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HAWAIIAN ELECTRIC COMPANY

HECO, HELCO, and MECO Outage and Restoration Comparison
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1 System Comparison Summary

In PUC Order No. 22986, Docket No. 2006-0431 ("PUC Order"), a reference under II.A Discussions, at the bottom of page 7 states: "… there may be some benefits to being able to compare the different utility systems on each of the three affected islands. These differences can and should be explained in the context of the outages and the varying restoration times." This report specifically addresses the comparison of the Hawaiian Electric Company (HECO), Hawaii Electric Light Company (HELCO) and Maui Electric Company (MECO) systems with respect to the power outages and restorations associated with the earthquake on October 15, 2006.

POWER Engineers, Inc. (POWER) was retained to investigate the cause of the outages on the islands of Oahu, Hawaii and Maui and provide professional opinions on the reasonableness of the responses of the HECO, HELCO, and MECO staff during the event and during power restoration. At this time, investigations of the outages and restorations on the HECO, HELCO, and MECO systems have been completed and separate reports have been submitted pertaining to each respective company. Based on data regarding the outages and historical information provided by the utilities, and analysis performed for each of the three reports, POWER has formed opinions regarding the comparison of the outage and restoration of the three power systems.

1.1 Findings

A. On Oahu, Maui and the island of Hawaii major portions of their generation fleet tripped due to effects of the earthquake or the actions of operators in response to the earthquake. The Oahu and Maui transmission and distribution systems remained intact, which kept all system load connected as multiple generators tripped and consequently upset the generation-load balance. The load shed schemes operated but the generation to load imbalance on Oahu and Maui was too great, resulting in automatic trips of generators, extended low frequency operation and operator trips of the remaining generators to protect the units. Island-wide blackouts ensued.

B. The initial events on the HELCO system differed from HECO and MECO. On the Island of Hawaii where the seismic activity was the strongest, transmission and distribution circuits opened and the Hamakua Energy Partners power plant tripped as a result of the earthquake shaking equipment and protective devices. The earthquake-induced separation of the HELCO transmission system resulted in significant load reduction and unlike on Oahu and Maui, initially caused an over-frequency condition. The over-frequency condition led other generators to trip which then led to an underfrequency condition. The ability of the system operator to quickly bring additional generators on line, and the operation of the load shed scheme allowed the HELCO system to stabilize a portion of the system and prevent total blackout.

C. The HECO and HELCO systems had protective devices that operated due to the earthquake shaking these devices and not by actual conditions for which the protective devices were meant to operate. The devices involved were the HECO Kahe 5-6 plant Electro-Hydraulic governor system “Low-Low Fluid Level” level switches and the HELCO transmission line auxiliary relays, transformer sudden pressure relays and transformer fuses.

D. On the island of Hawaii and Maui, vibration protection equipment tripped combustion turbine generators, which comprise a significant portion of both systems’ base load generation. These were deemed to be valid trips to protect the machines, even though they were caused by forces exterior to the turbine/generator units.

E. HECO dispatchers took appropriate actions to start additional generation and manually shed load to try to maintain operation of their system. The HELCO system operator took appropriate actions to start additional generation to maintain operation of their system. The MECO dispatchers were unable to assist the system with load shedding due to the faster loss of generation.

F. After starting generation that was immediately available, the HELCO system operator followed established procedures and began to close transmission lines that had tripped, start generation when the grid was restored to the plants, and restore load as additional generation became available. These actions minimized the length of the outage to HELCO customers in areas where the system could be restored by remote control.

G. The HECO system is comprised primarily of steam generation. In contrast, as is appropriate given the much smaller size of their islands' loads, the HELCO and MECO system generation resources are primarily diesel internal combustion engines and combustion turbines. The HELCO and MECO diesel plants provide a faster black start for each system than for the black start of steam plants on the HECO system. The main advantage for HELCO and MECO is the reduction of time to get diesel and combustion turbine generation on line after a blackout to start the other plants. However, due to the generally smaller unit ratings MECO must add generators and match expected feeder load pickup (in 2.5 MW to 5 MW increments) with the available online generator capacity.

