWh)	0.037	3.678	3.582	4.191	2.206	2.362	2.673	0.477
Control AC (kWh)	0.579	78.564	101.460	91.264	92.783	101.894	53.217	5.809
Experiment Lights (kWh)	80.79	77.616	77.159	77.273	77.581	79.928	82.482	78.794
Control Lights (kWh)	80.67	77.829	76.627	81.972	76.392	75.578	82.099	79.108
EER (Btu/Wh)	48.5	42.2	30.7	31.2	28.3	35.1	40.4	35.8
RTF (run-time-fraction)	0.128	0.270	0.262	0.292	0.164	0.169	0.184	0.034
ΔT (°F) (T_{return} - T_{supply})	4.13	4.75	3.52	3.62	3.26	4.01	4.52	3.95
Percent *NightCool* Savings	7.5%	19.0%	16.2%	11.3%	6.9%	9.4%	11.4%	7.3%
Building Conditions								
Experiment Attic Temp. (°F)	77.3	80.5	84.0	83.3	83.6	83.1	75.6	64.2
Control Attic Temp (°F)	83.8	82.2	84.1	83.7	84.4	84.2	76.5	65.8
Experiment Room Temp. (°F)	78.7	78.8	79.4	79.3	79.2	79.2	78.4	74.9
Control Attic Temp. (°F)	78.6	78.2	78.8	78.8	78.7	78.7	78.3	74.7
Experiment Room RH (%)	59.5	43.0	41.1	43.1	42.9	41.2	41.2	44.6
Control Room RH (%)	62.4	42.2	41.5	41.9	44.2	43.0	43.4	56.2
Weather Conditions								
Ambient Temp. (°F)	72.3	77.1	79.4	79.1	80.7	80.3	73.9	63.3
Ambient RH (%)	85.4	67.5	77.3	81.1	80.3	77.8	72.0	75.3
Solar Dewpoint (°F)	190.3	242.9	235.8	206.1	184.9	194.7	167.6	146.9
Sky Temp. (°F)	64.7	60.4	67.2	69.3	71.3	68.6	57.6	42.4

* Control roof changed to white metal as with the experiment
** Exterior walls of both buildings changed from tan to white

Evaluation of the Impact of Increasing Wall Reflectance

In an effort to obtain maximum experimental value from the *NightCool* facilities, we decided to nest another experiment into the 2008 schedule to examine how increased wall reflectivity could influence cooling energy use. This was done by equally treating both the experimental and control buildings at the same time so that the interaction with the nocturnal cooling system was unaffected.

In research spanning two decades, reflective roofs have been demonstrably shown to reduce cooling. Generally, we have found available cooling energy savings from white reflective roofing in residential buildings on the order of 20% vs. darker, less reflective colors.

Energy simulations like DOE 2.1E within *EnergyGauge USA* often shows a 5-15% reduction in space cooling from making walls more reflective in hot climates -- particularly if they are less insulated, or larger in area and less shaded as with two-story buildings. However, there have been very few experiments where this obvious influence has been measured.

We used the availability of the *NightCool* experimental buildings as a ready means to quantify the impact. After the roofs of both the experiment and control building had been changed to white metal in early June 2008, we decided to paint the walls white in mid July, split the summer season and examine how air conditioning changed from the pre to post period from altering wall reflectance.

The measured temperature inside the 200 square feet control building was maintained at 78.0˚F (±0.5˚) throughout the entire summer. Internal gains, simulating occupancy, including moisture generation was also kept constant. The walls of the *NightCool* control building is frame construction (16" on-center) with R-13 fiberglass cavity insulation with R-6 sheathing on the exterior and covered by lapped primed beige-colored *Hardiboard* siding. The gross wall areas over the conditioned section of the test building was 1536 square feet. Subtracting out the glazed areas, the net wall area is 1507 square feet. The impact of solar gain is graphically indicted in Figure 16 which shows an IR image of the *NightCool* test buildings with heat build-up on the exterior facing east walls during morning hours.

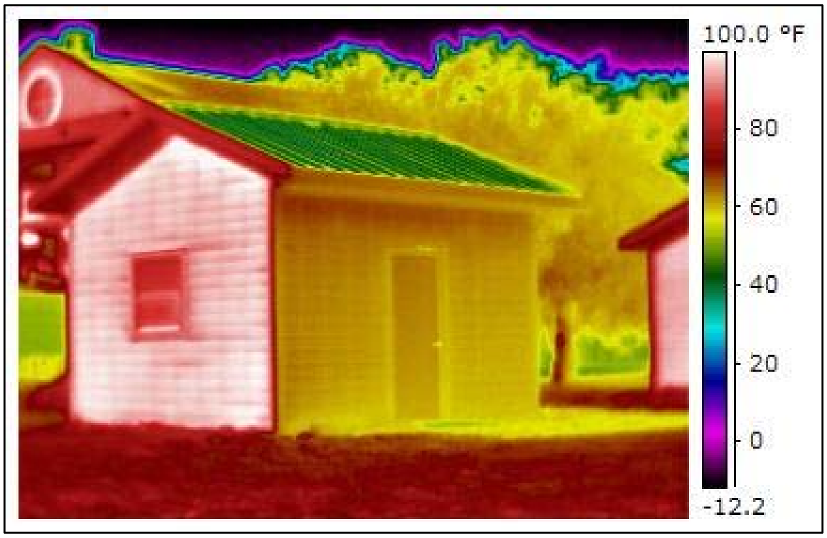

Figure 16. Infrared images of heat being absorbed on the east side of the Experimental *NightCool* building.

On July 8th, 2008 the walls were painted white using two coats of *Sherwin Williams* flat white paint (*Luxon: Extra White, A24 W351*; see Figure 17). Both buildings' walls were painted white, but here we concentrate on data for the control building since we were adjusting the NightCool nocturnal cooling system during the monitoring period to obtain more favorable results.

To obtain the pre and post wall reflectances, we set off samples of the painted and unpainted siding to *Atlas Material Testing Services.* A swatch of the unprimed Hardiboard siding had a tested solar reflectance of 53%. The priming and samples painted similar to the buildings had a tested solar reflectance of 72%. Thus, with painting the wall solar reflectance was increased by 19%.

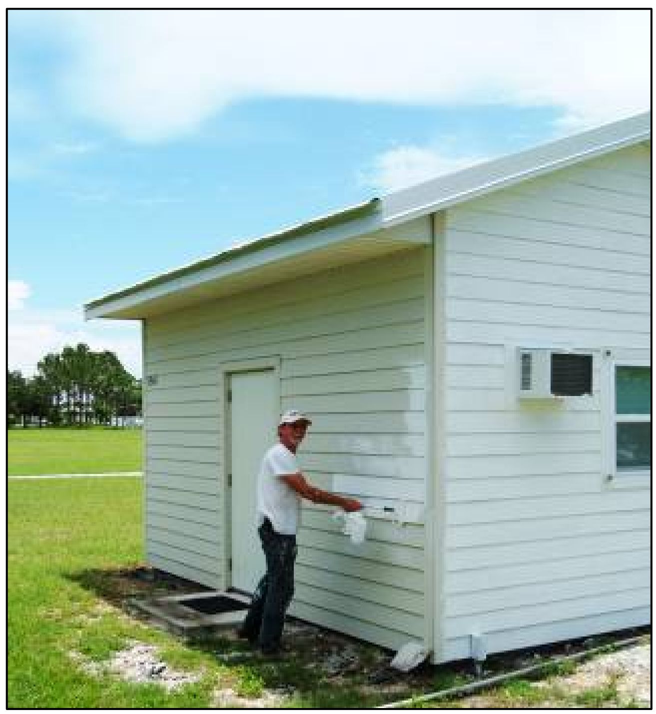

Figure 17. Walls of each building are painted on 8 July 2008.

We continued to collect data on the cooling energy use of the Control building over the entire remainder of the summer. Figure 18 shows our analysis results. Graphing the daily kWh/day for cooling against the measured interior to exterior daily temperature showed the expected behavior -- increasing as the average outdoor temperature climbs. Within the data, we plotted the data before the walls were made white as red circles. The period after the walls were painted white is shown as green triangles. The cooling energy reduction from the more reflective walls is obvious in even a cursory review of the data. However, to quantify impacts, we composed a regression line through the two data periods. This shows that the daily kWh for cooling varied as follows:

Tan colored unpainted walls:

$kWh = 2.952 + 0.280(DT)\ R^2 = 0.861$

White colored walls:

$kWh = 2.582 + 0.261(DT)\ R^2 = 0.874$

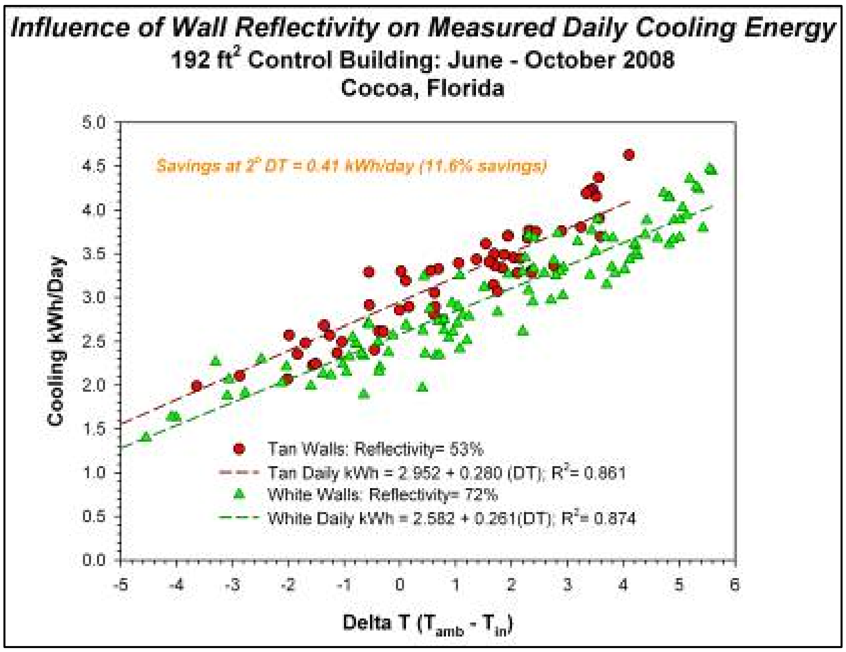

Figure 18. Measured daily cooling energy savings from increasing wall reflectivity.

The relationship shows that the change was only loosely associated with the daily temperature difference, with most of the effect showing up in the intercept term. This is not surprising as the more reflective walls will interact most with solar radiation. Evaluating the relationship at a 2°F outdoor to indoor temperature difference shows a 0.41 kWh/day difference – about a 11-12% savings. This is very similar to that expected from simulation analysis using *EGUSA*, particularly when one assumes that the wall framing fraction is greater in a smaller building.

However, given the fact that the solar insolation varied between the pre and post period it was necessary to do further analysis to evaluate this influence. The solar horizontal irradiance was 224 W/m² over the pre-period and 188 W/m² over the post period. Given that difference, we re-ran the regressions with daily average solar irradiance as a term to correct for solar that variation in the pre/post period.

Regression Analysis

```
. reg cacpwr cDT solari if wallwht==0

      Source |       SS       df       MS              Number of obs =      60
-------------+------------------------------           F(  2,    57) =  213.24
       Model |  23.4671642     2  11.7335821           Prob > F      =  0.0000
    Residual |  3.13640237    57  .055024603           R-squared     =  0.8821
-------------+------------------------------           Adj R-squared =  0.8780
       Total |  26.6035666    59  .450907908           Root MSE      =  .23457
------------------------------------------------------------------------------
      cacpwr |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         cDT |   .2646276   .0144959    18.26   0.000        .2356    .2936551
      solari |   .0016805    .000524     3.21   0.002     .0006313    .0027297
       _cons |   2.572886   .1223351    21.03   0.000     2.327915    2.817858
------------------------------------------------------------------------------

. reg cacpwr cDT solari if wallwht==1

      Source |       SS       df       MS              Number of obs =     105
-------------+------------------------------           F(  2,   102) =  428.77
       Model |   50.148988     2   25.074494           Prob > F      =  0.0000
    Residual |   5.9649151   102   .05847956           R-squared     =  0.8937
-------------+------------------------------           Adj R-squared =  0.8916
       Total |  56.1139031   104  .53955676            Root MSE      =  .24183
------------------------------------------------------------------------------
      cacpwr |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         cDT |   .2403982   .0101873    23.60   0.000     .2201917    .2606047
      solari |    .001968    .000455     4.33   0.000     .0010654    .0028705
       _cons |   2.247493   .0822252    27.33   0.000       2.0844    2.410586
------------------------------------------------------------------------------
```

The average values for cDT (indoor to outdoor temperature difference) was about 1.3^{o}F over the period. The average hourly horizontal irradiance (solari) was 203 W/m^2. Evaluating both regressions given these terms gives the following for the control AC kWh.

Pre-period (tan walls) = 3.25 kWh/day
Post period (white walls) = 2.96 kWh/day

The indicated difference after controlling for the varying sun conditions over the period was 8.9% vs. the 11.6% previously shown without normalizing. The simulation (9% indicated savings) and the experiment agree exactly -- likely a coincidental result, but one that increased confidence in the model.

Not surprisingly, there appears a strong collinearity between the solar irradiance and dT terms. Although not shown, we entered an interacted term (cDT * solari) in a regression and get a much higher value for the interacted term for the darker walls. The physical interpretation is that when the outdoor temperature is high the solar absorptance is much more important to cooling than when the outdoor temperature may be lower than the interior set point. This seems logical since much more of the collected radiation on the wall will flow inward with higher ambient air temperatures than those on the interior.

A key conclusion from the wall reflectance experiment is that simply changing wall reflectance by 19% was shown to produce a 9% reduction in cooling in the test building.

Future Development

When mated with metal roof Building Integrated Photovoltaics (BIPV), the *NightCool* concept shows potential to achieve an integrated roof system providing electric power, as well as supplemental heating and cooling. Conceptually, within this further development of the concept, thin film PV is adhered to metal roofing which then generates electric power. Such systems have been extensively tested by the Florida Solar Energy Center and others.

One disadvantage with most conventional BIPV systems is that when installed on decking, it operates at higher temperatures and thus suffers losses in solar to electrical conversion efficiency (Davis, Fanney and Dougherty, 2001). Typically this represents 5-6% losses relative to bracket-mounted stand-off arrays, depending on module temperature response characteristics. With implementation of BIPV with *NightCool*, the underside of the roofing system would be metal on battens so that BIPV operating temperatures would be beneficially reduced. The transferred heat to the attic would then be removed by daytime powered ventilation from the gable roof ends by small dedicated DC roof fans, whose current task is restricted to remove humidity desorbed by desiccant materials in the attic. Another advantage could be that with the darker roof system the effectiveness of the solar dehumidification system will even be improved similar to that achieved by Areemit and Sakamoto (2005).

During mild winter mornings and afternoons, however, collected heat from the darker BIPV could be conveyed by fans as useful heat to the interior space to offset a portion of space heating needs. During summertime periods, daytime heat would be removed by ventilating the attic to improve BIPV operating efficiency and lower ceiling cooling loads. At night, the *NightCool* system would operate conventionally to reduce cooling needs. This would result in a highly desirable building integrated solar power system that would also provide supplemental space cooling and heating (U.S. DOE, 2006).

NightCool takes ducts being in the conditioned space for granted to minimize losses. In evaluating *NichtCool* with real full scale home designs it becomes apparent that configuration of the system would implement most smoothly when combined with ductless mini-splits air conditioner or heat pumps used for auxiliary cooling.

Conclusions

This report describes the experimentally tested potential of a novel residential night cooling concept. *NightCool* uses a home's metal roof under a sealed attic as a large radiator to the night sky to provide effective nocturnal cooling. Measured cooling energy savings between the control and *NightCool* building averaged 15% over the eight month test period-- somewhat lower than the previous simulation analysis. Several measures have been taken recently to get a closer match between the theoretical and practical outcome of the *NightCool* concept. In 2008, the brown shingle roof of the control building was altered to a white reflective roof identical with that of the experimental building. While this could be expected to reduce savings, improvements were made to the distribution system such that a 12% cooling energy reduction was achieved in the cooling season of 2008 with identical roofs. System equivalent Energy Efficiency Ratios (EERs) typically exceeded 30 Btu/Wh during operation. It is noteworthy, the level of performance reported here considerably exceeds the performance of any available air source equipment.

Also, an integrated enthalpy-based ventilation system in the attic with solar drying of low-temperature regenerated desiccants resulted in a significant reduction in interior relative humidity during a period of minimal space conditioning where many buildings in Florida experience moisture problems. Notably, with the new system in the second season the Nightcool building had significantly lower humidity during periods of low space conditioning, such as in April and November in Central Florida.

The favorable experimental data collected indicate that *NightCool* can be a promising system technology for very low energy homes. It also appears possible to mate the concept with Building Integrated Photovoltaics (BIPV) to provide combined solar electric power, nighttime cooling and winter afternoon heating. A priority for any future experimentation would be to examine realistic performance in more moderate and drier climates with the objective of completely eliminating the vapor compression cooling system. Further steps for minimizing heat gains to the interior and clipping daytime temperature peaks will be analyzed to examine the potential to entirely eliminate the conventional air conditioner in appropriate climates. Combining *NightCool* with ductless mini-split heat pumps appear to be the best system for full scale implementation of the concept.

