

Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program

Final Report Describing the Field Evaluation of the Initial Prototype FDD System

CONSULTANT REPORT

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1. Objectives for the Field Evaluation of the Initial Prototype FDD System

The objectives for field evaluation of FDSI's initial prototype embedded FDD system were:

- a) To evaluate the performance of the FDD system in the field, including observations on faults identified by the FDD system, faults observed by operating staff, repairs done, and the like;
- b) Identify issues associated with field use that were not identified during the emulation and laboratory testing.

2. Field Deployment of the Initial Prototype FDD System

The FDSI embedded FDD system consists of the following components:

- Data acquisition hardware,
- Data processing,
- Fault detection and diagnostics algorithms, and
- Web user interface.

Further description of the system was provided in *Final Report Describing VM Implementation, Emulation / Bench Testing and Laboratory Testing, and Field Installation* (deliverable D5.6a to the California Energy Commission, Contract 500-03-030, September 2006).

The FDD data acquisition hardware was installed at six sites with a total of thirty-seven units. The site and unit information is shown in Table 1.

The FDSI VM hardware was installed at Walgreen's Anaheim and Rialto sites during 2002. The original task assumed that the FDSI VM hardware would be upgraded at these two sites. However, as the system design shifted to the use of Point Six hardware for the initial prototype (as an intermediate step toward new FDSI hardware), the VM hardware at the Walgreen sites was never upgraded. FDD software was upgraded at these two sites.

The initial prototype based on Point Six hardware (rather than FDSI's VM hardware) was installed at the Honeywell GSRC site in December 2004, at the CSU East Bay site in December 2005, at the UCLA site in January 2006, and at the UCSD site in February 2006.

The FDD software implemented on the central server in early 2005 is the diagnostic software being used for the Honeywell GSRC site and the three California university sites. This is a centralized approach, with all data processing and fault detection and diagnostics being done at the central server. In comparison, the older FDSI VM system could process some data locally, and transfer data to the central server once per day. However, the Point Six-based systems cannot process data locally, and therefore they send data to the central server in near real time, for later processing. At the central server, the data processing algorithms and FDD algorithms are executed once per day, at the end of the day. Unit performance status (for data collected up to approximately midnight of the previous day) can be accessed via the Web user interface.

3. Field Data Evaluation

3.1 Field Data Evaluation Approach

The evaluation of the field data has been constrained by several factors, including communications problems (e.g., data not being transmitted at all), and reliability issues (e.g., sensor problems).

3.1.1 Units Included in the Field Evaluation

The data collected during 2005 and 2006 are used as the main data source for the evaluation. During the monitoring period from January 2005 to December 2006, a number of things happened that affected the collection of data from certain units.

- All of the monitored units at the two Walgreen sites stopped sending data in the middle of 2005. For this reason, and the related fact that the hardware was not upgraded, the Walgreen data has been excluded from the field evaluation.
- At the Honeywell GSRC site, no data was received at all from RTU-4 until some work was done on the unit in mid December 2006. Therefore, this unit has been excluded from the field evaluation. Also, RTU-1 and RTU-2 have a configuration of two compressors sharing one circuit. This configuration is not well supported by the current FDD algorithms and therefore, these units are not included in the evaluation list.
- At CSU East Bay, no data has been received from RTU-6 since February 2006, and no valid compressor side data has been received from RTU-8 since February 2006. These units have been excluded from the field evaluation.
- All the units at the UCSD site were subject to an inappropriate communication setting, whereby the Point Six module that collects the data from the sensors was mistakenly set to repeat a prior reading when the wireless communication link between a sensor module and the data collection module was temporarily disrupted. This meant that for any set of sensor readings, the measurements might not have all been taken at the same time. One or more of the measurements might have actually been made minutes or even hours earlier. Unfortunately, this mistaken setting was not discovered until December 2006. Subsequent observations have shown that, most of the time, the measurements are being taken within a minute of each other, but because there is no way to know for sure that the measurements were all taken at the same time when a fault was diagnosed, these units have been excluded from this evaluation.
- At the UCLA site, RTU-4, RTU-5, RTU-6, and RTU7 all had the same inappropriate communication setting as at the UCSD site. These units have been excluded from this evaluation.

By excluding those units with the above problems, eleven units were selected for the field evaluation of the FDD algorithms. Table 2 shows the list of the final set of units. In the previous

presentation given at the 2006 PAC meeting, the field demonstration and observation of FDD was based on 29 units. Among these 29 units, 18 units are excluded from the current field evaluation due to the issues stated above.

3.1.2 Faults Included in the Field Evaluation

One problem area that developed was the supply airflow sensor. No supply airflow sensor was installed at the Honeywell GSRC site, and it was later determined that the supply airflow sensors installed at CSU East Bay, UCLA and UCSD did not operate properly. Therefore, the FDD system cannot identify faults requiring fan status as a diagnostics input.

Based on the sensors installed and their actual performance, the FDD system covered by this field evaluation has the ability to identify the following types of faults:

- 11 control faults shown in Table 3,
- 9 airside faults shown in Table 4, and
- 11 refrigeration cycle faults shown in Table 5.

In addition to the fault detection and diagnostics, the FDD system also monitors the following unit performance parameters: mechanical cooling runtime statistics, compressor cycle statistics, outdoor air damper operation, outdoor air fraction statistics and mechanical cooling efficiency index.

3.2 Field Data Evaluation Results

During the monitoring period, the FDD system identified and reported a number of faults for the selected units, as summarized in Table 6. It can be seen that 8 refrigeration cycle faults, 9 airside faults and 21 control faults were identified. The “short compressor run time” condition was the most common fault identified by the FDD system.

Some of the identified faults are discussed in the following paragraphs.

Figure 1 shows the correction for the “loss of charge” fault for RTU-3 at Honeywell GSRC during 2005. The loss of charge occurred due to leakage at the connection point for the pressure sensors. The loss of charge occurred after the installation was completed in January 2005. It can be seen from Figure 1 that as the charge fault develops (charge index < -5), the suction line superheat goes up, while the liquid line subcooling, the charge index and the mechanical cooling efficiency all go down until the fault was corrected in early April. This fault was confirmed by the on-site operating staff.

A “liquid line restriction” fault was identified by the FDD system for RTU-3 at Honeywell GSRC during 2006, as shown in Figure 2. When the restriction fault occurred (fault index > 1), both suction line superheat and liquid line subcooling are high while the evaporating temperature is low. Figure 3 shows the efficiency index and capacity index for this unit. The efficiency index is below 90 and the capacity index is about 85.

Figure 4 shows a “low side heat transfer” problem identified by the FDD system for RTU-7 at CSU East Bay during 2006. When this fault occurred (fault index > 1), both the evaporating temperature and suction line superheat were low. The efficiency index and capacity index for this unit are shown in Figure 5. Both the efficiency index and capacity index are below 90.

The FDD system identified a “low charge” fault and a “high side heat transfer” problem for RTU-1 at UCLA. As shown in Figure 6, for the low charge fault (fault index >1), the evaporating temperature is low and the suction line superheat is high. For the high side heat transfer problem (fault index >1), the condensing temperature over ambient is high. Since the high side heat transfer problem has a significant impact on the efficiency index, this unit shows an efficiency index of 70 as indicated in Figure 7. With an efficiency index of 70, this unit has an annual potential savings of \$515 (assume energy cost is 10 cents/kWh).