H. Although overall restoration time was not significantly delayed, black start of steam units on Oahu and Maui was initially delayed by malfunctions on equipment in the steam plants being started and problems in reconfiguring auxiliaries. These equipment malfunctions were attributed to the earthquake or subsequent shock of the emergency shutdown of the boiler/turbine/generator sets that complicated the restart and contributed to errors in reconfiguring auxiliaries. The steam plant black start generators for Oahu and Maui are sized such that they require the steam plant personnel to configure the black start auxiliary load so that it is within the rating of the black start unit. Additional reconfiguration of these auxiliaries, as a result of equipment malfunctions, added complication to the black start process. As this island-wide black start procedure is seldom put into actual use, and those rare occurrences usually follow an emergency shutdown which stresses the equipment, it is understandable that problems and malfunctions could arise and delay the restart.

I. Overall, internal utility communication systems worked well on Oahu and Hawaii, but primary communications were temporarily lost on Maui due to loss of station service power at the power plants. The initial communication setbacks on Maui did not appear to have delayed the restoration or contribute to the outage.

J. HECO's distribution system is much larger than the HELCO and MECO distribution systems. HECO, HELCO and MECO must first sectionalize their transmission system and disconnect distribution feeders before black starting generating units. The transmission grid must be systematically re-energized and distribution circuits carefully restored to avoid overloading generators as they return online. HECO has SCADA control over the 138 kV and 46 kV breakers and some of the 12.47 kV distribution breakers. A large portion of HECO's distribution level breakers require a trouble-man or maintenance crews to travel to the station to open the breakers, and then again be present to close the breakers. Due to the large geographic size of its transmission and distribution system and a greater reliance than HECO on load shed to deal with generation trips, HELCO has all of its transmission system and 60% of its distribution system available to SCADA control. Because of a similar reliance on load shed to deal with generator trips, MECO can control about 65% of its distribution breakers by

SCADA. HECO, HELCO, and MECO system operators can utilize SCADA remote control to sectionalize the transmission system and close sections of the transmission system to provide starting power to the other power plants, so this attribute is common to all three systems. The smaller number of distribution circuits and greater portion of the remote SCADA control on the HELCO and MECO distribution system breakers provides an advantage for their dispatchers to select loads to restore across the system, without a need to have personnel at the substations.

With its distribution system feeder breakers mostly manually operated, HECO needs to direct personnel outward from its power plants and baseyards in an organized manner. All feeders are restored at a particular substation, before moving methodically to the next substation to minimize travel time and thus restoration time. On October 15, 2006 availability of crews to perform manual operations was not a major limiting factor on Oahu, as HECO had sufficient crews to close in feeders at several substations simultaneously. For most of the day and evening, the HECO maintenance crews were in place and awaiting generation to stabilize so they could restore the next feeder under direction from the dispatcher.

K. Making a meaningful comparison between restoration times between the island systems is difficult, as the size and makeup of each system is different and the events that transpired on each island were different. Unlike HECO and MECO, HELCO did not have an island-wide blackout and therefore, did not have to undergo black start procedures. When looking at the initial time required to restart the systems, the predominance of diesel internal combustion engines (ICE) and combustion turbine (CT) generation on Maui provides a much quicker black start and restoration capability. However, when looking at the overall rate in which generation capacity was added and load restored over the length of the outage, HECO added load more than twice as fast as HELCO or MECO. This is consistent with the larger generator ratings and number of personnel available to restore the HECO system.

1.2 Conclusions

A. The earthquake on October 15, 2006 was of large enough magnitude and energy to cause damage or operational failure on equipment in all three systems. This led to the island-wide outages on Oahu and Maui and a partial system outage on the island of Hawaii.