Acknowledgment

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Appendix:

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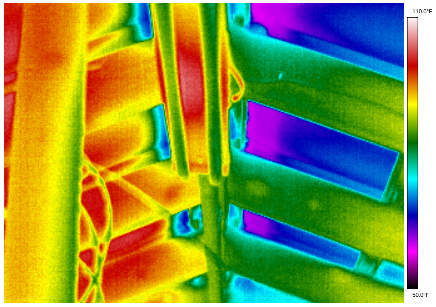

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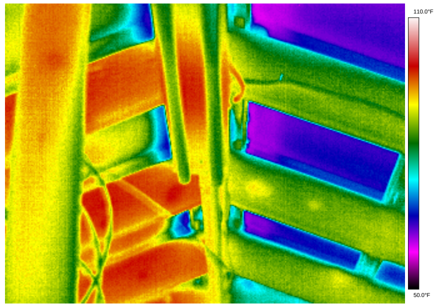

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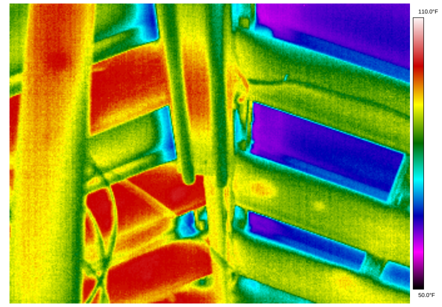

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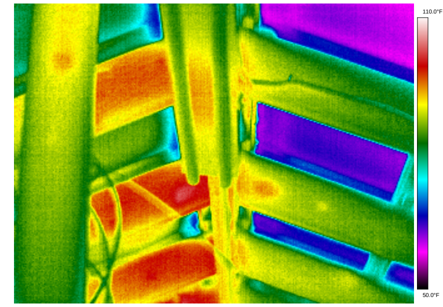

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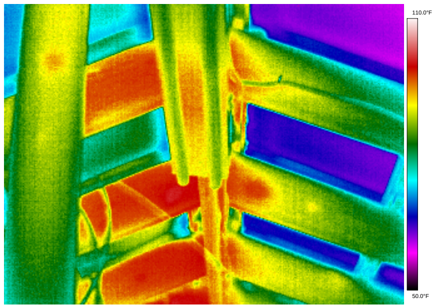

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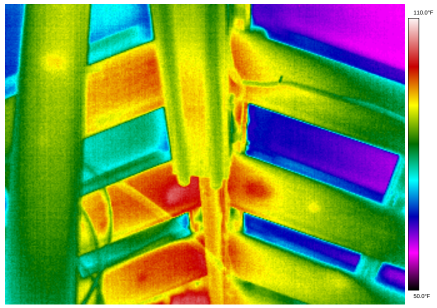

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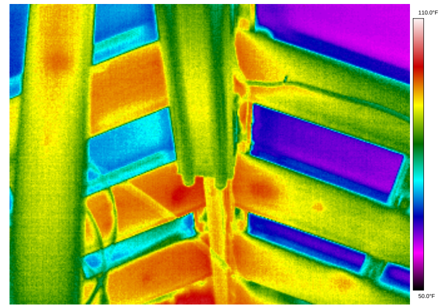

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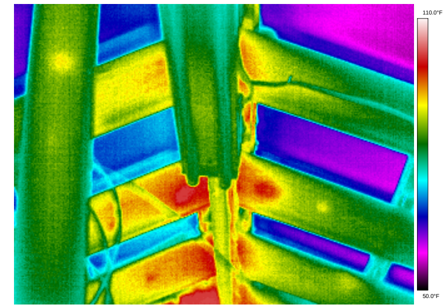

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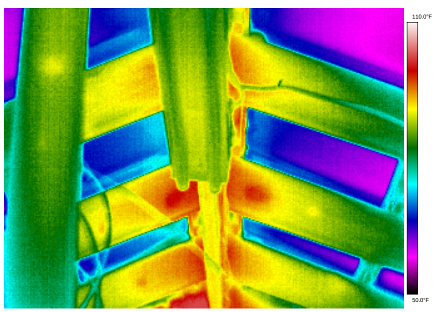

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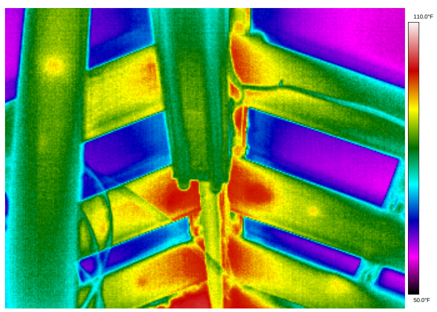

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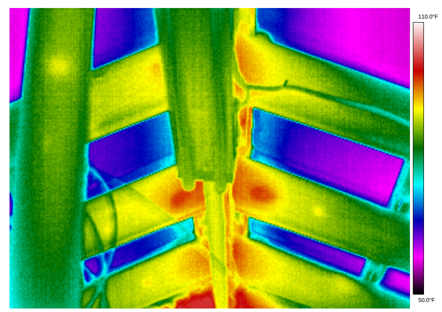

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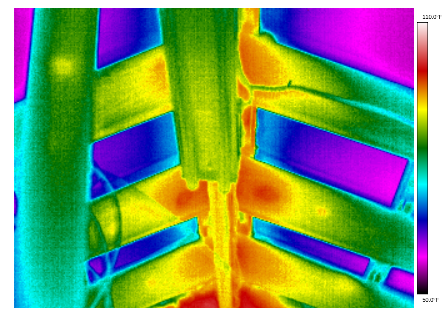

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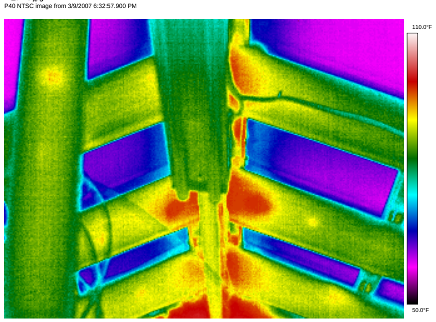

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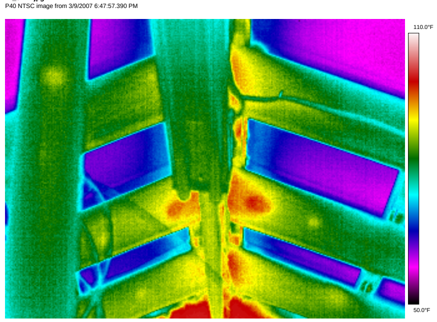

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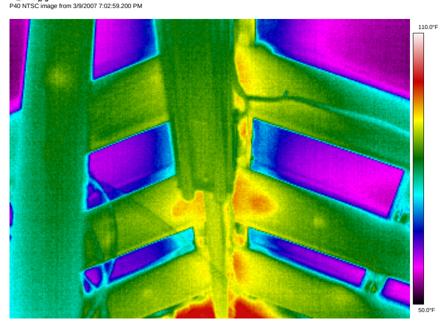

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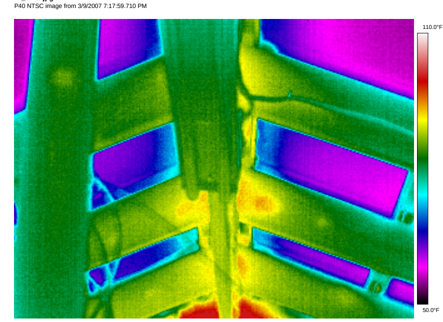

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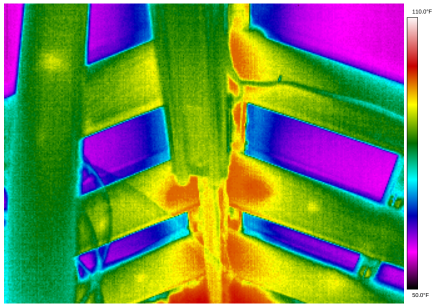

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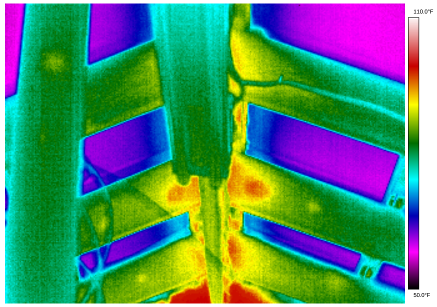

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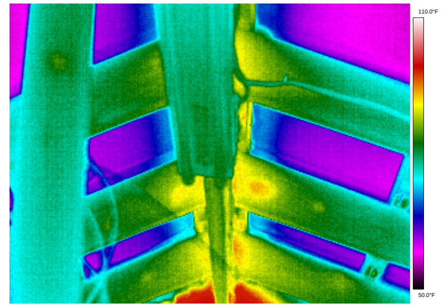

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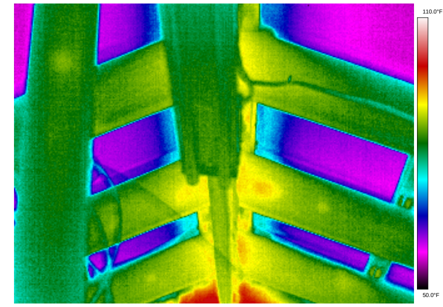

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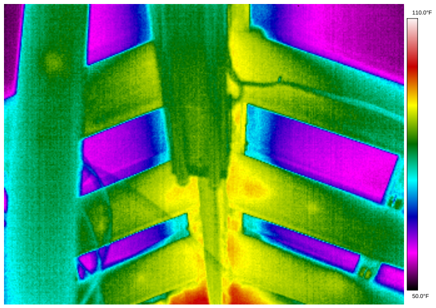

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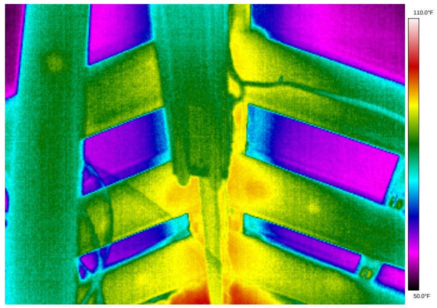

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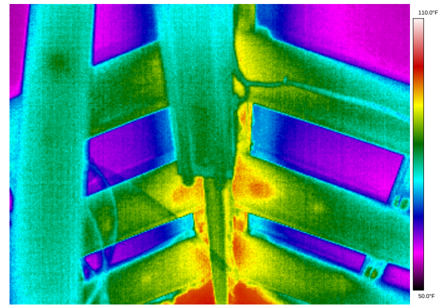

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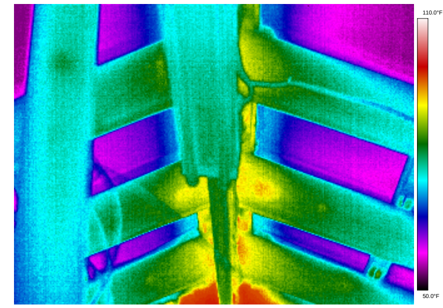

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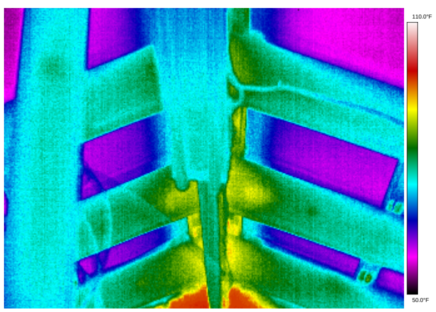

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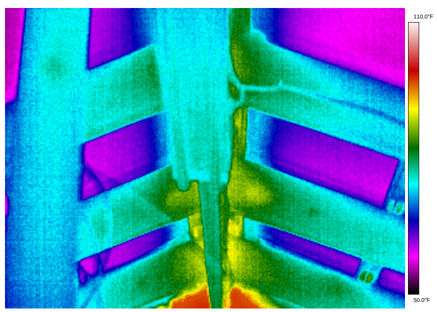

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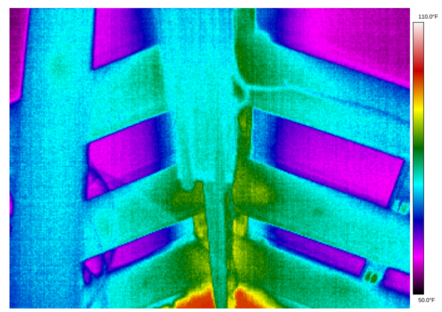

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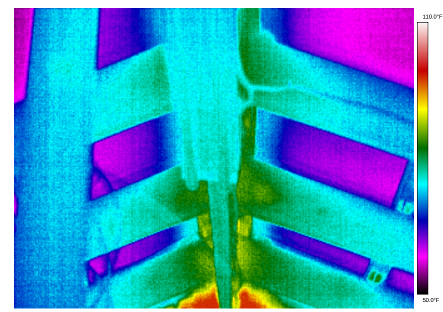

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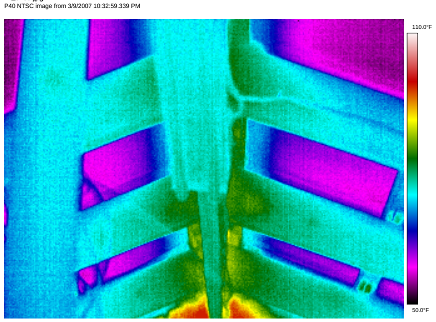

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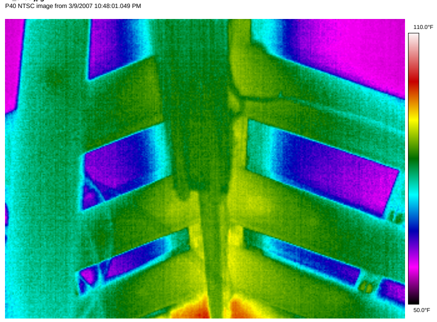

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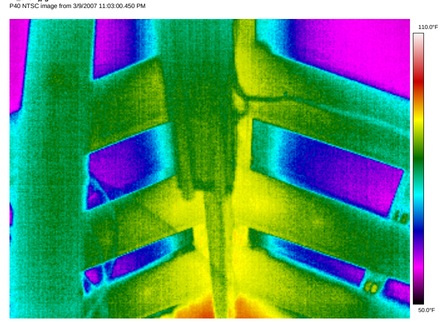

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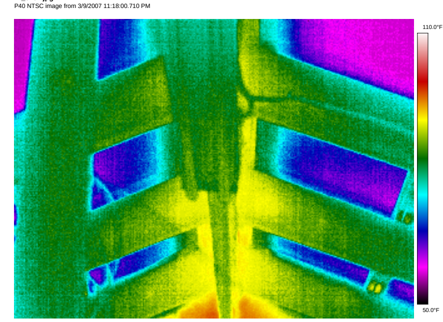

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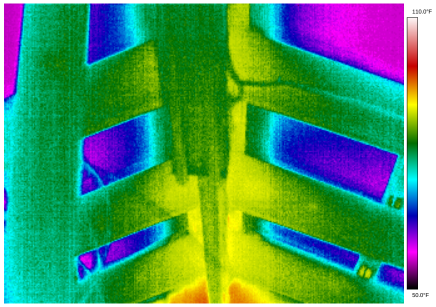

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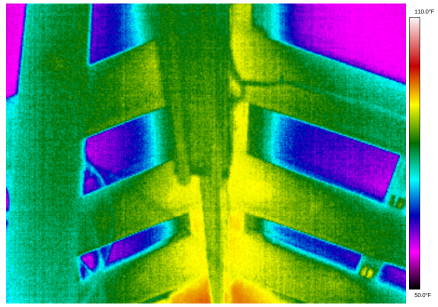

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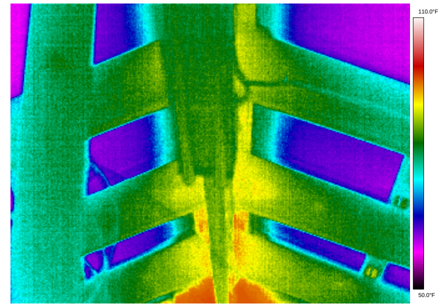

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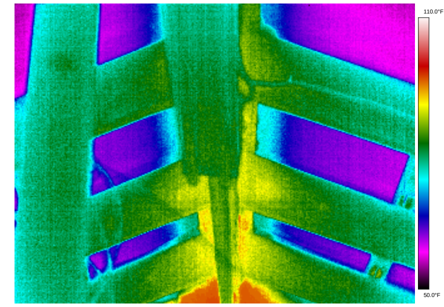

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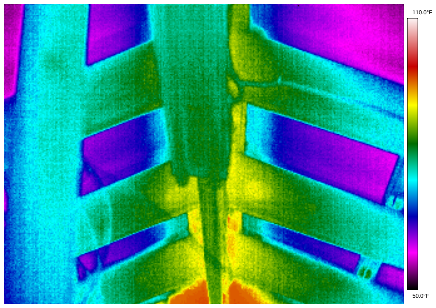

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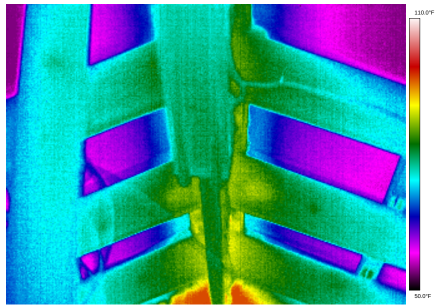