The FDD system diagnosed a number of compressor short cycling problems. For example, RTU-3 at Honeywell GSRC site was diagnosed with both “short compressor-on cycle” faults and “short compressor-off cycle” faults. As shown in Figure 8, the numbers of short compressor-on cycles (less than 5 minutes) and short compressor-off cycles (less than 5 minutes) were significantly high during the spring season. This may be caused by the light load during the spring. Figure 9 shows the compressor short-on cycle fault for RTU-2 at UCLA. During the month the compressor cycle data is available, the unit ran with a severe short compressor-on cycle problem because almost all the compressor-on cycles are less than 5 minutes.

Eight units of the selected eleven units have economizers installed. During the monitoring period, the FDD system diagnosed a number of economizer faults. Figure 10 shows that, at CSU East Bay, RTU-4 has a high outdoor air fraction when ambient temperature is high. This is indicated by a lot of operating points located above the minimum OAF line (OAF=0.2) when OAT is greater than RAT. This fault can increase the energy consumption of the unit. Figure 11 shows that, at Honeywell GSRC, RTU-3 has a low outdoor air fraction during the occupied period. This is indicated by the operating points located below the minimum OAF line (OAF=0.2). This fault can cause comfort problems and can reduce the productivity of the building occupants. Figure 12 shows that, at Honeywell GSRC, RTU-5 has no economizer cooling at low ambient temperature (OAT-RAT <-5). This fault can cause the unit to run mechanical cooling instead of using free cooling, thereby increasing energy consumption. Figure 13 shows a properly operating economizer of RTU-7 at CSU East Bay. It can be seen that when ambient temperature is higher than return air temperature, the outdoor air damper stays in the minimum position. When the ambient temperature is cool, the outdoor air damper is open beyond the minimum position.

The FDD system monitors the compressor cooling cycle statistics. Figure 14 shows the compressor cooling cycle statistics for two units at the Honeywell GSRC site. It can be seen that most of the compressor cycles for these two units are between 5 minutes to 10 minutes. Table 7 shows the cooling runtime data of the monitored units during 2005 and 2006. At CSU East Bay, RTU-2, RTU-3, RTU-4 and RTU-5 did not run cooling very much. Similarly, RTU-2 at UCLA did not run cooling very much. There was significant economizer operation for RTU-5 at Honeywell GSRC, and RTU-4 and RTU-7 at CSU East Bay.

4. Lessons Learned

4.1 Evaporator Inlet Air Condition Measurement

The evaporator inlet condition is important to the diagnostics of refrigeration cycle faults and economizer faults. An averaged mixed air temperature sensor array and a single point mixed air humidity sensor were installed at Honeywell GSRC site to measure the evaporator inlet condition. The averaged mixed air temperature sensor array was installed at the California university sites.

For the latter, the mixed air humidity is estimated based on the ambient temperature and humidity, and the return air temperature and humidity. Unless there is very limited mixing space, the averaged mixed air temperature sensor array can measure the mixed air temperature with reasonable accuracy. However, the single point humidity sensor cannot measure the average humidity at the evaporator inlet with reasonable accuracy. Therefore, an alternative approach was proposed to estimate the mixed air humidity based on the ambient temperature and humidity, and the return air temperature and humidity.

4.2 Redesign of Airflow Sensor

A sensor measuring the indoor airflow status is used to diagnose some of the control faults associated with the indoor fan status and to verify fan is on, a condition required for accurate airside measurements. The supply airflow sensor was designed and installed for the units at the California university sites. However, based on the field data, it was observed that the airflow sensor did not work properly. The airflow sensor was then re-designed and was tested in the lab. The tests indicate that the new design can detect indoor airflow status properly.

4.3 Time Response of Temperature Sensors

All the temperature sensors installed for measuring airside temperatures and refrigerant side temperatures are thermistor-based. Compared to the pressure sensors, the temperature sensors experience relatively long response times (about 2 to 3 minutes) to reach quasi steady state, when the system changes its status, for example, from ‘fan off’ to ‘fan on’ or from ‘compressor off’ to ‘compressor on’. The startup data of temperature sensors created a certain level of ‘noise’ to the diagnostics algorithm and resulted in false alarm or anomaly in the performance data. The data processing algorithm was revised to filter out those startup data of temperature sensors.

4.4 Consistent FDD Over a Time Period

The original diagnostics algorithm was designed to provide one diagnostic for one set of measurement. Due to measurement uncertainty and model error, this approach resulted in inconsistent diagnostics over a time period (e.g., a day). The revised diagnostics algorithm analyzes the data over a given time period (e.g., a day) and the diagnostics are based on the set of data. The revised algorithm is more robust under measurement uncertainty and model error.

4.5 FDD Tolerance for Missing Data in the Data Inputs

During the monitoring period, it was observed that most units experienced intermittent communication loss between one or more sensors and the data collection module. That means that at some point, there is no data available for a particular sensor due to the unreliable communication link between the data acquisition hardware and the local data collection point. The original data processing algorithm had limitations in tolerating the missing data in the sensor data inputs, especially the suction pressure and liquid pressure that are used to determine the unit on/off status. Therefore, the diagnostics capability was significantly limited. The data processing algorithm was revised to accommodate some limited cases of missing sensor data by using history data. An example is the determination of the compressor run status that is normally

determined based on both suction and liquid pressure. When current data are missing for one pressure, the diagnostic algorithm will use historic data to determine the compressor status.

4.6 Ambient Measurements

Outdoor ambient temperature and humidity are important driving conditions of air conditioning units. An accurate measurement of ambient conditions is important to FDD because they are the inputs to the refrigeration cycle diagnostics and economizer diagnostics. In the current field installation, the ambient temperature sensors were installed under the economizer hood for those units with an economizer installed. The sensor was installed at the inlet of the condenser for those units without an economizer. It was observed that the ambient temperature measurement taken from an economizer hood facing south can be 10°F higher than that taken from an economizer hood in the shade or not in direct sun (when unit is not operating). It was also observed that there is a significant difference in ambient temperature measurements depending upon whether the unit was on or off. Where and how to install the ambient sensor is being evaluated.

4.7 Special Unit Configurations

The current FDD system design does not consider some special HVAC unit configurations. For example, RTU-1 and RTU-2 at Honeywell GSRC each have two compressors sharing the same circuit. Each of the two-stage ‘call for cooling’ signals controls one compressor. The two-stage call for cooling signals alternate in controlling the compressors. The current FDD algorithm does not support this configuration. The units at UCLA site are controlled by a Trane thermostat that does not have a 24 V signal. The FDD system had no interface for this Trane thermostat. This limits the diagnostics capabilities of the FDD system when applied to systems with these particular configurations.

5. Summary

The initial prototype implementation of the FDSI FDD system was deployed in the field and has been monitoring air conditioning units for one to two years. The FDD systems identified refrigeration cycle faults, economizer faults and control faults. Some of these faults were confirmed by on-site staff. The FDD system also provided trend statistics and graphs for unit performance from different perspectives.

During the field evaluation of the FDD system, issues were identified both in hardware and software that were not well considered in the initial prototype system. Among those issues, some have been resolved, while others require further investigation.