B. On all three systems the seismic activity triggered multiple automatic and manual generator trips which severely stressed the systems and caused generation to load imbalances. During the course of the events, operations personnel on all three systems responded in an appropriate and professional manner to protect equipment and prevent system wide collapse where possible. Dispatchers on Oahu followed their established system operating procedures, starting remote generation and shedding load, in response to the system upset and resulting frequency decline. The HELCO system operator took appropriate actions to start additional generation to maintain operation of their system.

C. The generation mix on Oahu is primarily comprised of steam units which take longer to start up. In contrast, the generation mix on Maui and Hawaii are primarily comprised of diesel internal combustion engines and combustion turbines of smaller capacities which by their inherent nature can be black started more quickly.

D. Total restoration times for the HECO, HELCO and MECO systems varied due to differences in system size and generation mix for each island, the fact that HELCO did not experience an island-wide outage, and the fact that the earthquake caused damage and trips on the HELCO transmission system. Considering these factors, we conclude that no there were no discernable delays in restoring the HECO system compared with the HELCO and MECO systems, with the exception of the time to get the first unit black started on the grid, and even in this case, the delay did not significantly impact the total restoration time.

2 System Comparison

2.1 System Background

Approximate system loads on October 15th, 2006, just prior to the earthquake were HECO at 837 MW, HELCO at 126 MW, and MECO at 137 MW. Energy demand was increasing on all three systems. Table 1 below shows a comparison of the number of transmission and distribution system components between the three systems. Please refer to Section 3 of the HECO, HELCO and MECO individual reports for specific details regarding the outage and restoration analysis of the separate systems.

Table 1: HECO, HELCO and MECO T&D System Summary

T&D System Summary HECO, HELCO and MECO *Approximate values only	HECO	HELCO	MECO (Maui)
Transmission Substations			
138kV	17		
69kV		20*	15
23kV			7
13.8kV		1	
Distribution Substations	134	50	33
Total subs	**151**	**71**	**55**
*(11 of HELCO 69kv transmission stations also serve distribution load)			
Transmission Circuits			
138kV	32		
69kV		28	17
46kV	5		
13.8kv		3	
Sub-transmission Circuits			
46kV	62		
34kV		6	
23kV			15
Distribution Circuits	455	126	92
Total circuits	**554**	**163**	**124**

When comparing the three systems, the approximate customer count (# of meters) for the three systems are: HECO: 292,779; HELCO: 76,144 (only 62,000 affected by the outage); and MECO: 59,998. This indicates that the HECO system has about 3.8 times the number of customers as HELCO and 4.9 times the number of customers as MECO. Of particular note in Table 1 is that the HECO system on Oahu has significantly more distribution substations and feeders to restore than the systems on Hawaii and Maui.

HECO's system on Oahu can be remotely controlled by the dispatcher for all of the 138 kV and 46 kV transmission system breakers and about 10% of the 12.47 kV distribution system circuit breakers. The majority of the distribution breakers must be opened/closed locally by a trouble-man or maintenance crew during system restoration. HECO has an automatic load shed scheme which initially trips 12.47 kV distribution breakers to drop small blocks of load. Then, if frequency continues to decay, it trips 46 kV breakers and drops substations with larger load blocks. On October 15th, 2006, approximately 1,737 MW of generating capacity was currently installed on the island of Oahu, with 1,278 MW owned and operated by HECO, and 459 MW by Independent Power Producers (IPPs). The HECO-owned 1,278 MW plant capacity consists of 1,162 MW steam boiler/turbine plant equipment, 103 MW of combustion turbine and 15 MW of distributed diesel generation. HECO's system is of sufficient size that it operates with a spinning reserve capacity to absorb the loss of the single largest plant in operation at the time (up to 180 MW for Oahu).