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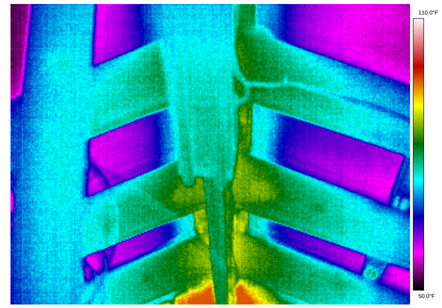

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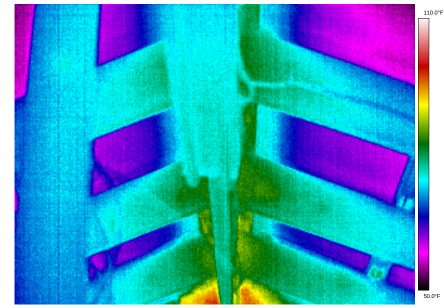

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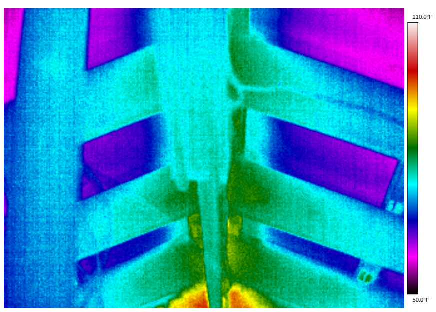

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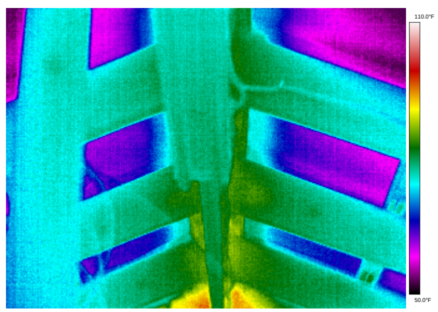

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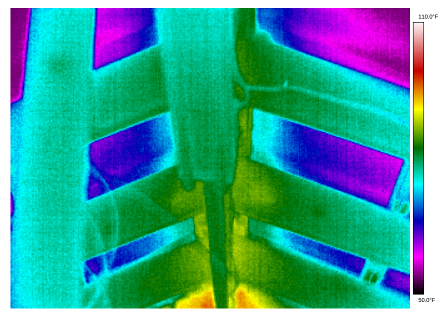

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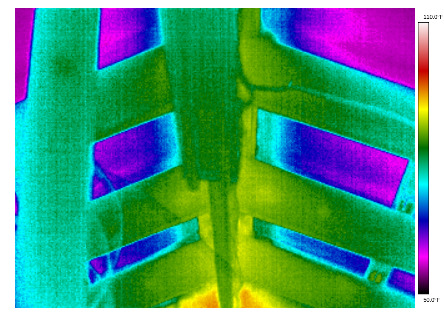

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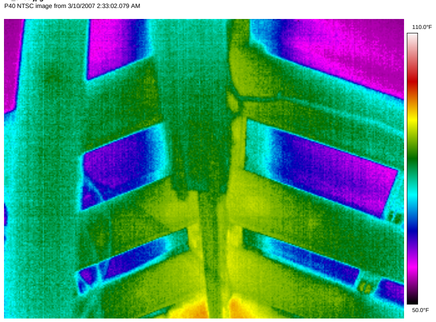

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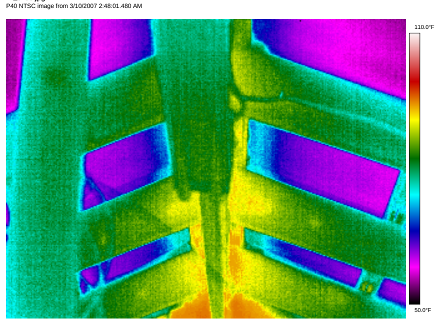

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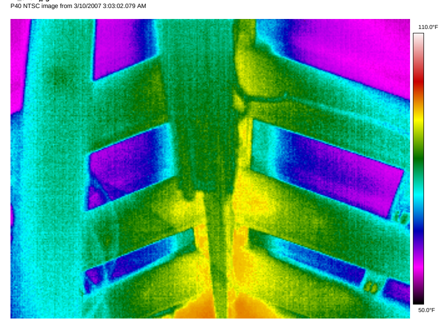

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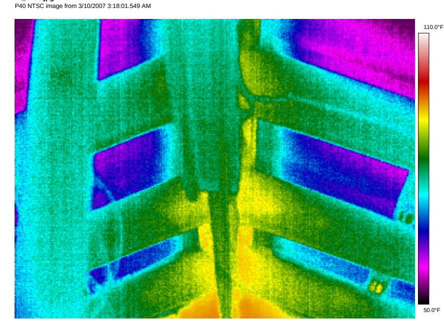

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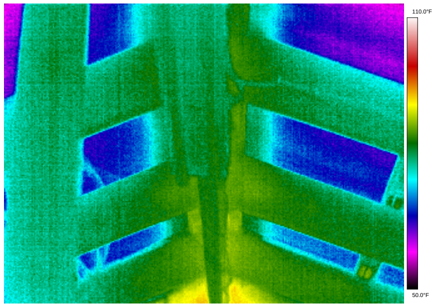

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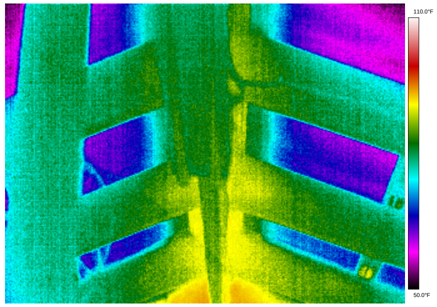

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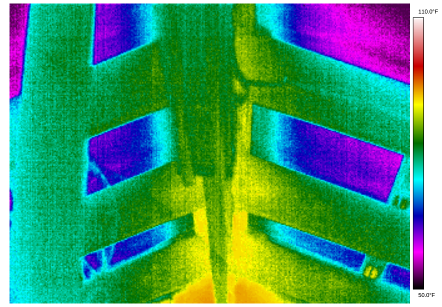

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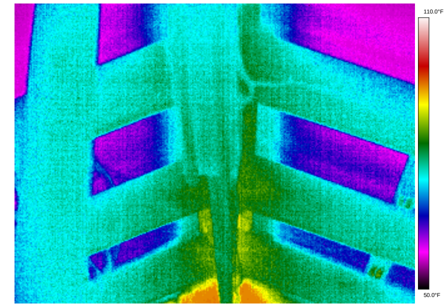

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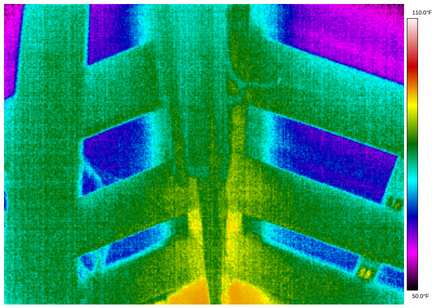

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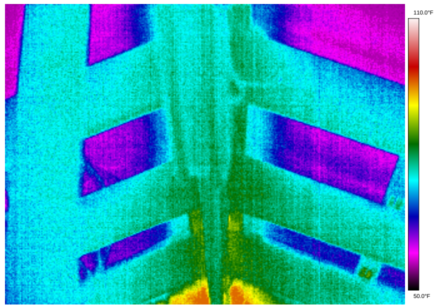

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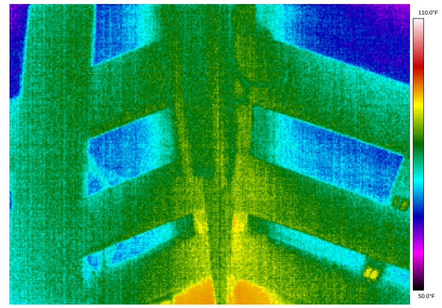

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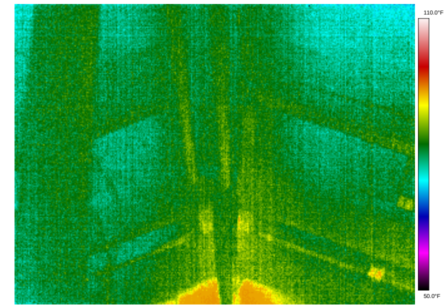

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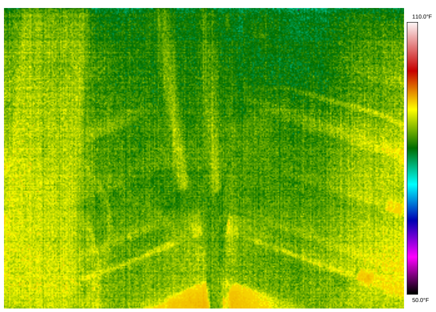

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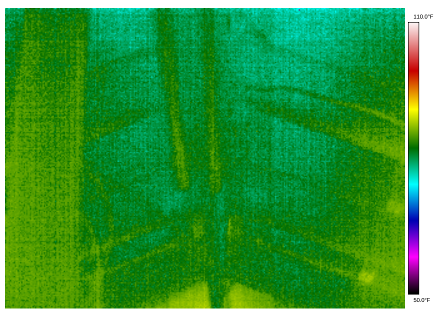

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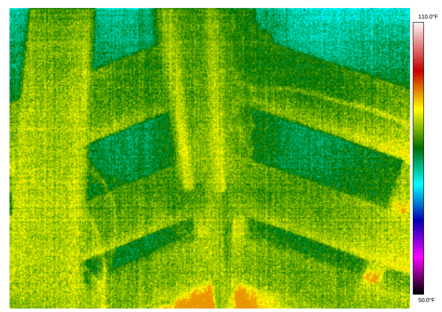

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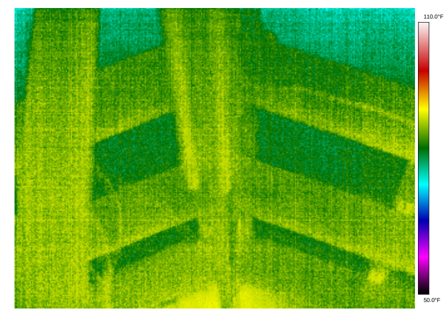

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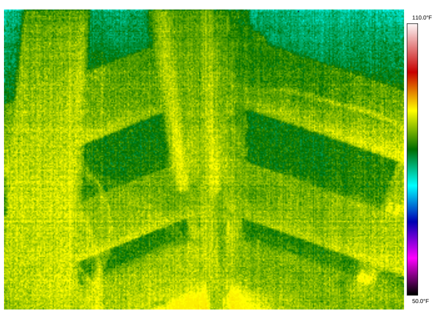

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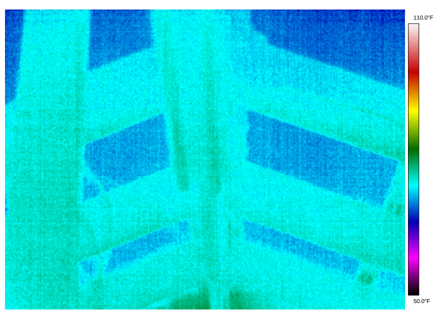

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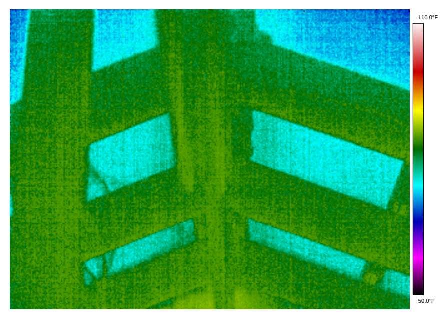

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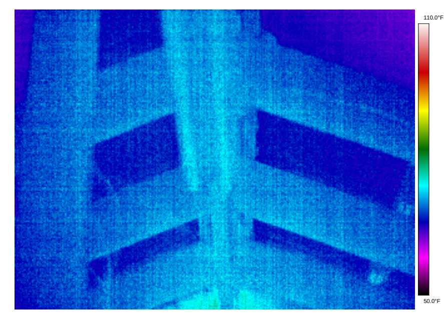

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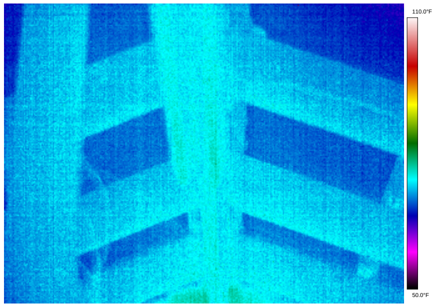

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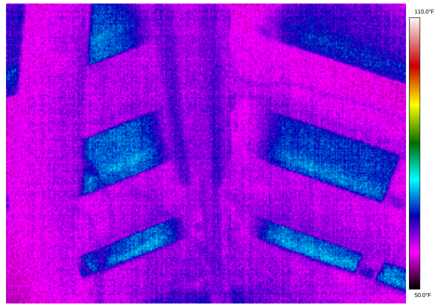

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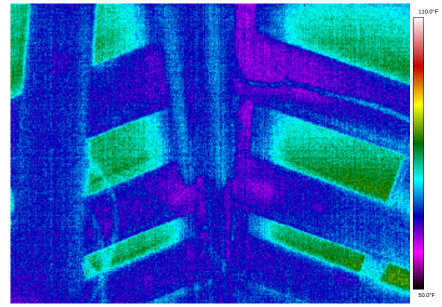

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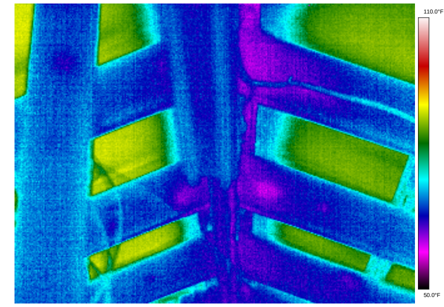

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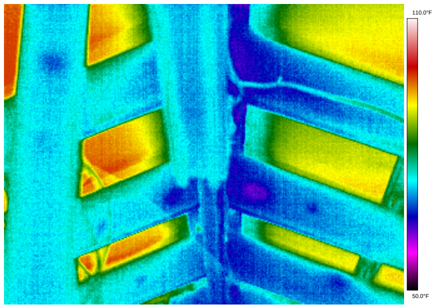

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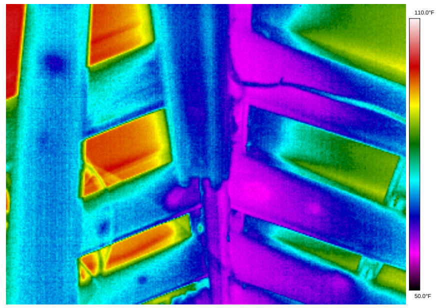

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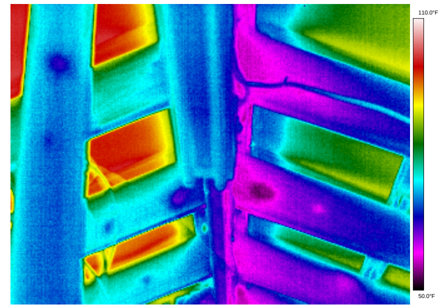

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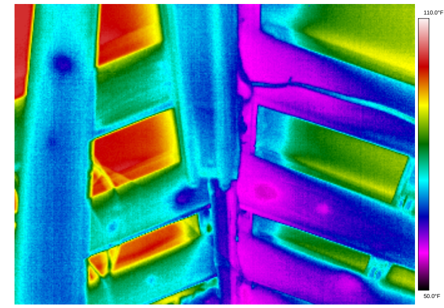

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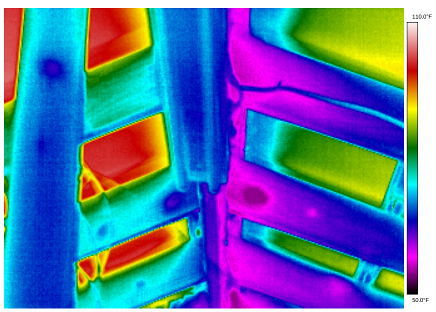

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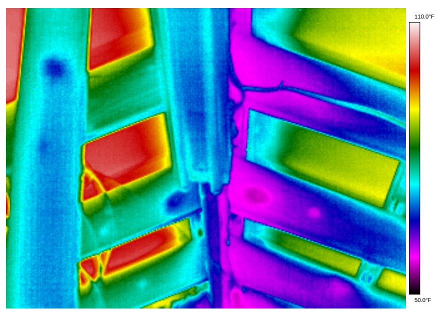

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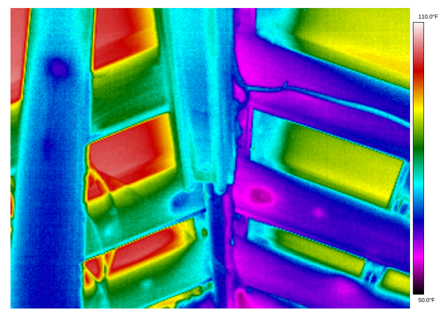