6. References

FDSI, September 2006. Final Report Describing VM Implementation, Emulation/Bench Testing and Laboratory Testing, and Field Installation. Deliverable D5.6a to California Energy Commission under Contract 500-03-030.

FDSI, November 2006. Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program, Presentation given at Program Advisory Committee Meeting under Contract 500-03-030.

Table 1. Field Test Sites

Site Description	Location	No. of Units	Operational Date	Hardware	General Unit Description
Walgreens – Anaheim	Anaheim, CA	5	2002	FDSI VM	Packaged HP with economizer
Walgreens – Rialto	Rialto, CA	5	2002	FDSI VM	Packaged HP with economizer
Honeywell GSRC	Atlanta, GA	5	December 2004	Point Six	Packaged AC with economizer
UCLA	Los Angeles, CA	8	January 2006	Point Six	Packaged AC or HP (1 or 2-stage) no economizer
UCSD	San Diego, CA	7	February 2006	Point Six	Packaged AC (1-stage) with gas heat and economizer
CSU East Bay	Hayward, CA	7	December 2005	Point Six	Packaged HP (1-stage) with economizer

Table 2. Selected Units

Site	Unit	Stages	Indoor Exp Dev	Equip Type	Nominal (total) cooling capacity (tons)	Economizer control	MOAF (estimated)
Honeywell GSRC	RTU-3	2	Fixed	Package Cool	10	Yes	0.20
Honeywell GSRC	RTU-5	1	Fixed	Package Cool	7.5	Yes	0.20
CSU East Bay	RTU-1	1	Fixed	Package Cool	5	Yes	0.20
CSU East Bay	RTU-2	1	Fixed	Package Cool	5	Yes	0.20
CSU East Bay	RTU-3	1	Fixed	Package Cool	5	Yes	0.20
CSU East Bay	RTU-4	1	Fixed	Package Cool	5	Yes	0.20
CSU East Bay	RTU-5	1	Fixed	Package Cool	5	Yes	0.20
CSU East Bay	RTU-7	1	Fixed	Package Cool	5	Yes	0.20
UCLA	RTU-1	2	Fixed	Package Cool	10	No econ	0.20
UCLA	RTU-2	2	Fixed	Package Cool	15	No econ	0.20
UCLA	RTU-3	2	Fixed	Package Cool	15	No econ	0.20

Table 3. Control Fault Diagnostics

General Fault	Specific Fault	Basic Fault Criteria	Occurrence Criteria	Possible Causes
Sensor problem		Y2=on and Y1=off	10 minutes in 24h period	Thermostat or wiring problem
Sensor problem		W2=on and W1=off	10 minutes in 24h period	Thermostat or wiring problem
Sensor Problem		Y1=on and G=off	10 minutes in 24h period	Thermostat or wiring problem
Simultaneous heating and cooling	Controls signal	(W1=on or W2=on) and (Y1=on or Y2=on)	25 minutes in 24h period	Thermostat or other controls problem
Simultaneous heating and cooling	Economizer cooling and heating	ECOOL=on and DCV=off and HEAT=on	25 minutes in 24h period	Controls problem
Mechanical cooling at low outdoor air temperature when should be only economizer		MCOOL=on and OAT<50°F	25 minutes in 24h period	Controls setup or economizer problem
Thermostat cooling demand but no cooling		(Y1=on or Y2=on) and MCOOL=off and ECOOL=off	2h in 24h period	Controls or cooling system problem
Unit short cycling; short off-time or runtime for compressor	Short off-time for compressor (cycle data) Reference: Copeland, 1981	Off-time < 5 minutes and (mechanical cooling or HP heating)	10 occurrences or 10% of occurrences in 24h period	Controls problem
Unit short cycling; short off-time or runtime for compressor	Short runtime for compressor (cycle data)	Runtime < 5 minutes and (mechanical cooling or HP heating)	10 occurrences or 10% of occurrences in 24h period	Thermostat or other controls problem
Cooling without call for cooling	Mechanical cooling with call	Y1=off and MCOOL=on	25 minutes in 24h period	Controls problem or sensor problem
Cooling without call for cooling	Economizer cooling without call	Y1=off and ECOOL=on and DCV=off	25 minutes in 24h period	Controls problem or sensor problem

Table 4. Airside Fault Diagnostics

General Fault	Specific Fault	Basic Fault Criteria	Occurrence Criteria	Possible Causes
Sensor problem	RAT out of valid range	RAT < 65°F or RAT > 85°F	10 minutes in 24h period	Bad or misplaced sensor
Sensor problem	OAT out of valid range	OAT > 125°F or OAT < (-15°F)	10 minutes in 24h period	Bad or misplaced sensor
Sensor problem	MAT out of valid range	MAT>OAT>RAT or MAT<OAT<RAT	10 minutes in 24h period	Bad or misplaced sensor
Sensor problem	SAT out of valid range	SAT > 130°F or SAT < 40°F	10 minutes in 24h period	Bad or misplaced sensor
Sensor problem	OAH out of valid range	OAH > 100% or OAH < 5%	10 minutes in 24h period	Bad or misplaced sensor
Sensor problem	RAH out of valid range	RAH > 70% or RAH < 15%	10 minutes in 24h period	Bad or misplaced sensor
No economizer cooling at low outdoor air temperature	Fault with dry-bulb control	Y1=on and (OAT-RAT) < (-10°F) and ECOOL=off and (ECON=1 or ECON=3)	25 minutes in 24h period	Faulty economizer control, damper problem
High outdoor air fraction when high outdoor air temperature		(OAT-RAT) > 0°F and OAF > mOAF and DCV=off and (ECON=1 or ECON=3)	10 minutes in 24h period	Faulty economizer control, damper problem
Low outdoor air fraction during occupied period		Occupied period and OAF < mOAF	10 minutes in 24h period	Faulty economizer control, damper problem

Table 5. Refrigeration Cycle Fault Diagnostics

General Fault	Specific Fault	Basic Fault Criteria	Occurrence Criteria	Possible Causes
Low Evaporating Temperature	Low Evaporating Temperature	Steady-state cooling operation and evaporating temperature less than 28 F	10 minutes accumulated during a day	Low indoor airflow, refrigerant flow restriction
High Evaporating Temperature	High Evaporating Temperature	Steady-state cooling operation and evaporating temperature greater than 55 F	10 minutes accumulated during a day	Faulty compressor

General Fault	Specific Fault	Basic Fault Criteria	Occurrence Criteria	Possible Causes
Low Superheat	Low Superheat	Steady-state cooling operation and superheat residual (actual – goal) less than -15 F	10 minutes accumulated during a day	High refrigerant charge
High Superheat	High Superheat	Steady-state cooling operation and superheat residual (actual – goal) greater than 20 F	10 minutes accumulated during a day	Low refrigerant charge
High Condenser Over Outdoor Air Temperature	High Condenser Over Outdoor Air Temperature	Steady-state cooling operation and the residual (actual – goal) of condensing temperature over outdoor air temperature greater than 15 F.	10 minutes accumulated during a day	Low condenser airflow
High Charge	High Charge			
Low Charge	Low Charge			
High Side Heat Transfer Problem	High Side Heat Transfer Problem			
Low Side Heat Transfer Problem	Low Side Heat Transfer Problem			
Liquid Line Restriction	Liquid Line Restriction			
Inefficient Compressor	Inefficient Compressor			