HELCO's system has a significant amount of SCADA controlled distribution breakers in place due to the large geographic area of the HELCO grid and the greater reliance on load shedding in lieu of spinning reserve. This normally allows the majority of distribution circuits (75 of 126) to be closed in remotely from the dispatch center rather than having crews drive to the substations and manually open/close breakers during restoration. This provides added flexibility in the load restoration sequence. HELCO employs an underfrequency load shed program with nine steps that would shed approximately 81 MW of load on a day peak (March 1, 2007 data). On October 15, 2006, approximately 276 MW of firm generating capacity was installed on the island of Hawaii; with a further 29 MW of wind and hydro power as-available. Of the 276 MW, 186 MW is owned and operated by HELCO and 90 MW by IPPs. Sixty four percent of the base load capacity (90 MW) is owned by two IPPs (HEP at 60 MW and PGV at 30 MW). Puna Geothermal Ventures (PGV) comprises a geothermal plant and HEP is a combined cycle plant with two combustion turbines and a heat recovery steam turbine. The remainder of the base load capacity is comprised of HELCO steam plants Hill 5, Hill 6 and Puna.

The MECO system operates in a similar manner to the HELCO system with a load regulating reserve rather than a spinning reserve and depends on an underfrequency load shed scheme to maintain generation-load stability on loss of a generation unit. MECO's system operator can remotely control the 69 kV and 23 kV system breakers and about 65% of the 12.47 kV distribution breakers, which allows significant flexibility in the system restoration sequence. MECO has a 3 step load shed program. On October 15th, 2006, approximately 293 MW of generating capacity was installed on the island of Maui, with 250 MW owned and operated by MECO and 43 MW by IPPs. The MECO generating equipment is split between reciprocating engines (approximately 33%), CT in combined cycle with steam turbines (approximately 40%) and boiler/turbine steam plants (approximately 12%), supplemented by a small amount of renewable generation (approximately 15%).

On Maui and Hawaii, the generating fleets are comprised mainly of diesel engines and combustion turbines. Steam plant capacity makes up only around 24% of HELCO's generating capacity, and 12% of MECO's. HECO (including both utility and IPP) has 91% of its generating capacity in its steam plant fleet. HECO's distributed diesel units are generally used only for peaking service as they are the least economical units to operate. HECO, HELCO and MECO all have combustion turbines (self-owned or IPP) which comprise a portion of their fleet. HECO's next planned generation is a 110 MW combustion turbine to be installed at Campbell Industrial Park in 2009, which will have black start capability. The types of capacity of installed generation on each of the islands appear to be reasonably selected to economically serve their respective loads.

The generation technologies and the smaller generating units on Maui and the island of Hawaii are quite different to start and operate compared to those employed by HECO. HECO's steam boiler/turbine units are inherently slower to start and bring on line and can be somewhat temperamental to start and re-load after a system upset. In the early stages of restoration on the HECO system, great care must be taken to stabilize the system, properly increase boiler pressure as load is added, and operate within the covered source permit constraints. The smaller individual unit ratings of the HELCO and MECO units provide a faster start for each unit, but this also limits the amount of load that an individual unit can pick up. Thus, HELCO and MECO also must carefully match expected feeder load pickup with the available on line generator capacity. We must also note that operation within the covered source permits also causes some constraints on starting sequence and loading of generators on all three systems.

2.2 Comparison

The separate outage investigation reports for the HECO, HELCO and MECO systems were reviewed and compared with respect to the events of the outages and varying times of system restorations.

A number of outages on the U.S. mainland were assessed to see if they had any comparable relevance. In all cases examined, the generation mix, cause of the outages, interconnections between utilities, and (in most cases) extensive transmission system damage from storms, were so dissimilar that they do not provide a reasonable basis for comparison to the HECO, HELCO or MECO system outages or restorations on October 15, 2006.