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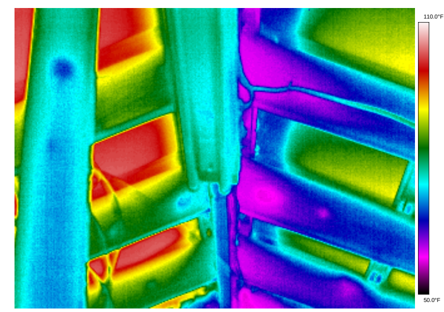

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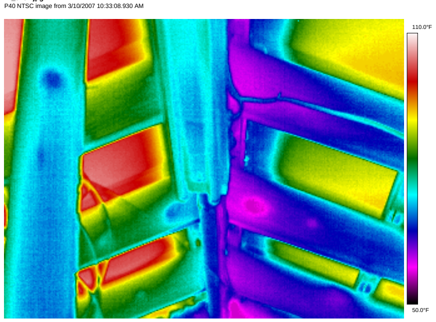

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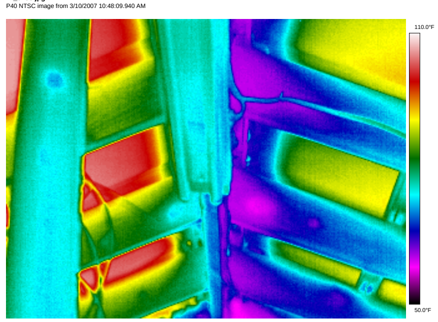

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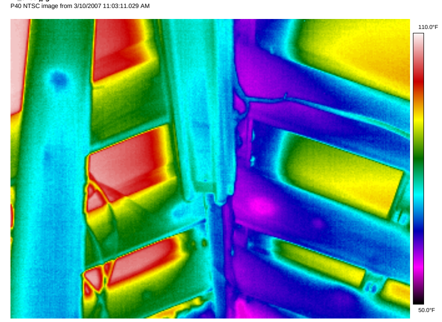

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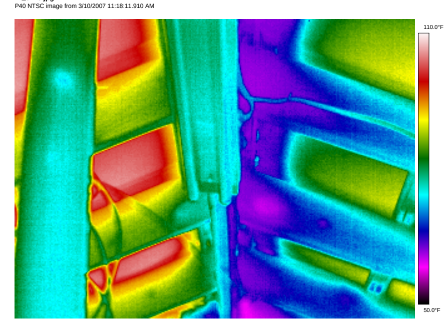

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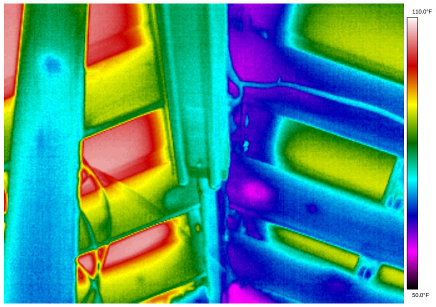

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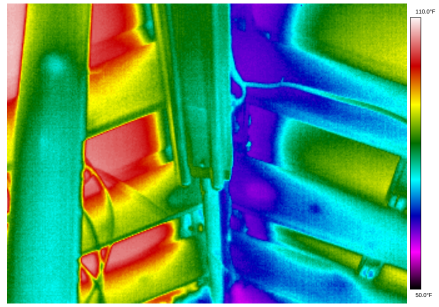

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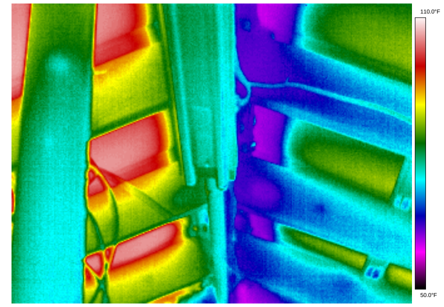

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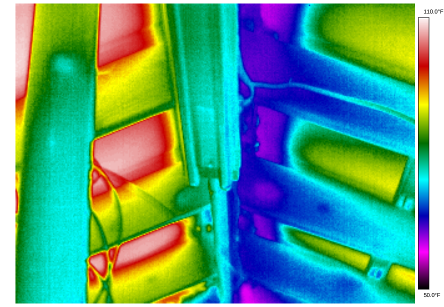

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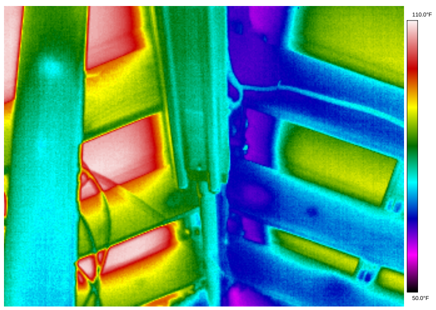

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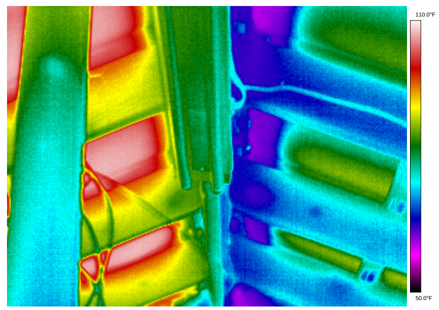

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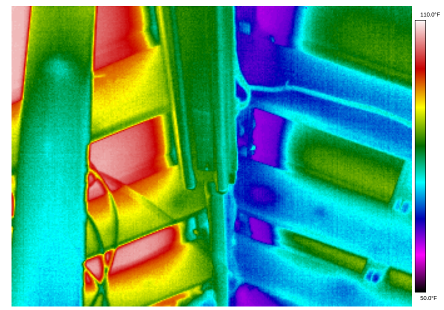

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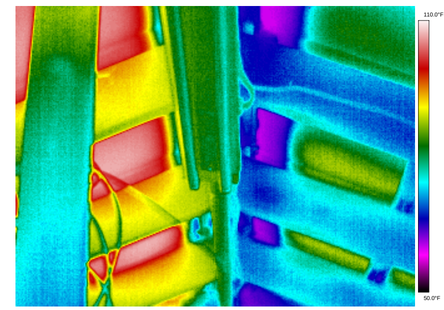

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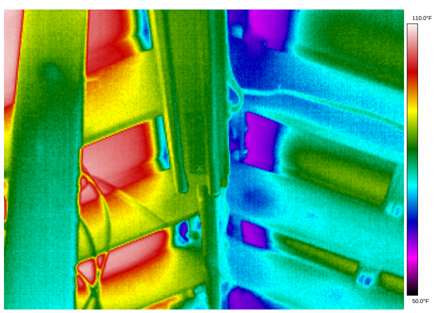

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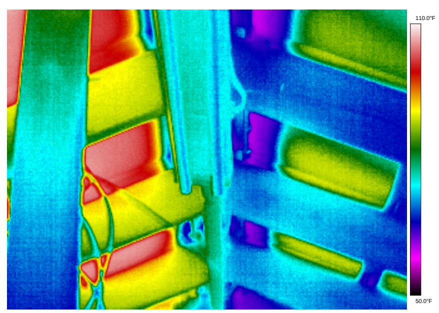

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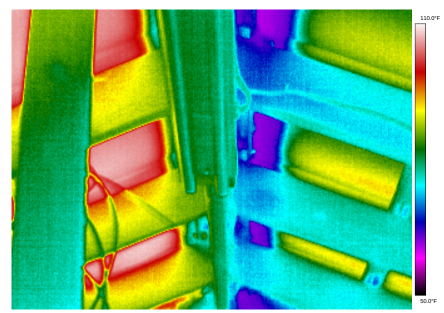

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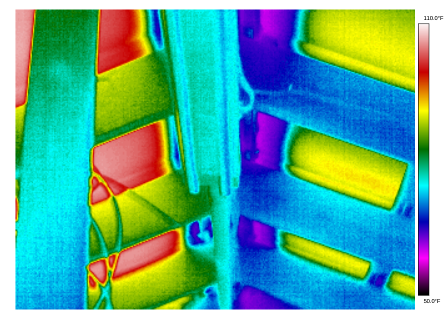

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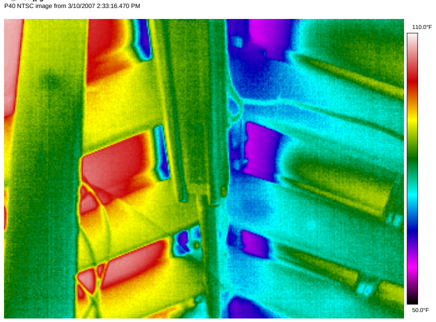

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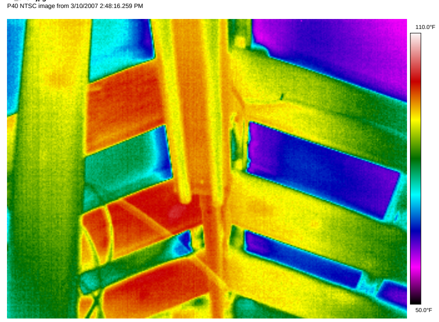

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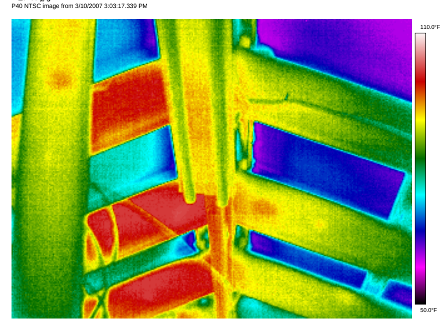

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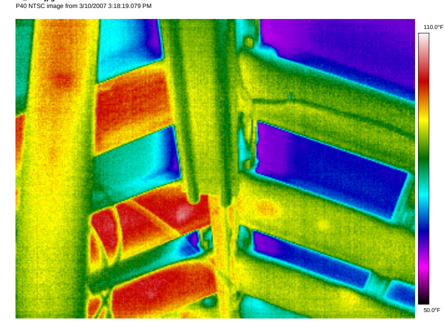

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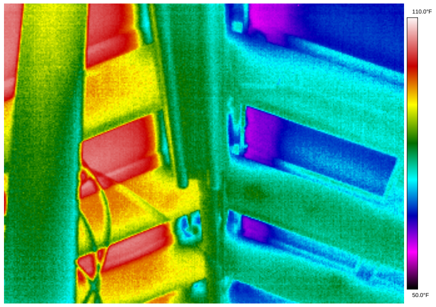

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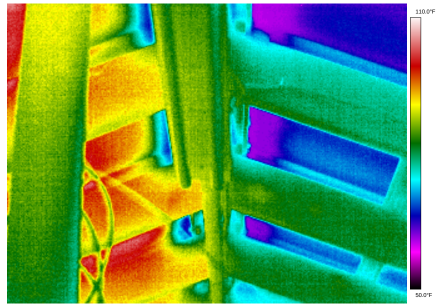

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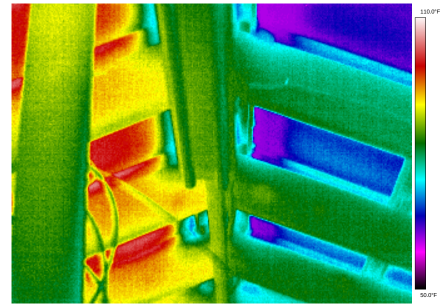

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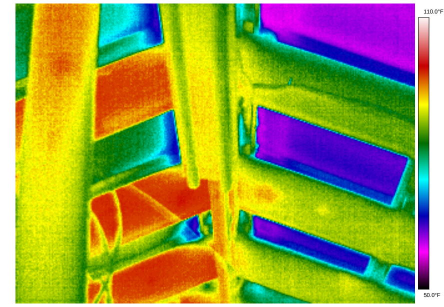

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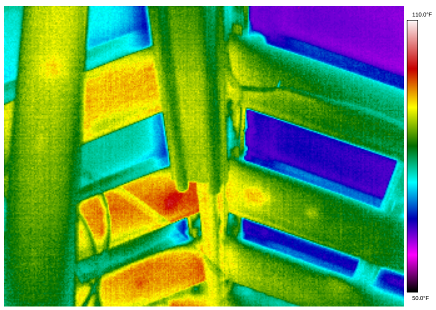

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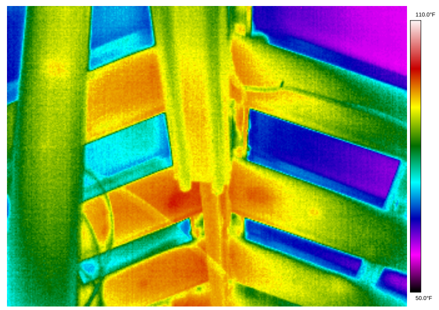

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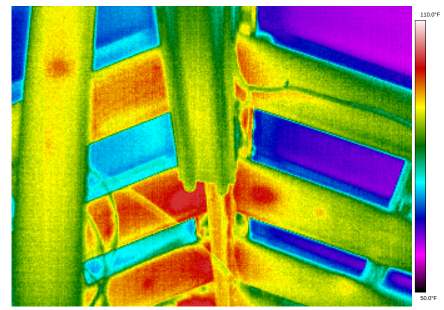

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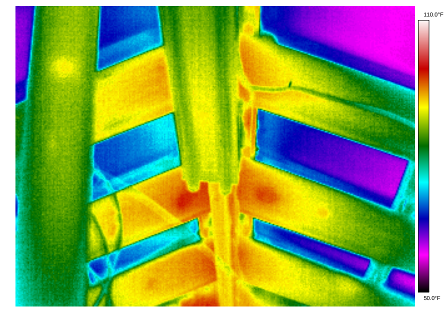

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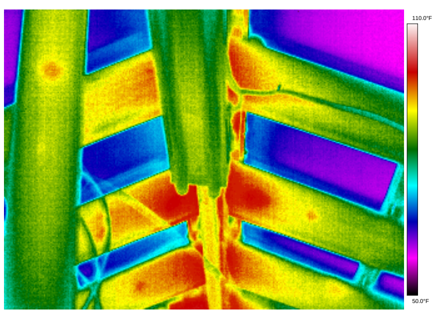

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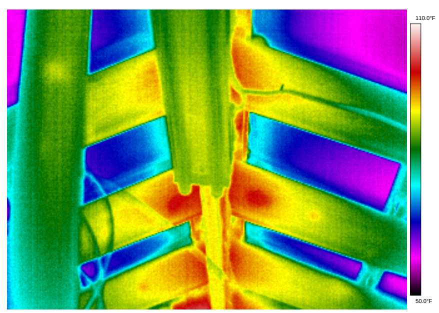

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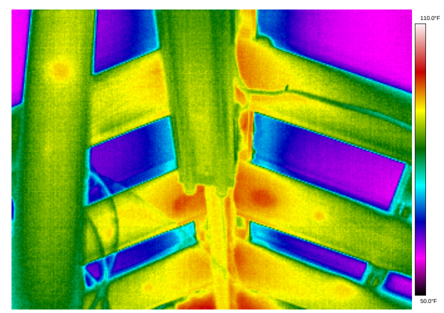

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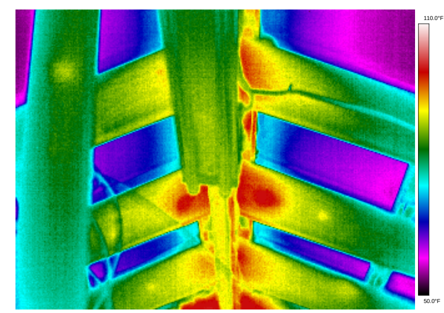

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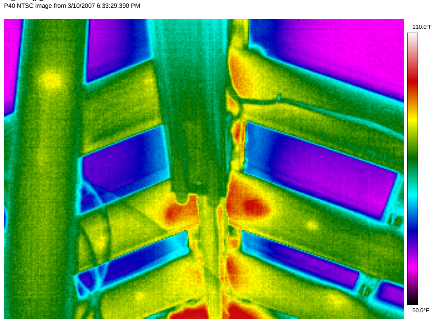

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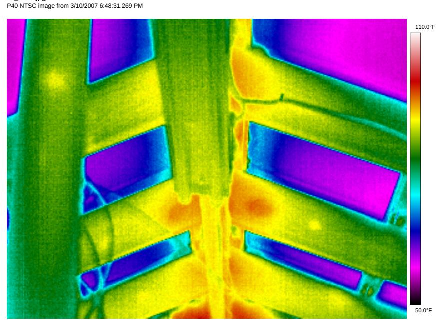

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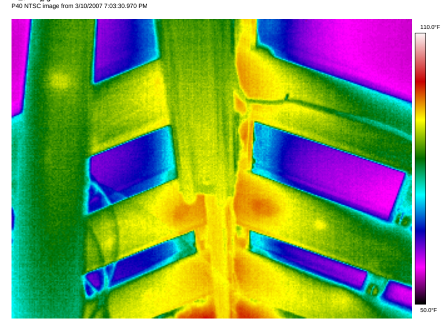

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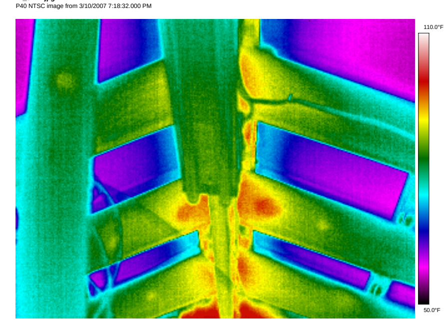