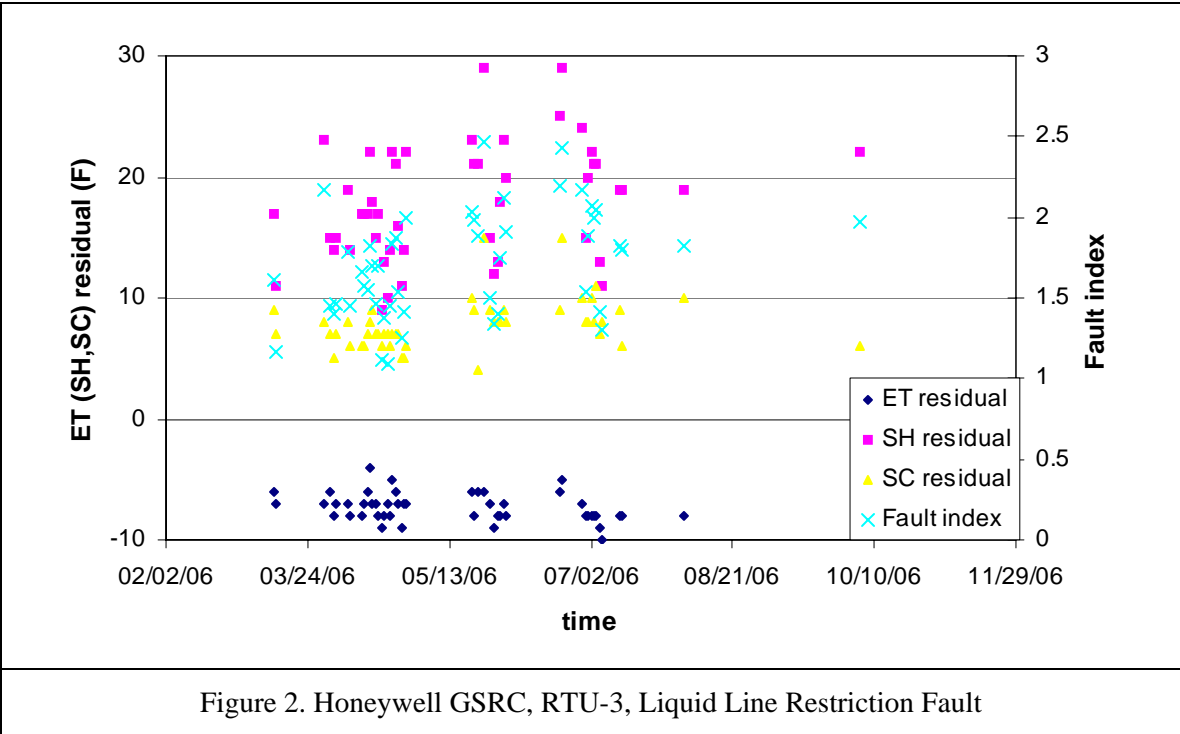
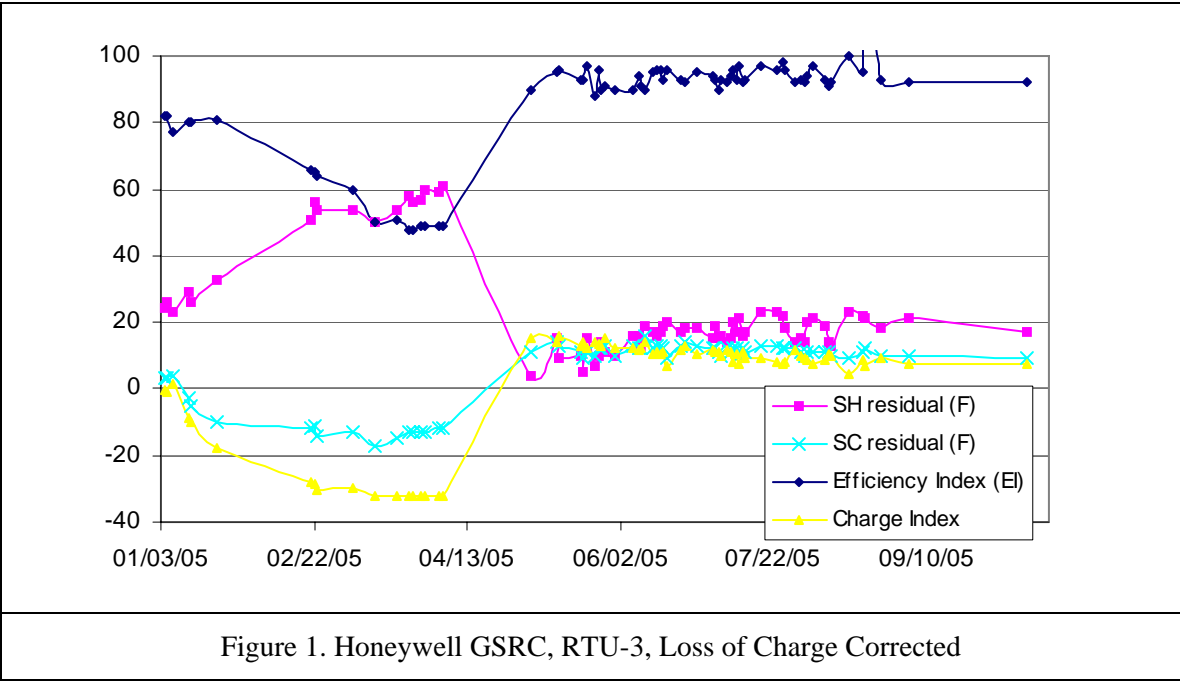
Table 6. Summary of Detected Faults

Fault Description	Fault Criteria	Units Observed	Potential System Impact
Loss of refrigerant charge		1	Reduced efficiency and capacity
Low side heat transfer problem		3	Reduced capacity and efficiency
High side heat transfer problem		1	Reduced efficiency
Refrigerant liquid line restriction		3	Reduced capacity and efficiency
Short compressor on cycle	Runtime < 5 minutes for 10 or more cycles during a day	11	Reduced equipment life; Part-load performance
Short compressor off cycle	Off-time < 5 minutes for 10 or more cycles during a day	9	Reduced equipment life
Low OAF during occupied period		2	Reduced ventilation

Fault Description	Fault Criteria	Units Observed	Potential System Impact
No economizer cooling during low ambient		3	Increased cooling energy use
Mechanical cooling at low ambient		1	Increase cooling energy use
High OAF during high ambient		4	Increased cooling energy use

Table 7. Cooling Season Runtime Data

Site	Unit	2005 mechanical cooling, stage 1 (h)	2006 Mechanical cooling, stage 1 (h)	2005 Economizer cooling (h)	2006 Economizer cooling (h)
Honeywell GSRC	RTU-3	649	687	935	6
Honeywell GSRC	RTU-5	695	805	1006	106
CSU East Bay	RTU-1		494		0
CSU East Bay	RTU-2		18		1
CSU East Bay	RTU-3		68		27
CSU East Bay	RTU-4		83		102
CSU East Bay	RTU-5		2		5
CSU East Bay	RTU-7		232		180
UCLA	RTU-1		1852		0
UCLA	RTU-2		63		0
UCLA	RTU-3		196		0