Significant comparison items between HECO, HELCO and MECO:

- All three systems had a major portion of their generation capacity initially tripped as a consequence of the earthquake.
  - HECO had trips of the "Low-Low Fluid Level" on the Electro-Hydraulic (E.H.) governor system that regulates steam flow to the turbines. These switches on Kahe 5 and Kahe 6 operated the "Low Fluid Level Lockout" relays that prevent the E.H. system pumps from restarting to maintain the required operating hydraulic pressure, thereby leading to the loss of power from Kahe 5 and Kahe 6. These were evaluated to be caused by operation of the switches by the earthquake shaking the contacts into closed position rather than actual low liquid levels. These two trips resulted in loss of 280 MW of generation capacity.
  - HEP's two combustion turbine generators on the island of Hawaii were tripped by their vibration protection when the minimum mechanical clearances were exceeded due to the earthquake shaking. When mechanical clearances are exceeded, the machine is in danger of sustaining damage even if the source of the problem is external shaking. The Hill 5 unit's boiler tripped and difficulties resetting the fuel oil valve resulted in a manual trip of the turbine as steam pressure fell. (74 MW)

- MECO's Maalaea M14 and M16 combustion turbine generators were tripped by their vibration protection due to the external shaking. Kahului Unit 4 was tripped by the supervisor noting visible shaking, but immediately thereafter recorded a vibration alarm which would have led to a trip of the unit. (40 MW without K4)

- All three systems had some generation capacity tripped by the operators.
    - In response to the shaking and alarms, HECO operators tripped Kahe Unit 3 and Honolulu Unit 8, suspecting that they had turbine vibration problems. In each case, the unit tripped was the only unit operating in the pair of units normally operated by the control room (108 MW). And as stated in the HECO report, we found these operator trips to be reasonable and in the public interest considering the alarms, observations, and previous experience.
    - HELCO operators tripped the Puna Steam turbine off-line when the unit went into a reverse power mode. This action was warranted and operators are provided specific training in this regard to protect the machine. (15.5 MW)
    - The MECO Kahului Power Plant Shift Supervisor was walking toward the control room when the earthquake occurred. He observed Kahului unit 4 turbine shaking violently and water leaking from the Kahului unit 4 boiler. He assumed that the turbine was ingesting water, went into the control room, and manually tripped the turbine. Immediately after the manual trip, the distributed control system (DCS) recorded a turbine vibration alarm which would have otherwise caused the unit to automatically trip. (12.5 MW)

- The HECO and MECO transmission systems remained primarily intact, keeping all system load connected as multiple generators tripped from earthquake or operator action and load shed operated. The initial loss of multiple generators resulted in an unrecoverable generation-load imbalance on both systems, causing additional generator trips and severe low frequency operation which the load shed was unable to correct. Both systems were subjected to extended low frequency operation while the remaining generation tried to support too great a load. Given the speed in which events occurred and the level of generation to load imbalance, the HECO system dispatchers were unable to manually shed enough load to correct the imbalance. The MECO system dispatchers also were unable to manually shed load to help correct the imbalance before the system collapsed.

- The earthquake caused transmission line auxiliary and transformer sudden pressure relays to operate from the shaking on the HELCO system, primarily on the west side of Hawaii in closer proximity to the earthquake epicenter. HELCO's system also had substation transformer primary fuses shaken from the fuse holders. These earthquake induced relay operations resulted in separation of the HELCO transmission system on the west side of the island. The resulting significant load reduction created an extreme over-frequency condition on the remaining portion of the grid. The combination of the events, the ability of the system operator to quickly bring additional generators on line, and the operation of the underfrequency load shed scheme resulted in a significantly different system stability response for Hawaii than for Oahu and Maui.
- Immediate Operator Response:
  - HECO's dispatcher initiated remote start of the dispersed diesels and called Waiau power plant to start the Waiau combustion turbine generators when he noted that the plant operators had tripped Kahe 3 and Honolulu 8, and that Kahe 5 lost power output as the E.H turbine governor shut off steam to the turbines. By the time the diesel and CTs could get through their start and warm-up sequence, Kahe 6 lost power as its E.H system shut off the steam to the turbines. System frequency continued to drop, which resulted in tripping of additional generation plants and prevented the distributed generators and CTs from synchronizing and connecting to the system. Automatic load shed operated and the dispatcher manually shed load but was unable to restore generation-load balance.