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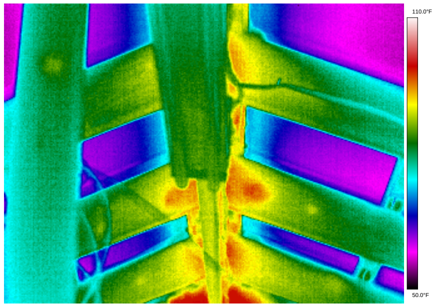

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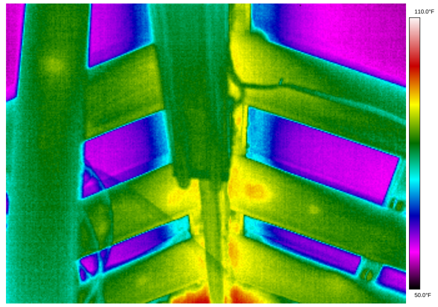

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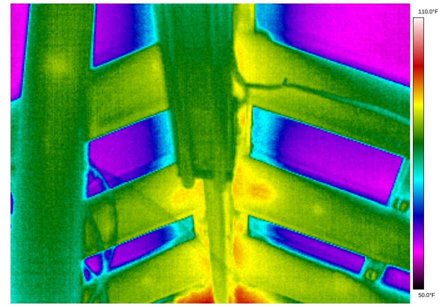

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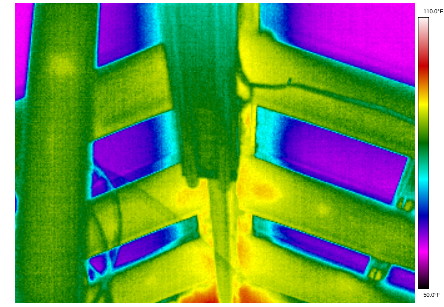

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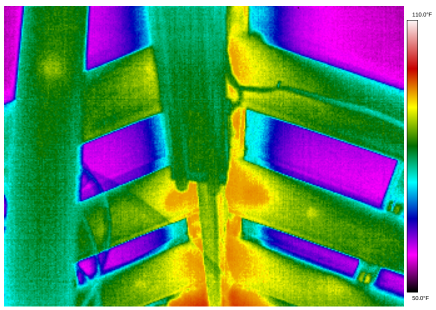

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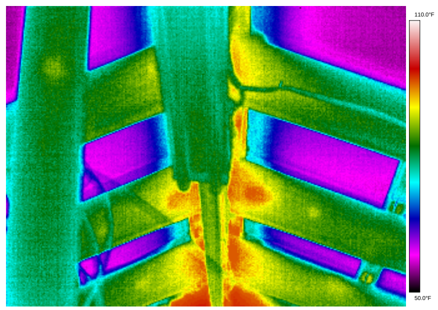

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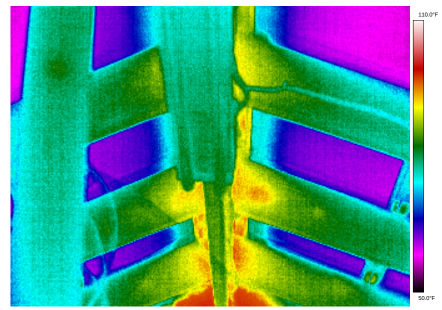

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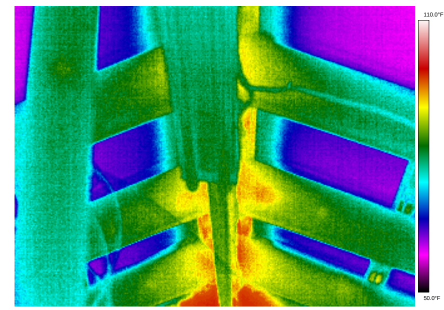

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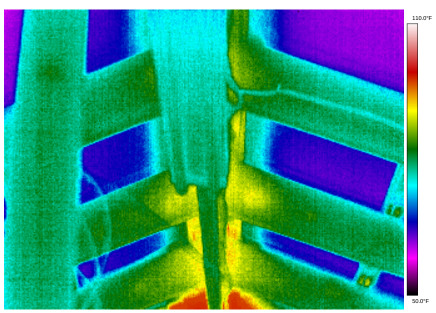

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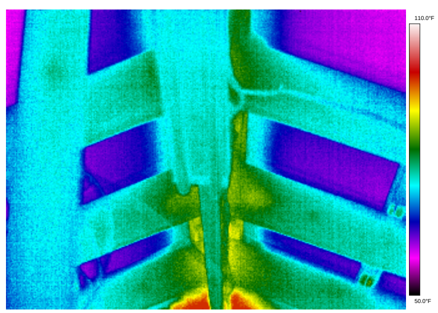

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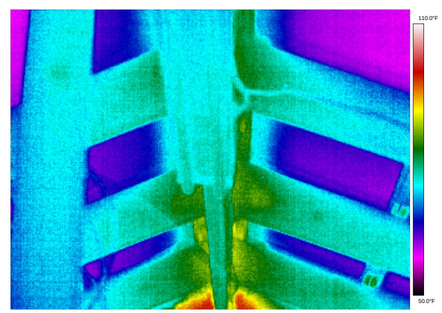

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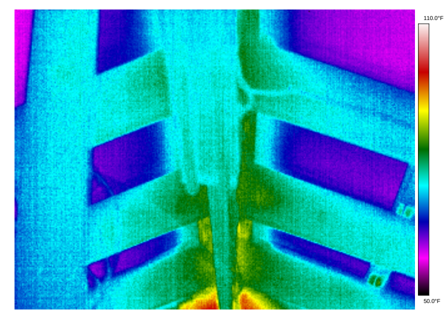

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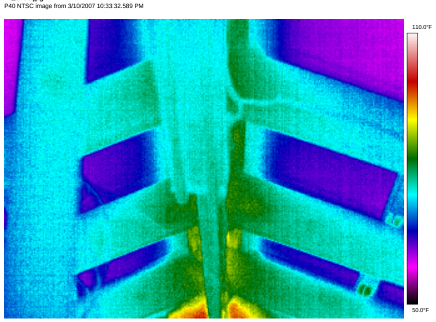

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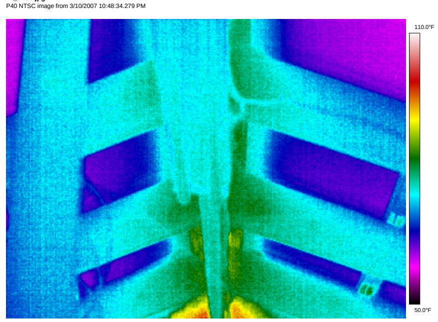

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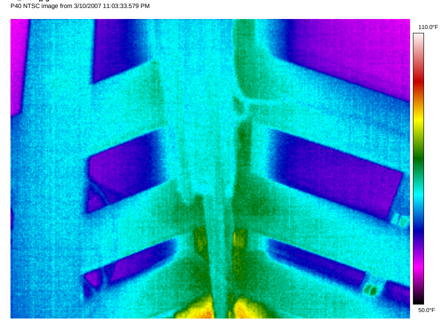

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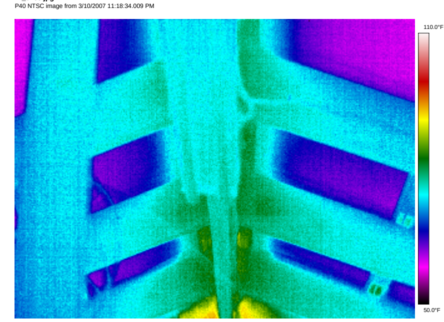

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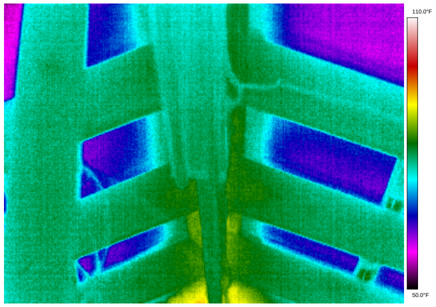

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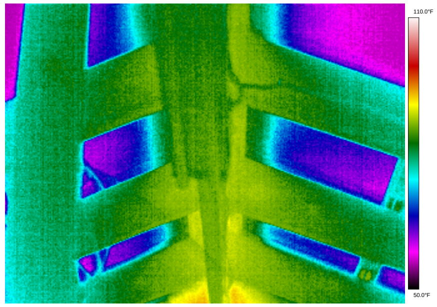

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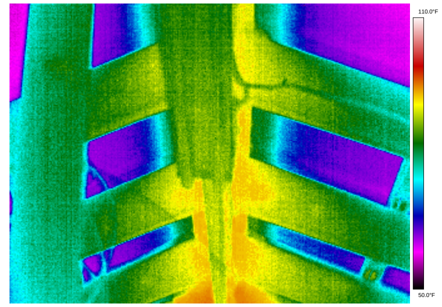

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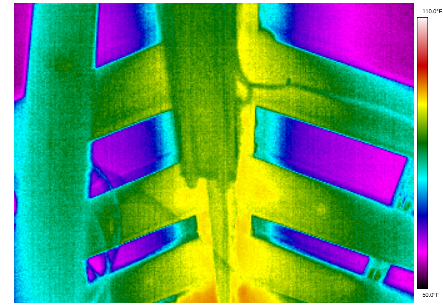

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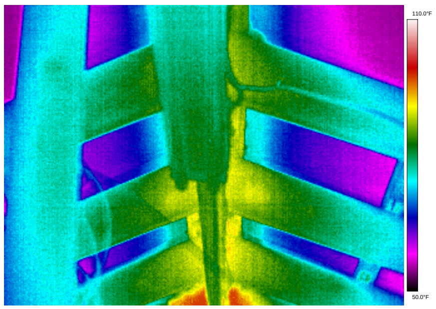

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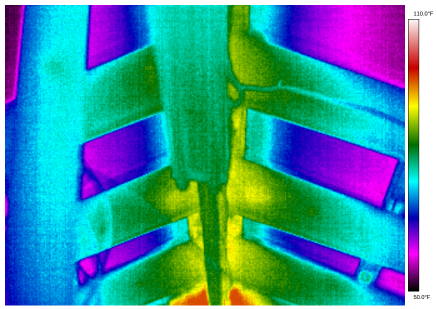

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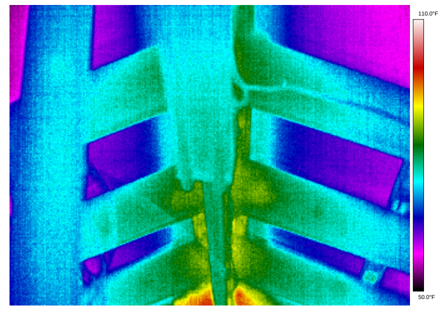

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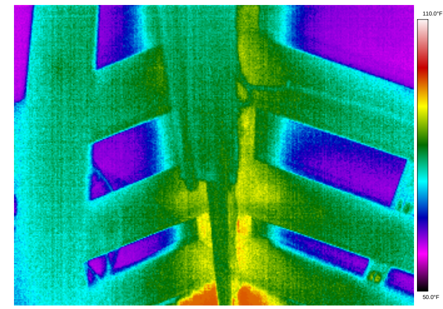

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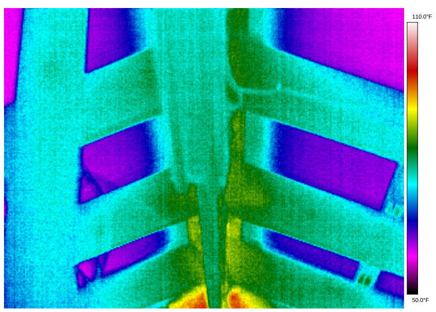

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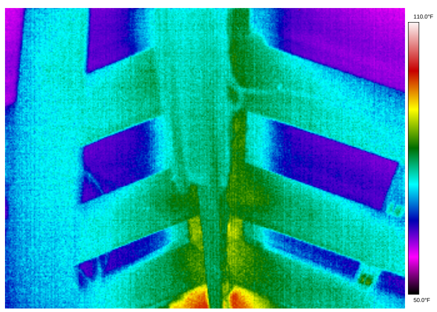

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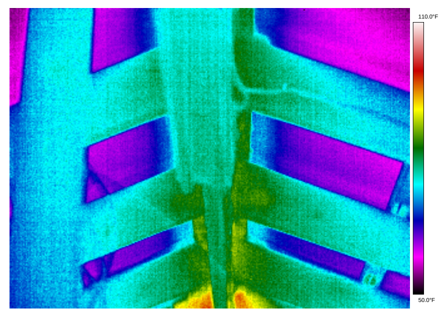

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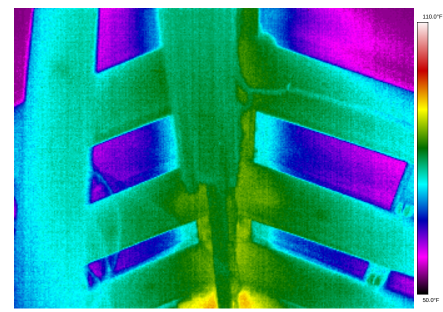

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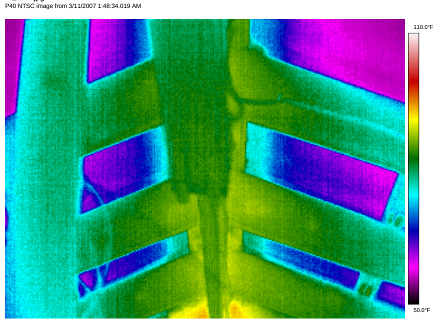

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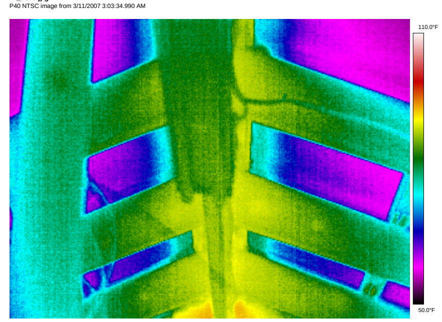

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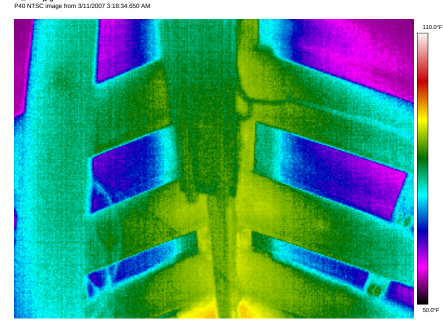

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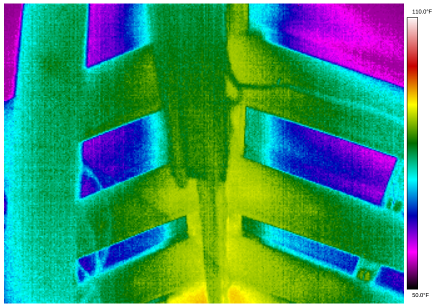

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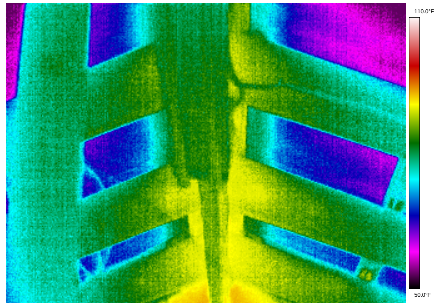

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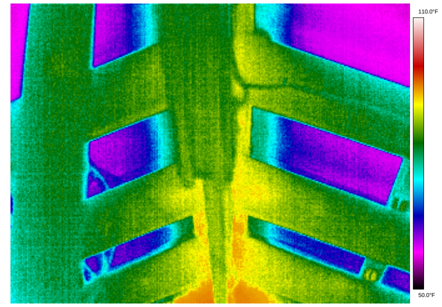

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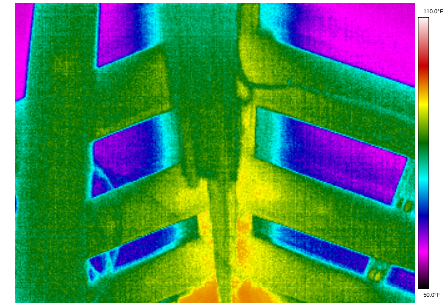

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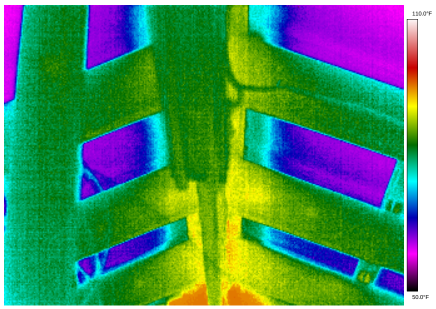

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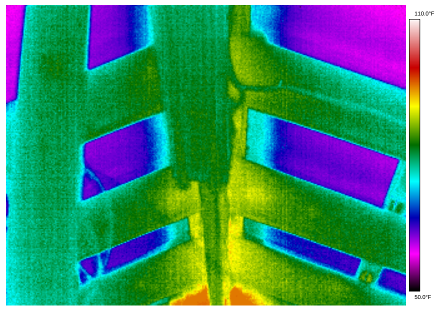

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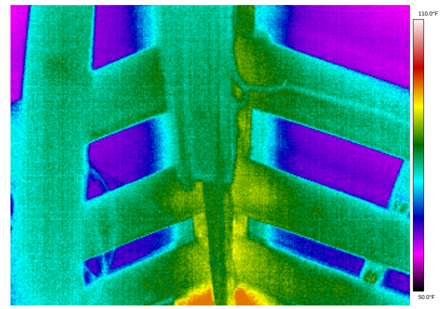