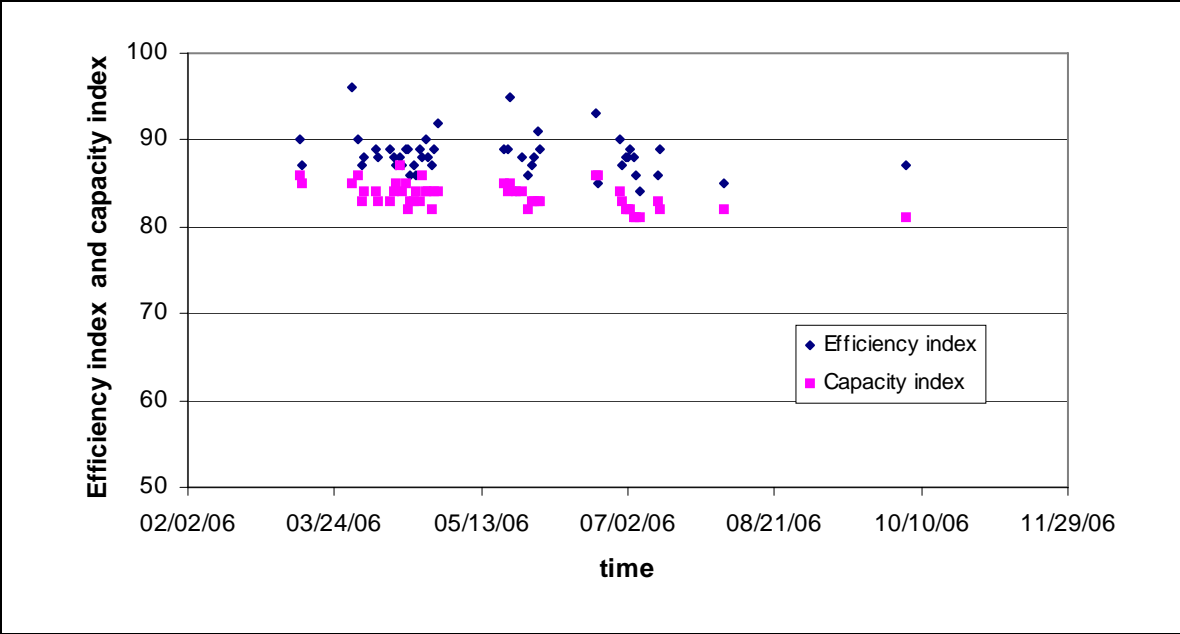


Figure 3. Honeywell GSRC, RTU-3, Efficiency Index and Capacity Index

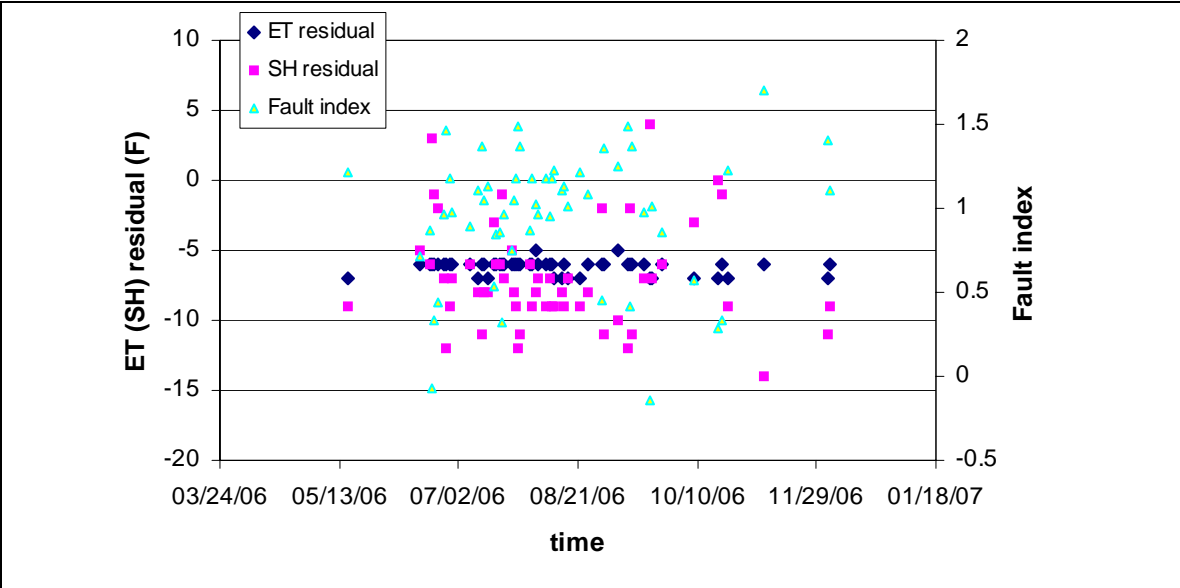


Figure 4. CSU East Bay, RTU-7, Lowside Heat Transfer Problem

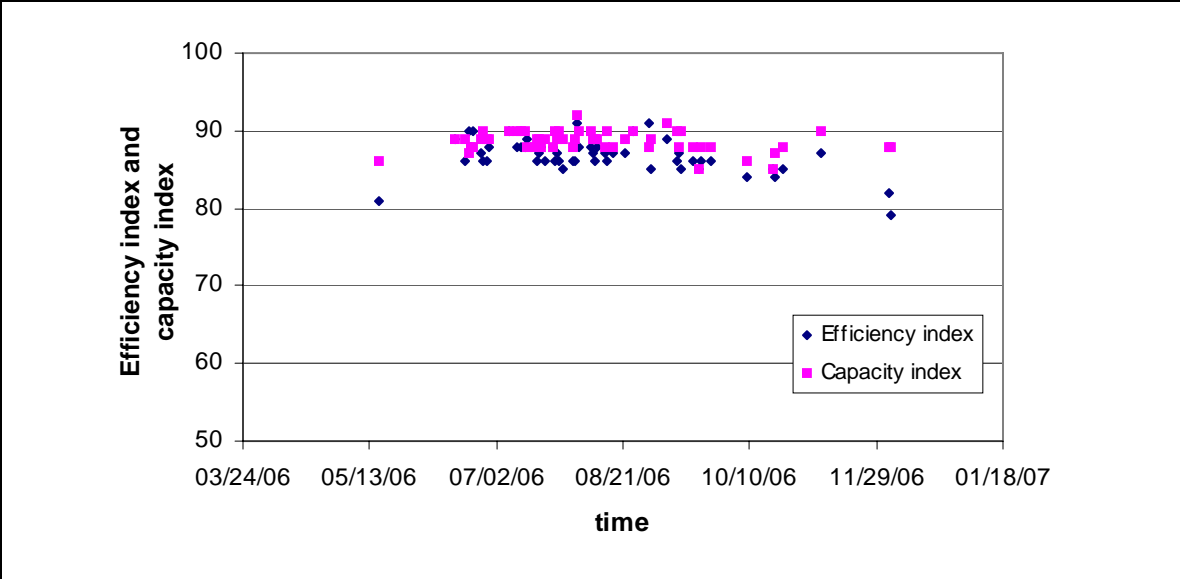


Figure 5. CSU East Bay, RTU-7, Efficiency Index and Capacity Index