- MECO operators experienced initial communication outages with the power plants. As the power output dropped off from the loss of units M14, M16 and Kahului 4, the remaining units began to pick up load. Some of these remaining units tripped due to over-temperature, under frequency or over load. The Maui automatic load shed scheme operated as designed but was insufficient to balance the load with the remaining generation due to the magnitude of generation-load imbalance. The system then went into extended low frequency operation and the operators tripped the remaining units to prevent low frequency damage.
- The HELCO system initially went into over-frequency when the transmission system separated. The system operator was able to start additional diesel, steam and combustion turbine resources and get them on-line, consistent with established HELCO procedure during a system upset. These units were able to connect to the grid to balance generation lost from the steam units. With the manual trip of the Hill 6 steam unit, an underfrequency load shedding event occurred with the frequency recovering to 59.05 Hz. With the decline of the Hill 5's output, the frequency continued to decay and triggered a second underfrequency event, with recovery to 59.15 Hz. In parallel with these events the system operator began remotely reclosing transmission lines and starting additional power plants as they were reconnected to the grid.
- Both HECO Waiau CTs were not scheduled to run and were off line at the time of the event in accordance with economical unit commitment practices. The Kalaeloa Power Partners CT that separated from the HECO system during the event was put on turning gear but it still incurred shaft warp, which required additional time to correct the problem before returning the unit to service. MECO had three combustion turbines operating -- M14, M16 and M19 -- that went into thermal lock when they could not be put on turning gear within 7 to 10 minutes of the shutdown. HELCO's CTs were all off-line when the event occurred. The two HEP CTs on the island of Hawaii tripped on vibration and were

put on turning gear, powered by their plant diesel generator, and were ready to be restarted when the grid was restored to the plant.

- System Restart: The HECO restart took 4 hours and 27 minutes. The Maui system restart took 1 hour and 17 minutes. HELCO maintained power to a portion of its system on the east side of the island, so a black start and complete system restoration was not required. After experiencing the earthquakes, each utility required extra care to assess whether there was equipment damage in the plants and on the transmission/distribution systems. In all cases, some equipment was damaged or had problems due to the earthquakes or the emergency shutdown. HECO and MECO steam units had black start delays due to trips of the black start generators for various reasons. The primary reasons were related to malfunctions on equipment in the steam plants being black started and properly configuring the auxiliary loads and connections.
  - Power plant personnel at the Kahe power plant on Oahu and at the Kahului power plant on Maui encountered trips from too much auxiliary load for the black start generator capability. As the black start progressed at Kahe, equipment failures encountered on Kahe 1 and Kahe 3 led to switching the startup priority from one unit to another, which eventually resulted in a trip of the black start diesels because the progress of each unit was not fully communicated, resulting in overload of the units from too many auxiliary loads. The HECO Waiau 6 unit also had a trip when the DCS tripped while troubleshooting a problem with the DCS on the sister unit, Waiau 5. This is indicative of the fact that steam plants are, in general, more difficult to black start. In the case of HECO, the decision to parallel black start efforts at both Kahe and Waiau soon after the onset of the island-wide blackout reduced the impact of black start delays encountered at Kahe from affecting the overall island restoration effort. Similarly, on Maui the trip of the Kahului black start unit did not delay system restoration as the decision was made to

parallel black start efforts at both Kahului and Maalaea and that Maalaea diesel units were restarted in much less time.