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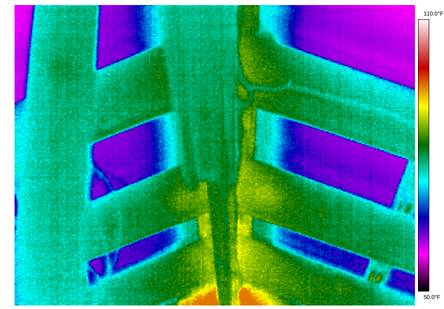

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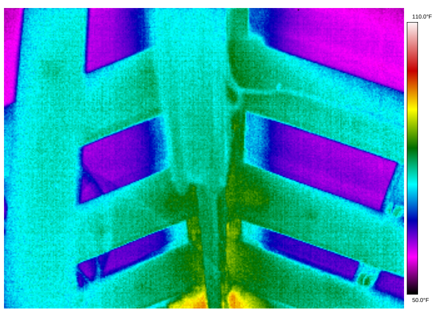

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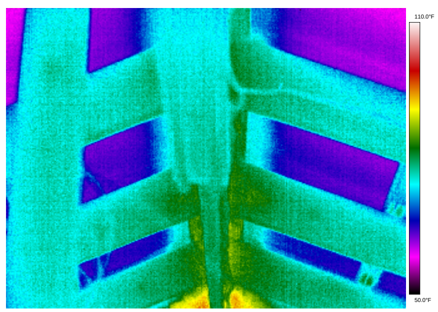

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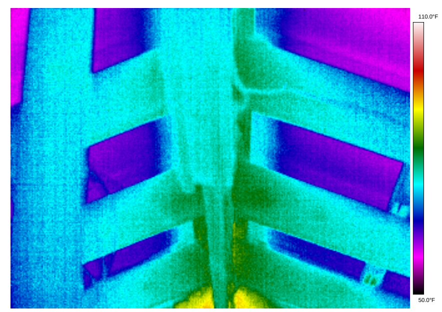

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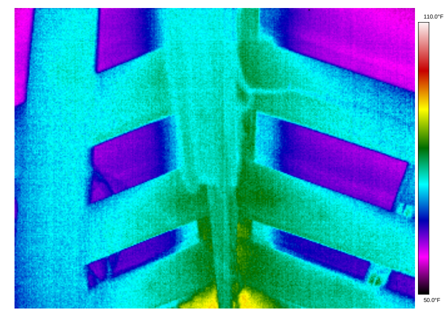

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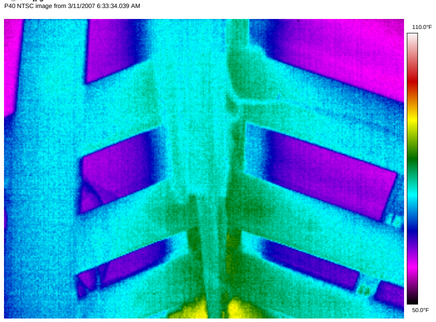

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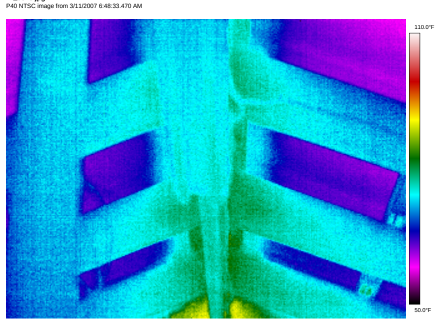

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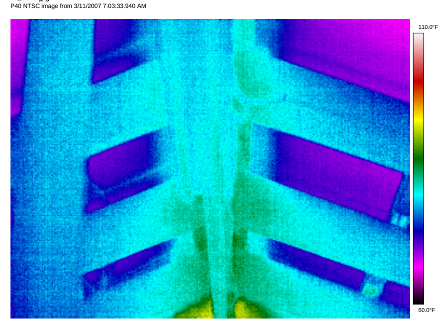

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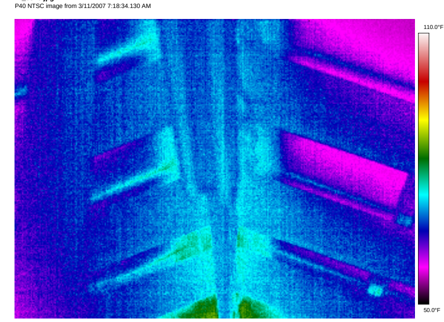

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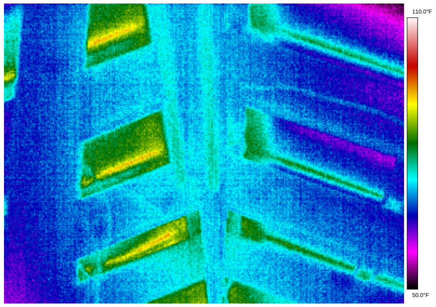

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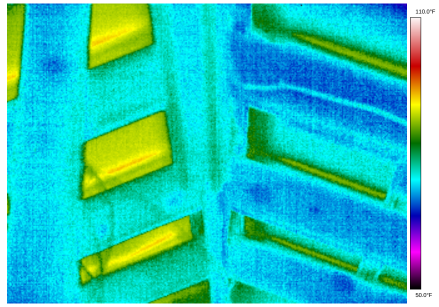

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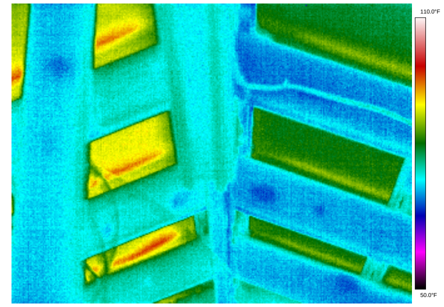

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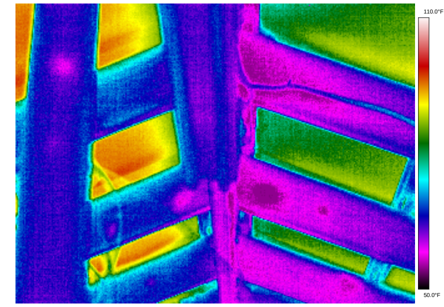

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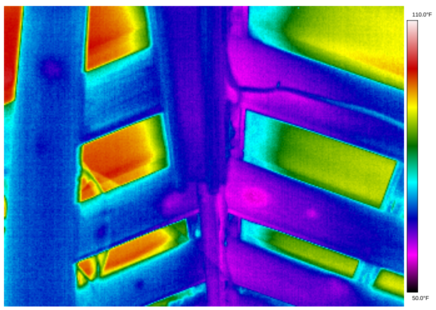

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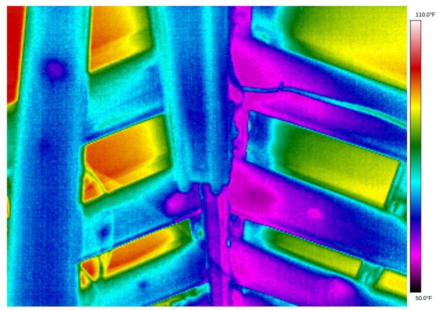

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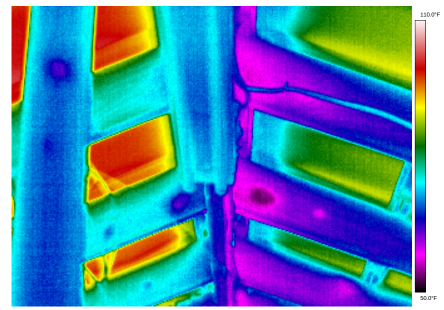

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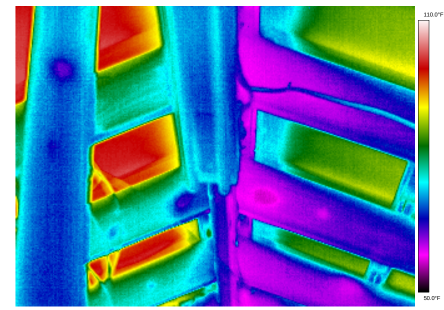

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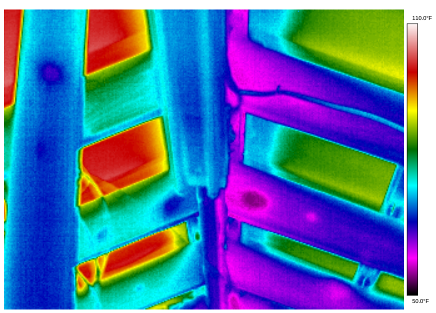

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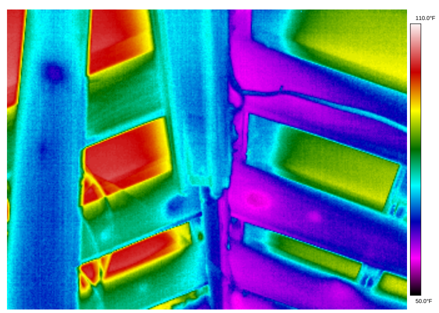

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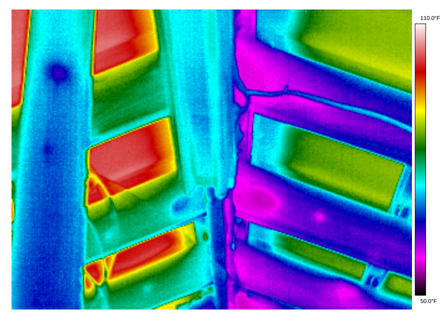

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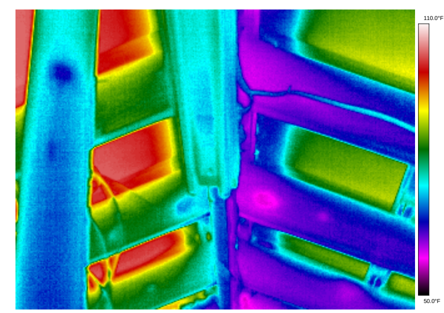

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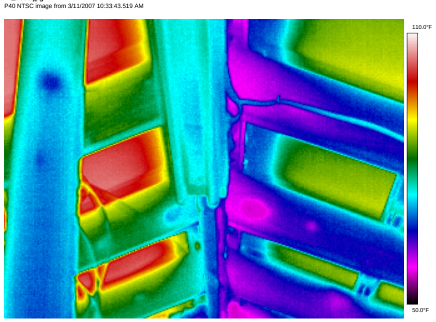

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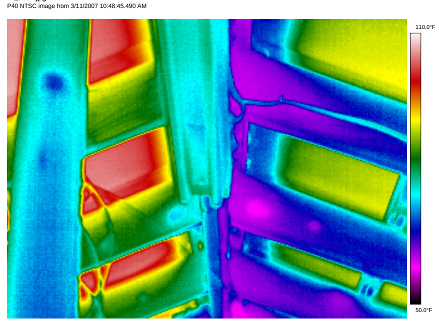

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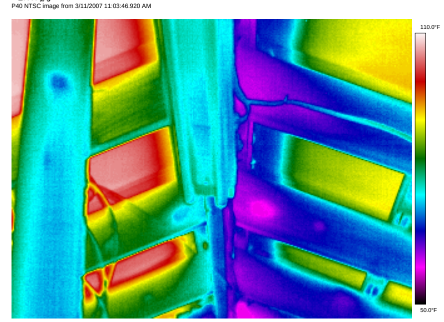

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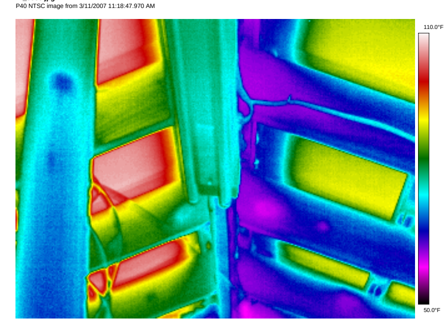

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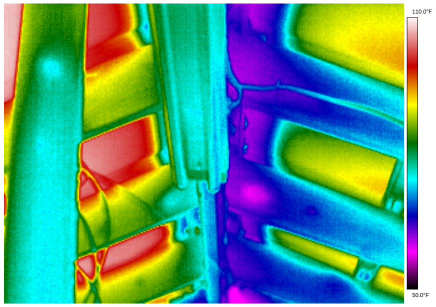

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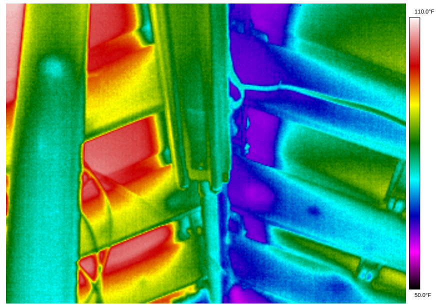

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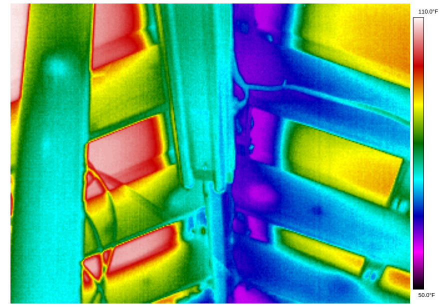

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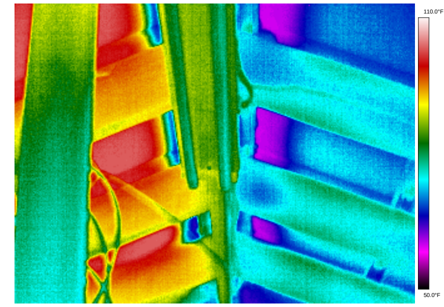

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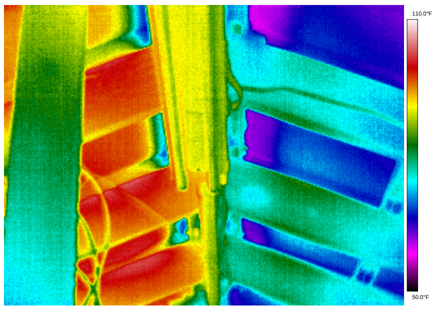

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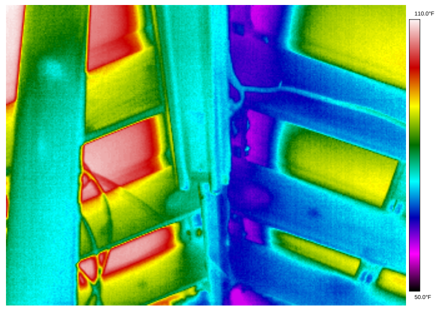

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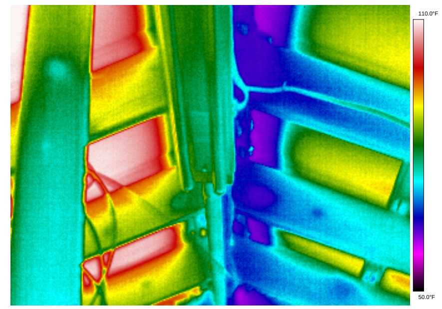

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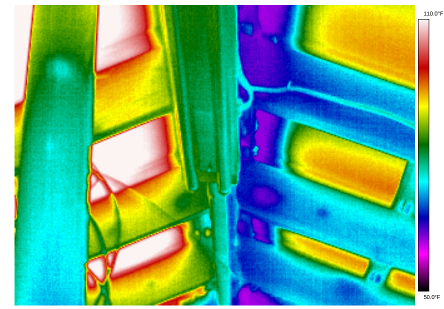

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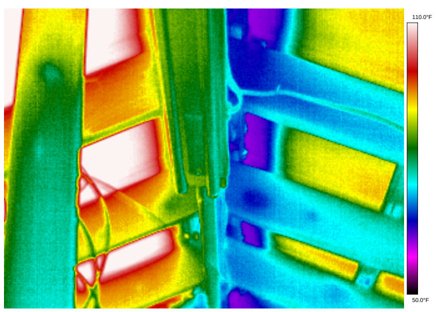

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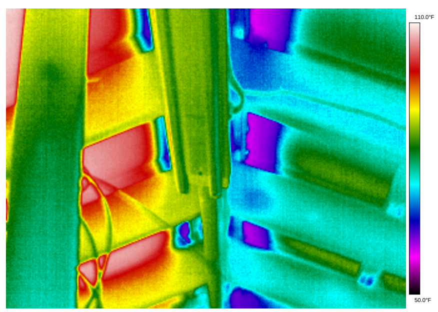

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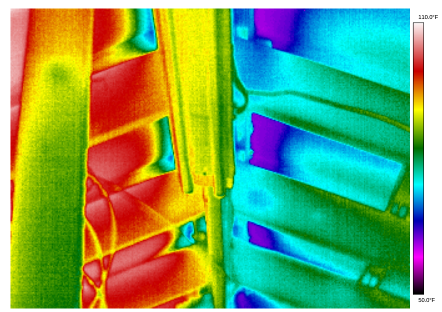