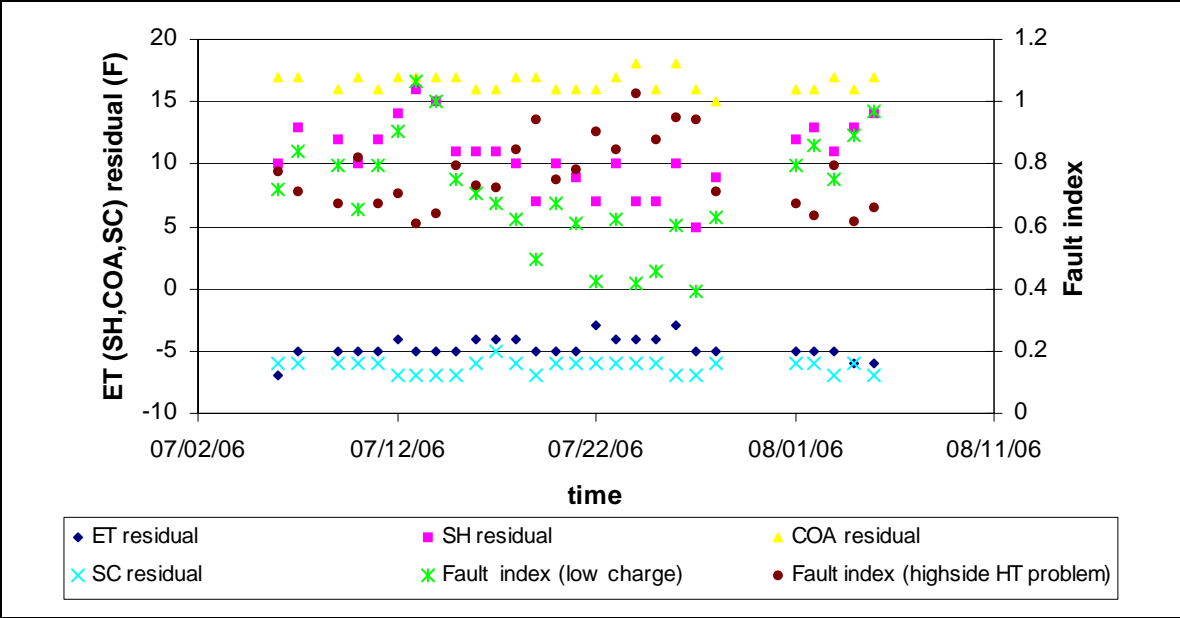


Figure 6. UCLA, RTU-1, Low Charge and High Side Heat Transfer Problem

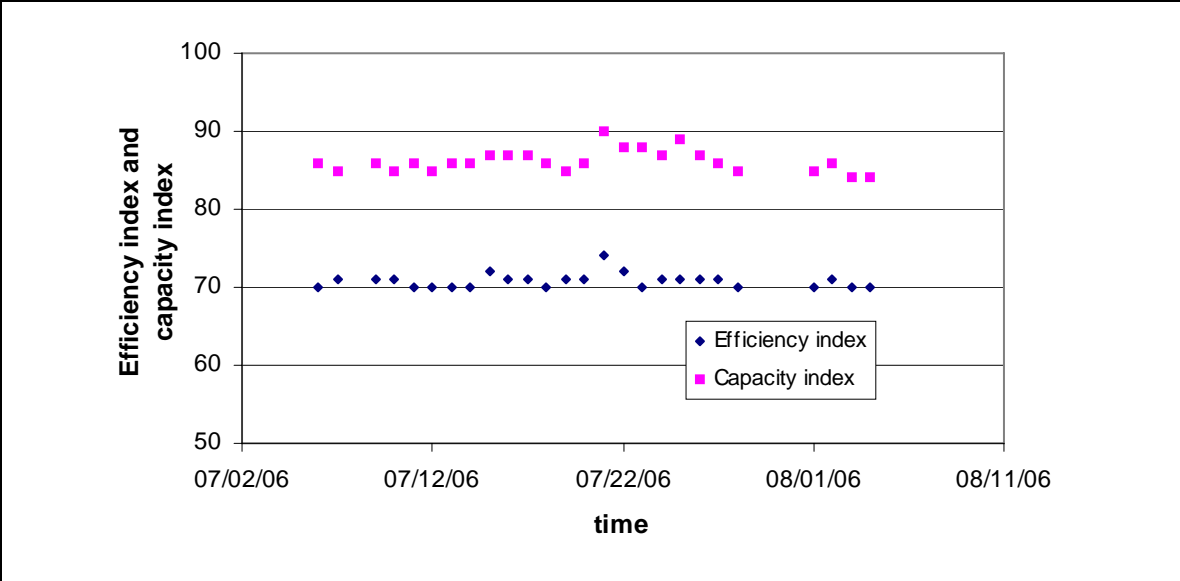


Figure 7. UCLA, RTU-1, Efficiency Index and Capacity Index

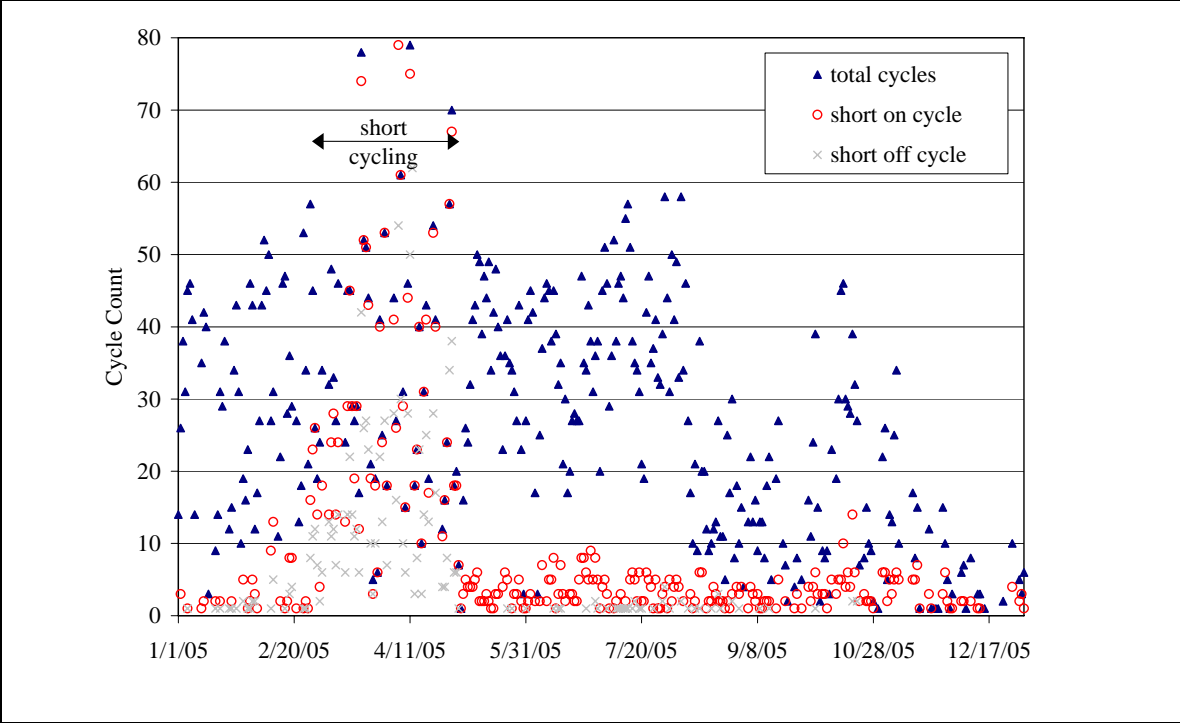


Figure 8. Honeywell GSRC, RTU-3, Compressor Cooling Short Cycling

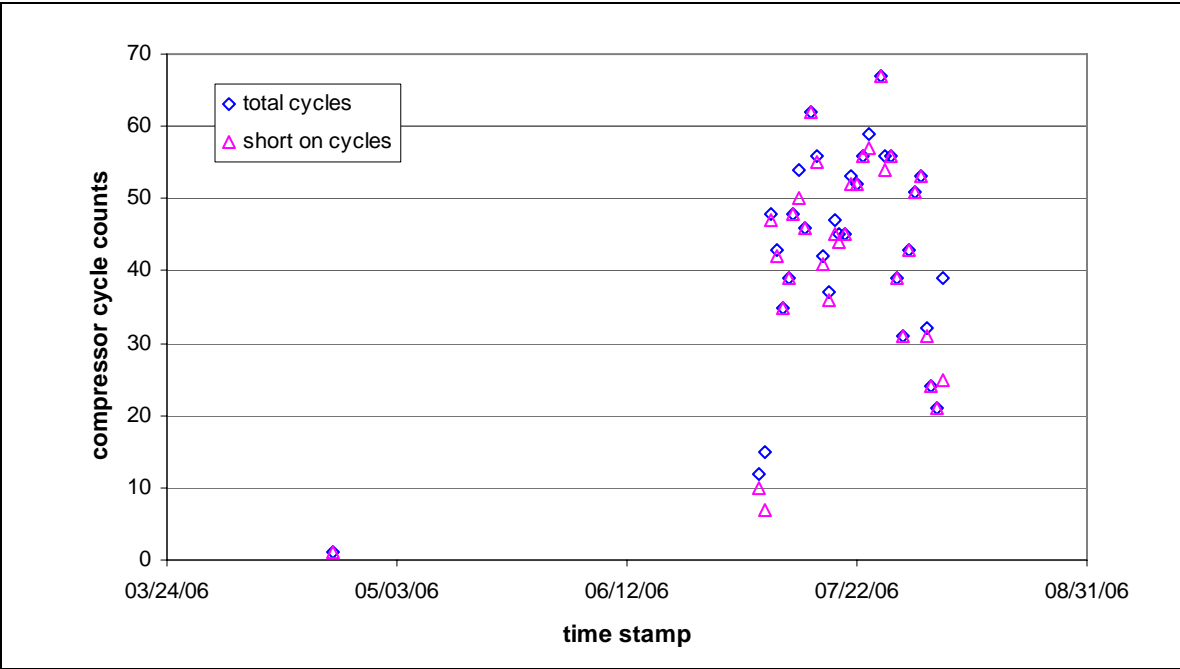


Figure 9. UCLA, RTU-2, Compressor Cooling Short On Cycling

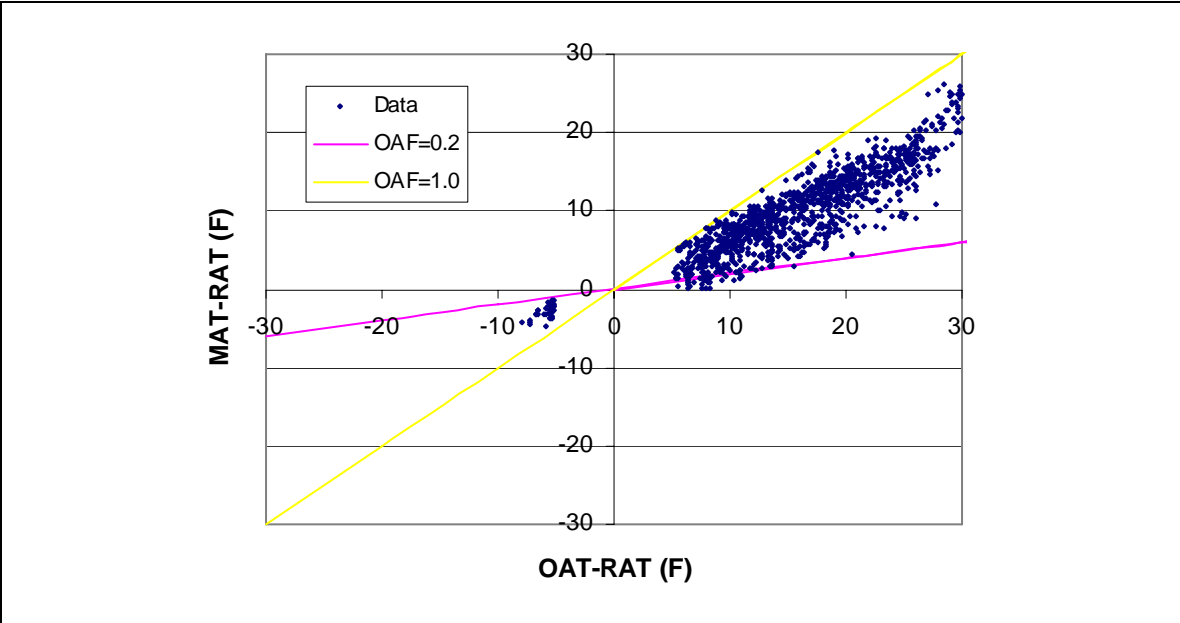


Figure 10. CSU East Bay, RTU-4, High OAF When High OAT Fault

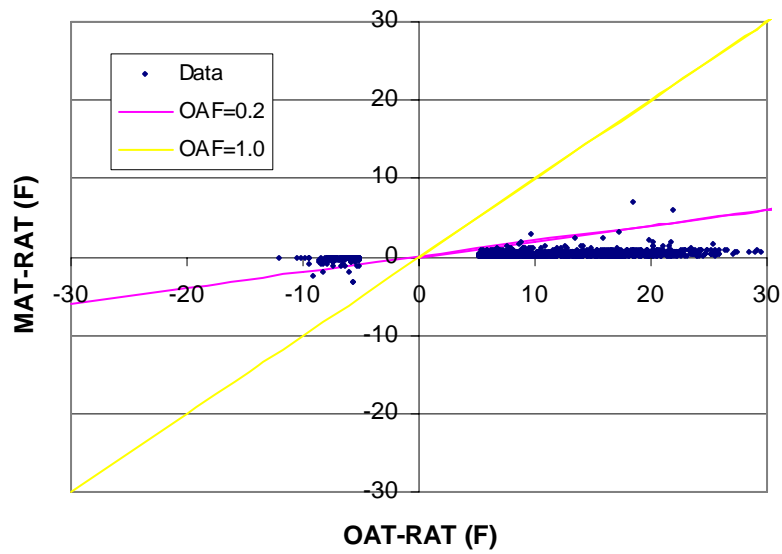


Figure 11. Honeywell GSRC, RTU-3, Low OAF During Occupied Period Fault (2006 data)