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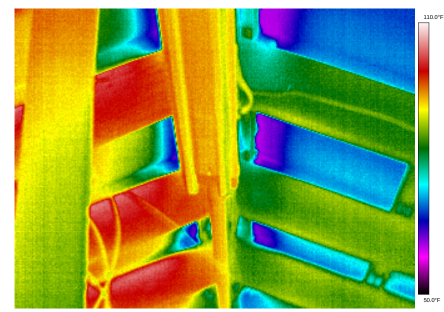

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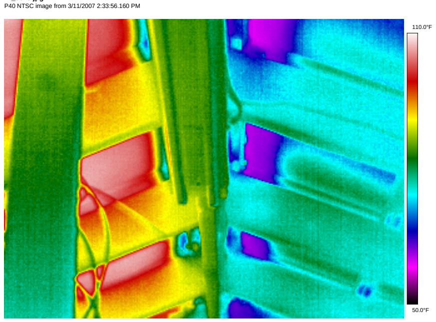

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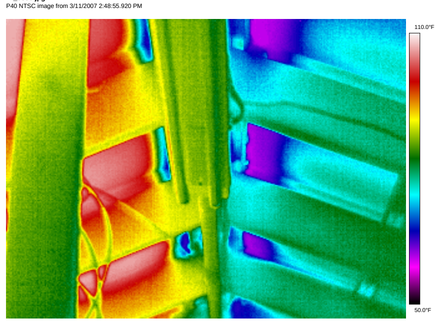

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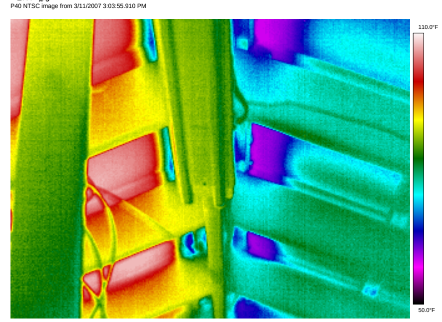

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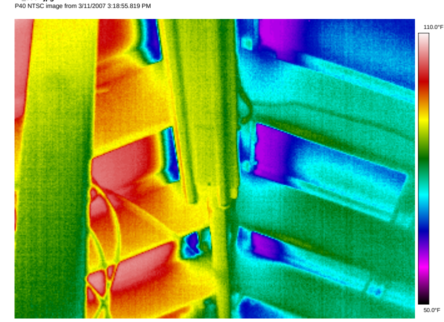

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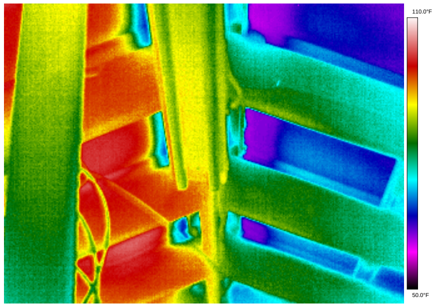

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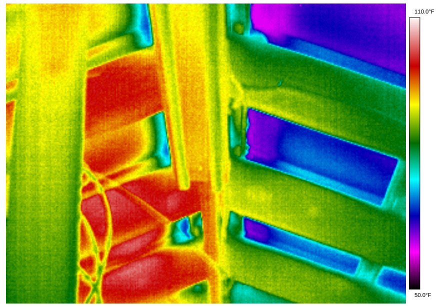

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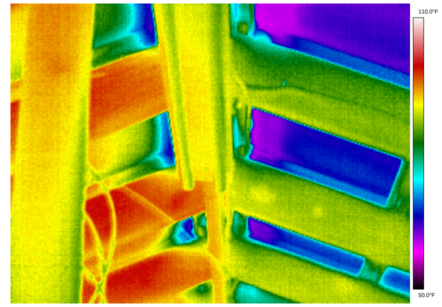

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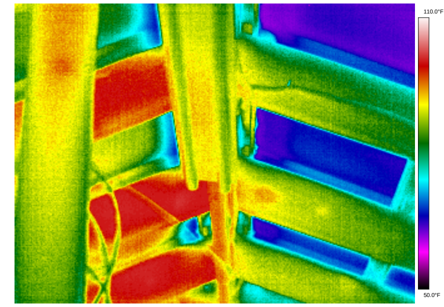

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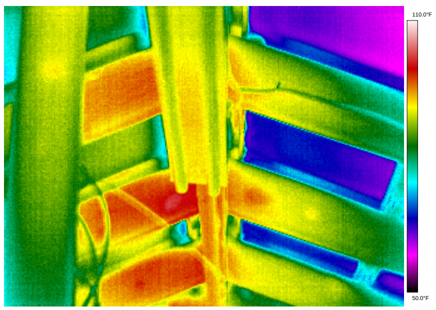

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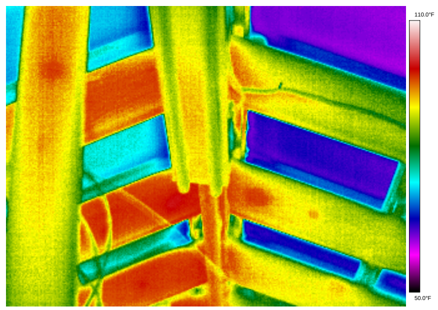

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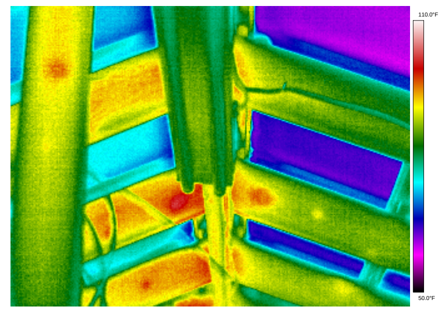

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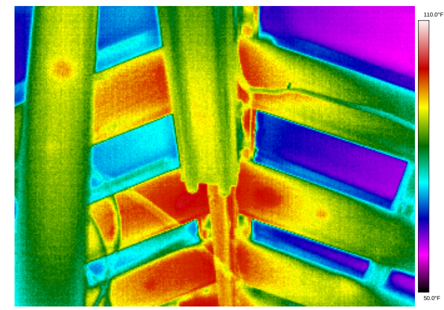

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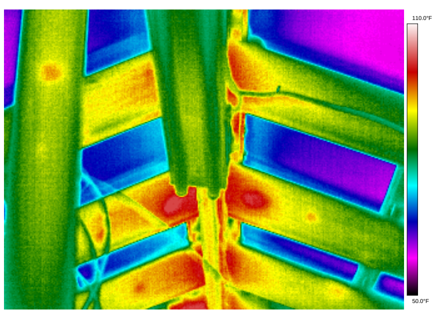

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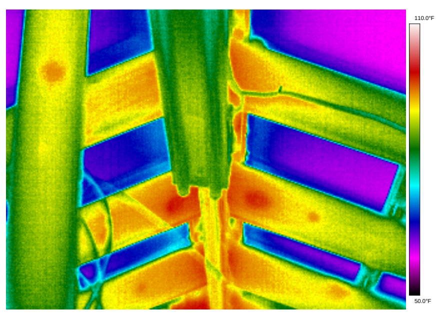

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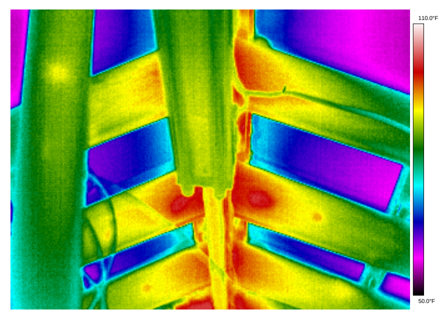

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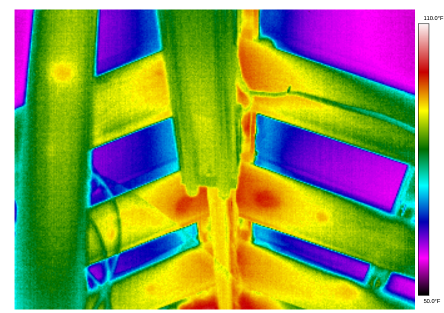

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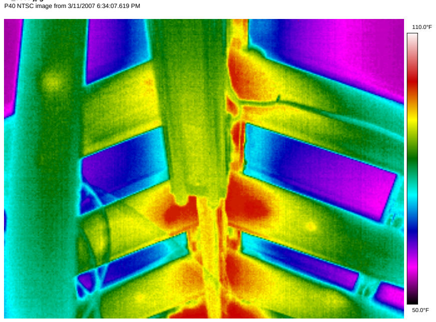

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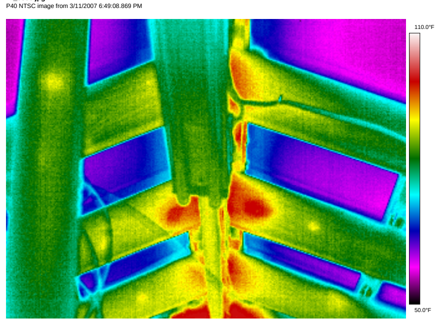

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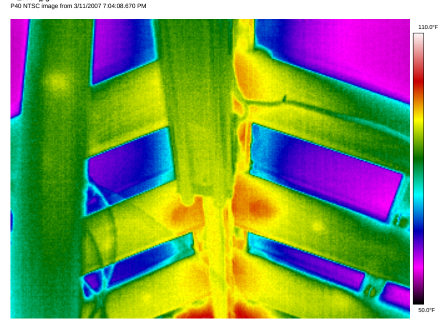

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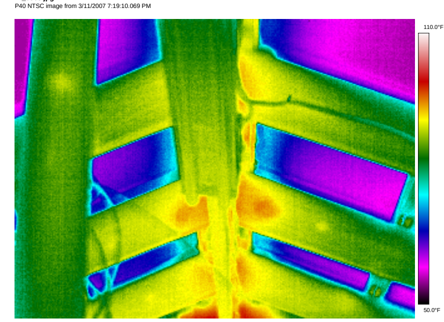

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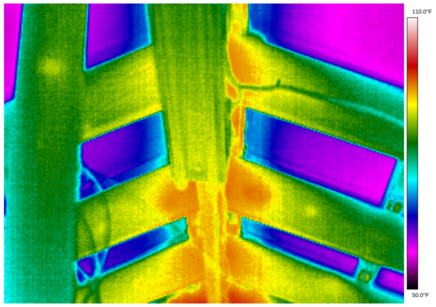

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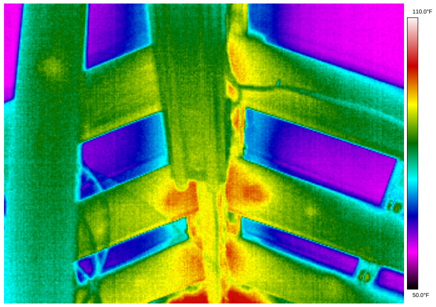

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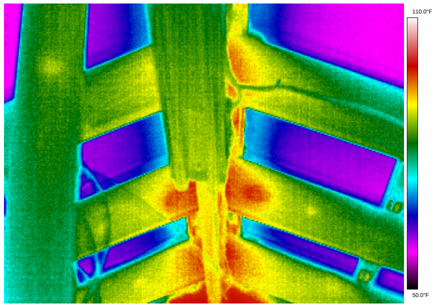

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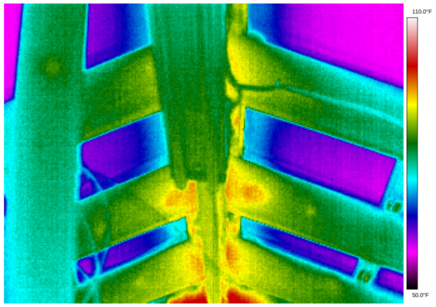

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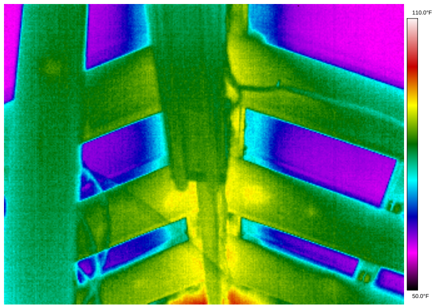

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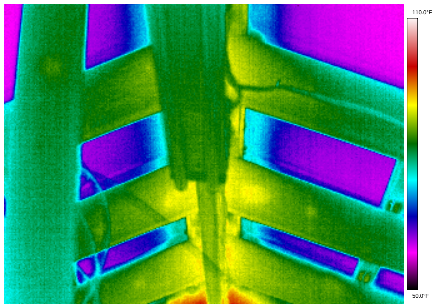

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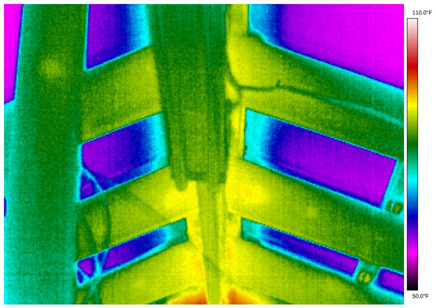

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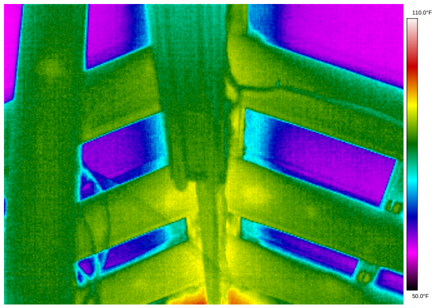

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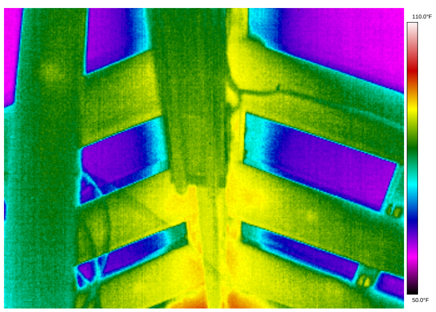

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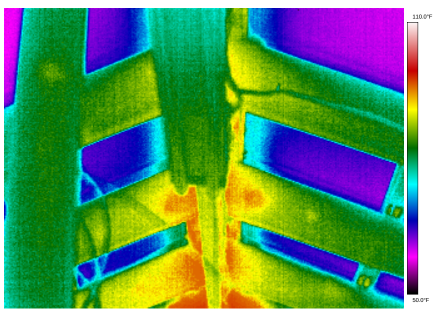

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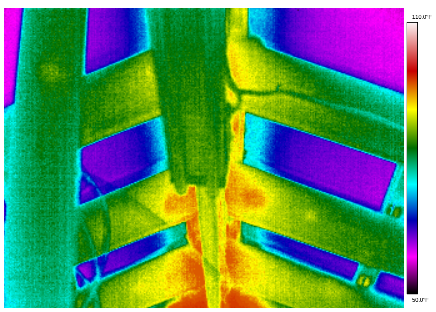

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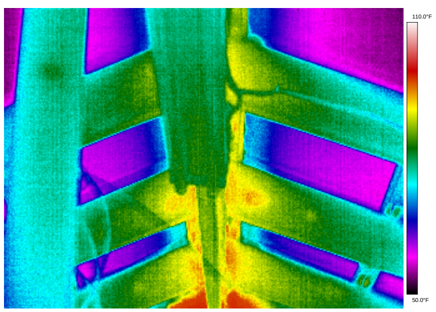

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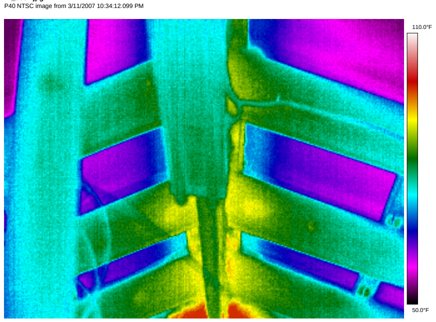

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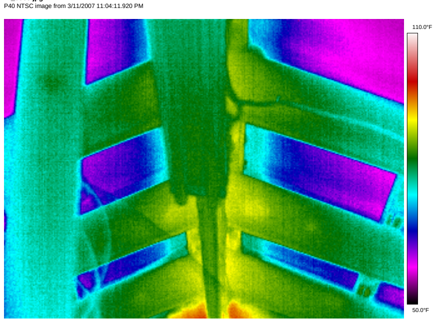

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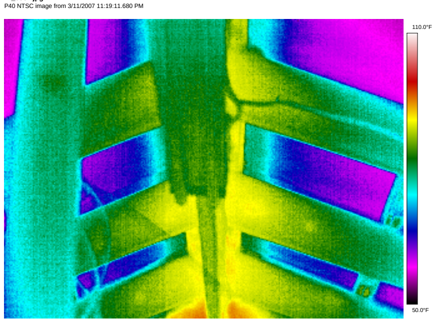

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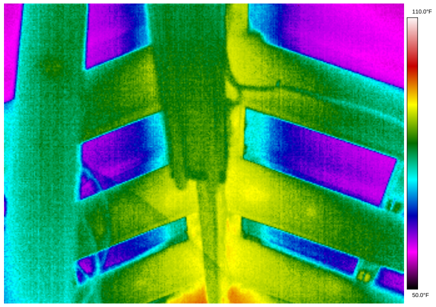

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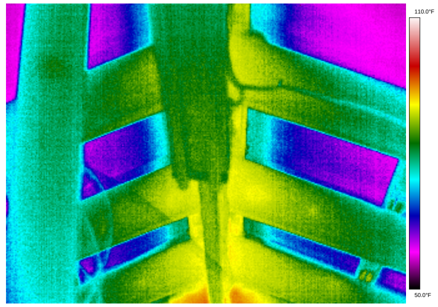