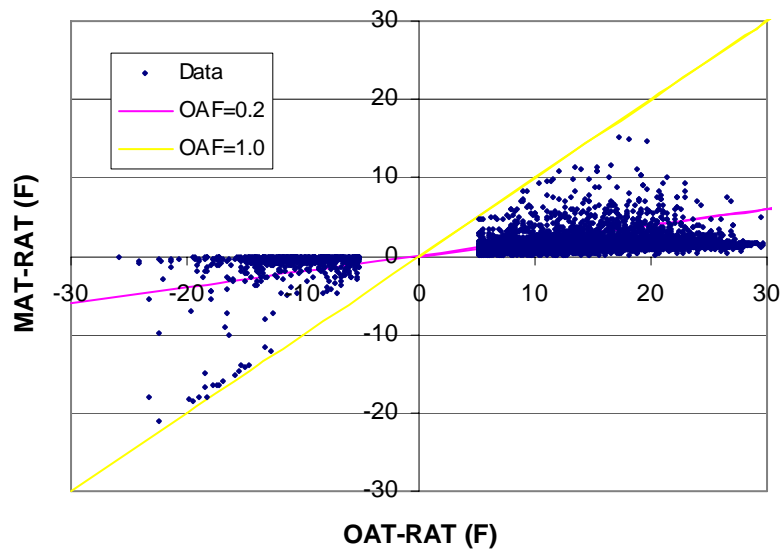


Figure 12. Honeywell GSRC, RTU-5, No Economizer Cooling at Low OAT (2006 data)

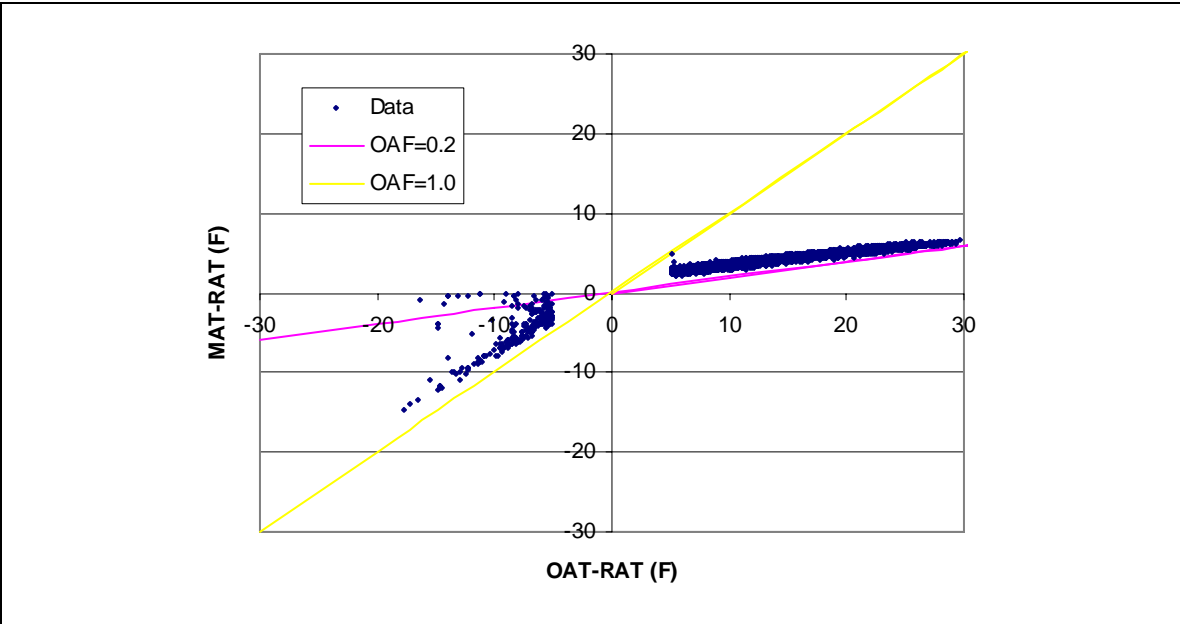


Figure 13. CSU East Bay, RTU-7, Outdoor Air Damper Operation (2006 data)

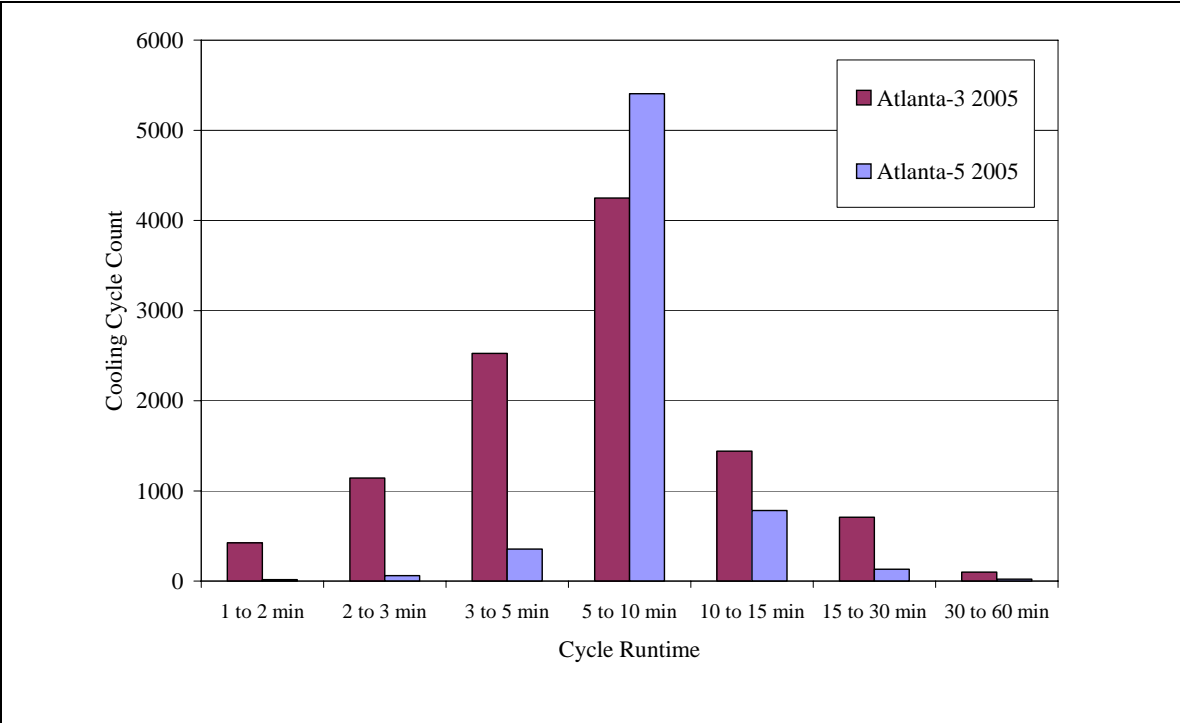


Figure 14. Honeywell GSRC Cooling Cycle Runtime