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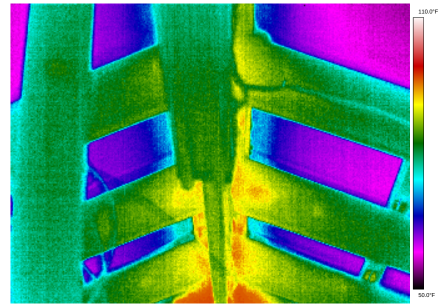

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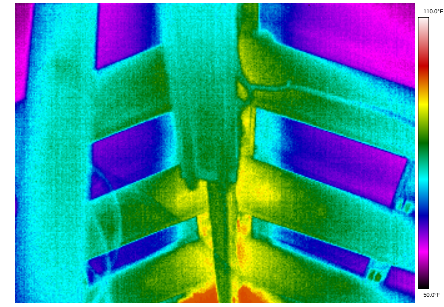

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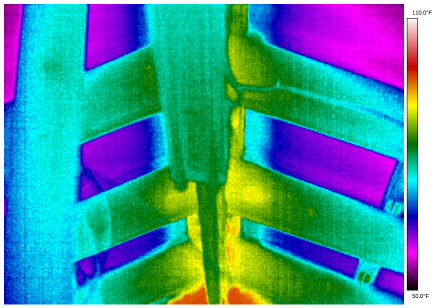

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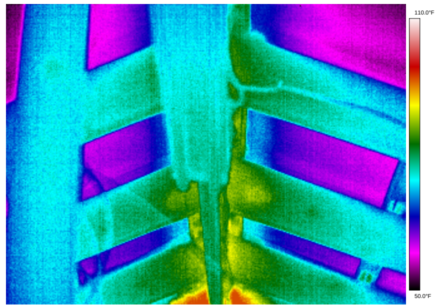

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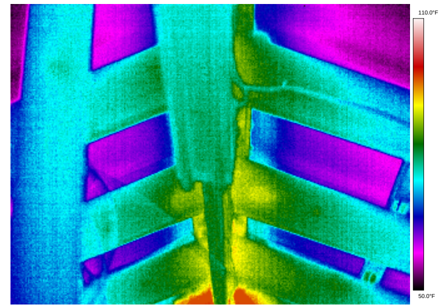

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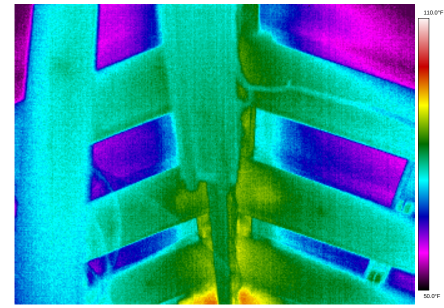

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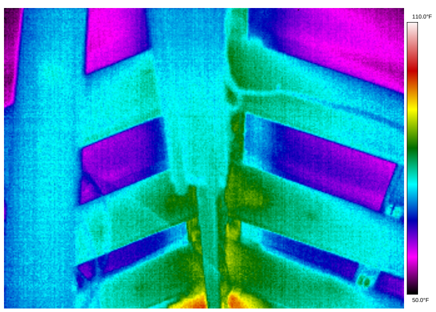

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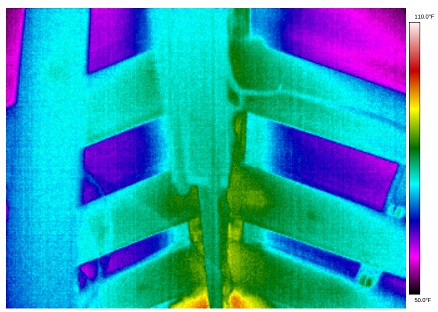

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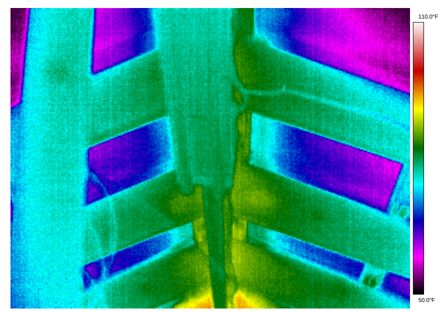

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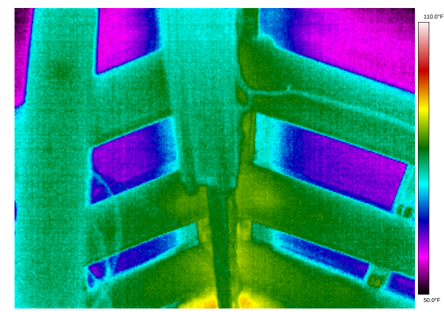

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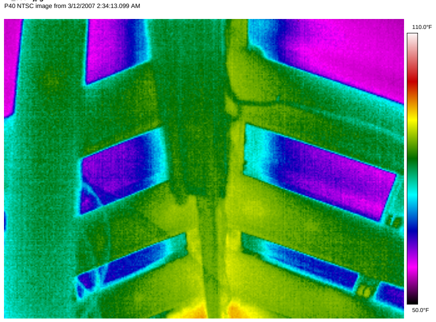

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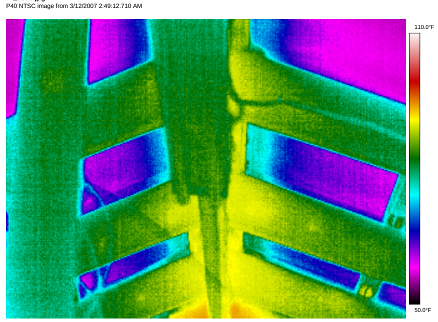

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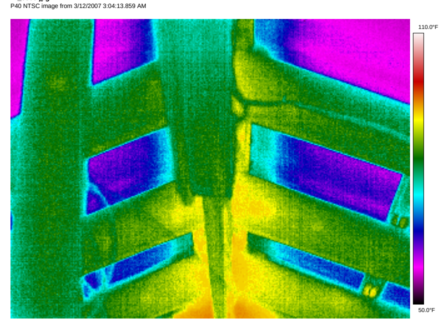

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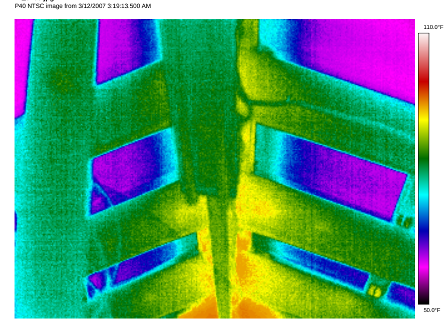

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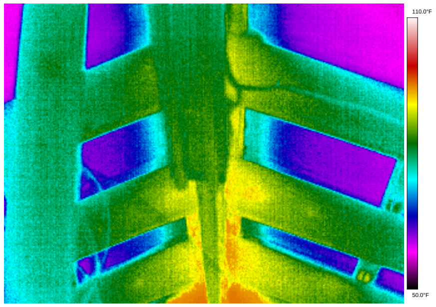

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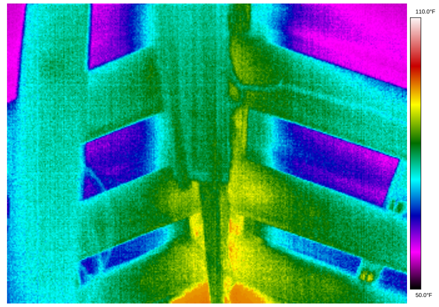

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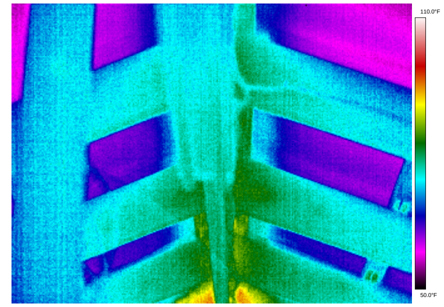

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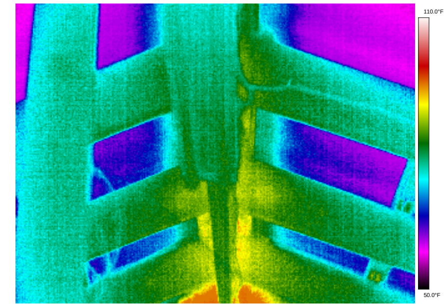

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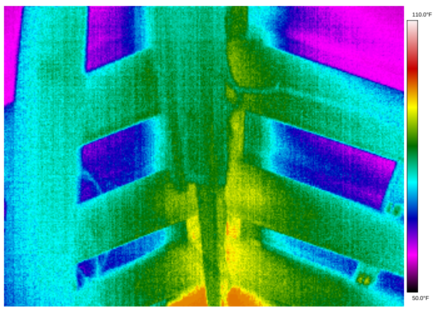

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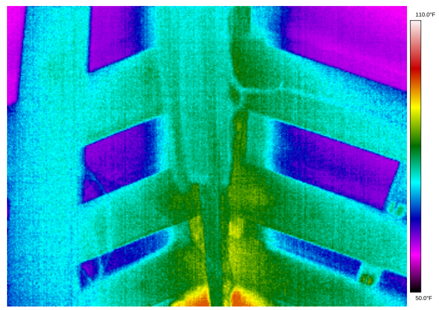

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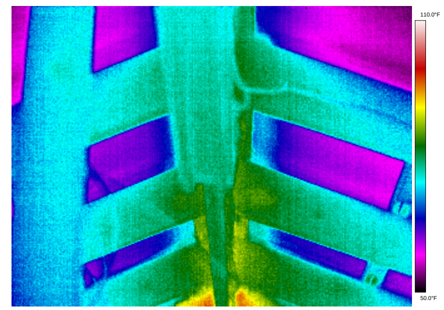

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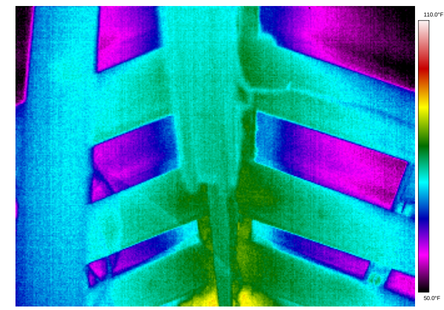

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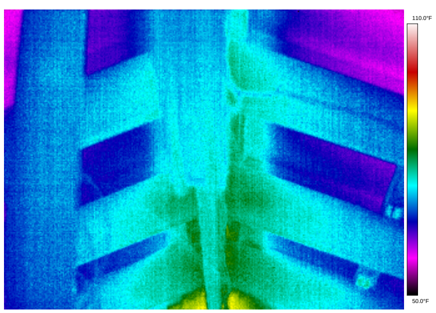

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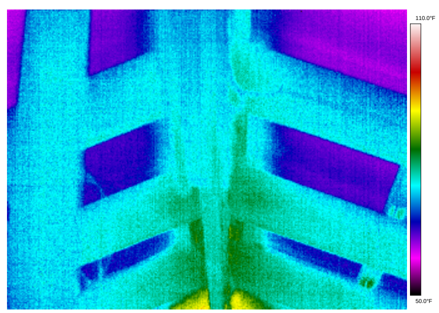

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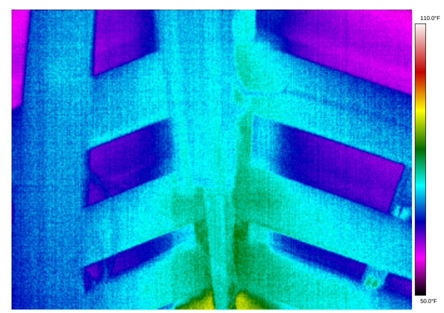

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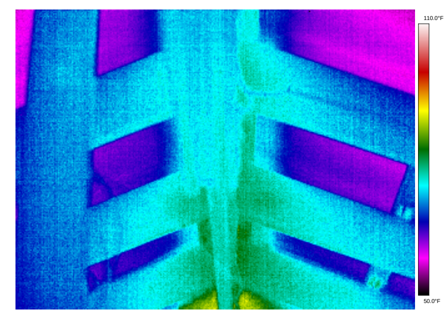

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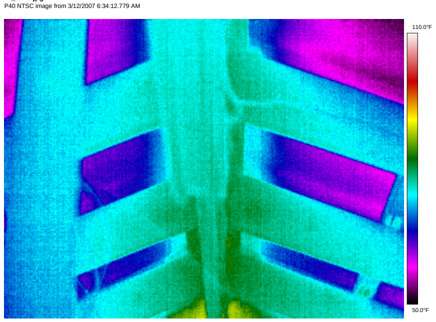

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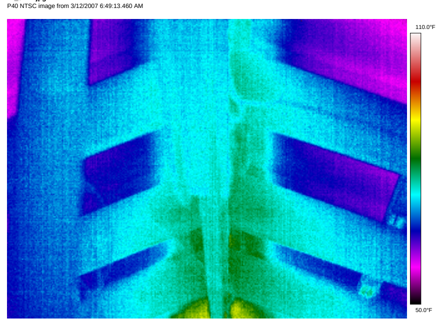

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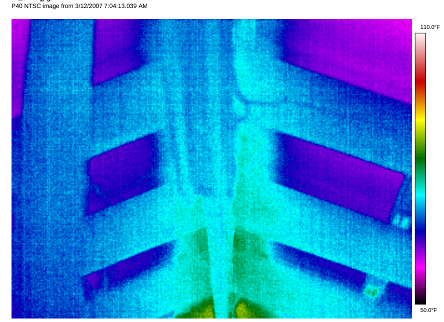

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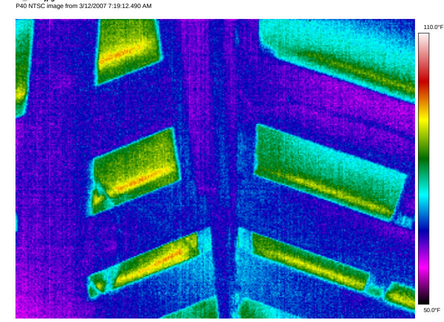

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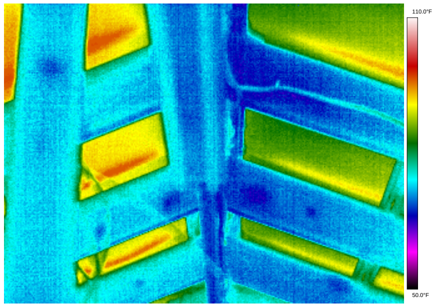

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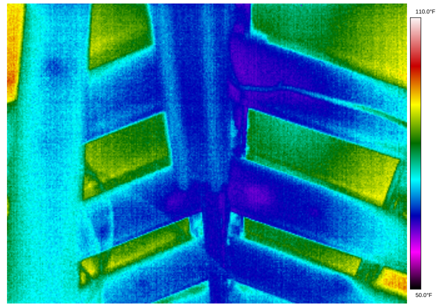

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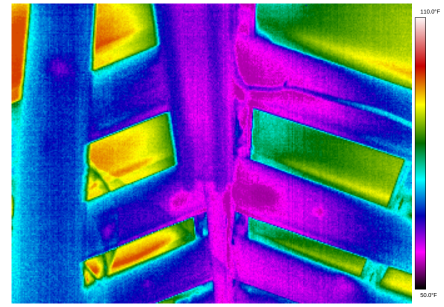

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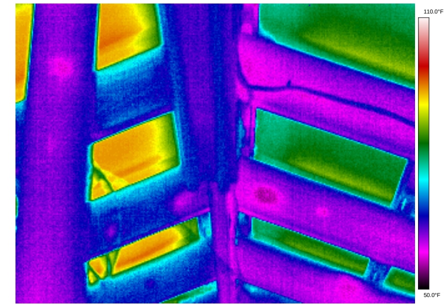

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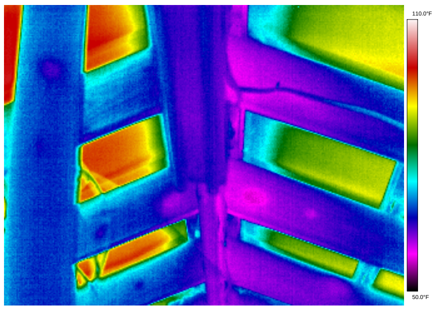

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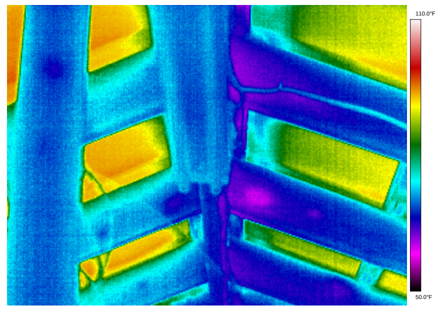

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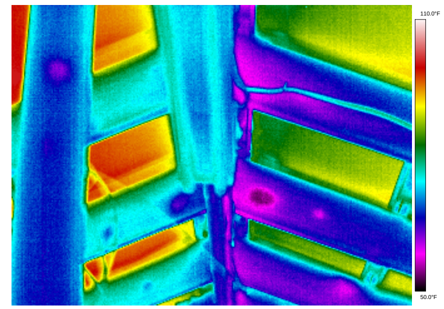

IR_0424.jpg
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