- On Oahu, black start capability is presently provided at Kahe and Waiau. This capability is installed in a similar manner at the Kahului power plant on Maui, though much larger in size. The black start generators are sized such that they require the steam plant auxiliary load to be matched to the generator capabilities to prevent trip on overload. There are step by step procedures for the proper sequence for turning on auxiliary systems. In a typical blackout situation such as one caused by a system separation event, an outage would leave a number of steam units with their boilers pressured up, in which case they could come back on line in approximately two to three hours. On Oahu, it takes two to three hours to open feeder breakers to prepare the system to begin load restoration.
- The Maui Maalaea Power Plant has diesel internal combustion engine units which are battery-started, and with a capacity of 2.5 MW, those units are sufficient to start and connect to the dead 69 kV bus without any modification of the auxiliary load connections. The auxiliary load required to start one of the larger diesels units or one of the combustion turbines at Maalaea is well below this rating. One of the peaking generators can be started in minutes, but time is still required to open all of the 69 kV breakers at Maalaea and open the system distribution feeder breakers to isolate loads. It then takes about 15 minutes after power is restored to the other generators to recharge their system air pressure and start one of the larger diesels that can better handle load pickup. This provides MECO, with a restart capability of one to two hours to begin restoring load, depending primarily on the time required to sectionalize the transmission and distribution system. On October 15th, MECO had the M6 unit started and ready to take load before the grid was completely sectionalized so the unit twice tripped on overload attempting to reenergize the system. This is not deemed to have significantly

impacted the restart time as the diesel units were able to restart in minutes while additional sectionalizing was performed.

- ➢ Combustion turbines can be started, warmed up, connected to the bus and loaded within 30 minutes and some even as fast as 5 minutes on the HELCO system, although a key issue is that the CTs need to be able to quickly pick up to their respective minimum loads (5-8 MW) of load to maintain operation in compliance with covered source permit requirements. The CTs are equipped with turning gear that must be used to rotate the turbine rotors and circulate air through them after a shutdown to ensure that the rotor cools evenly with the outer case. Without this gear in operation, the turbine rotors can distort slightly as they cool or the outer case can cool faster than the rotor causing "thermal lock", and then the unit cannot be restarted until it has cooled down completely. The LM 2500 CTs on Maui and the island of Hawaii must be on the high speed turning gear within 7 to 10 minutes of shutdown to prevent going into thermal lock. The Maalaea combined cycle plant operator was unable to reconfigure the auxiliary bus, start the emergency generator, and put M14, M16 and M19 on the turning gear within this time window. Consequently the units went into thermal lock and required about 3 hours to cool down before they could be restarted.

- o Communications: Internal utility communications worked well on Oahu and Hawaii. MECO experienced initial communication problems, but these were resolved once station power was restored to the power plants and did not delay restoration or contribute to the island-wide outage.
- o System Sectionalization: The HECO crews needed to travel to, make condition assessments of and energize 3-1/3 times as many substations as the HELCO system and 4-1/2 times as many as the MECO system. The HECO system requires about 3 hours to configure the distribution substations and MECO requires about 1.5 hours. Because of the larger geographic area of the transmission and distribution system and the greater reliance of load

shedding instead of spinning reserve, the HELCO T&D system is almost fully automated and the distribution loads can be quickly stripped by SCADA.

- System Restoration: It is difficult to find a meaningful method of comparing the pace of restoration, as the makeup of each of the systems is unique to their island, generation mix, and load. However, we can offer the following observations.
  - Each utility has a priority to restore the transmission system to the power plants to allow them to start additional generation units.
  - Each utility has a practice to close in on loads sized from 2.5 MW to 6 MW to maintain system generator stability as load is added (during later stages of the HECO restoration, load was restored in larger blocks, up to 10 MW in size once more units were in operation).
  - HELCO and MECO have much more distribution automation than HECO which allows them more geographic flexibility to match available generation capacity with anticipated feeder loads at different substation locations. HECO's practice is to close in all feeders in a substation, fanning out from the power plants, and then have the crews move to the next substation to avoid backtracking between substations.
  - Restoration of the majority of the customer load took 15.5 hours on Oahu and 6 hours on Maui. On the island of Hawaii, all feeders were closed in by 1245 hours (5.6 hour outage), with the exception of those where the circuits or substations required repairs in order to be restored to service.
  - Despite greater SCADA control of distribution breakers and faster black starting of their first units on Maui and start of generation the island of Hawaii (black start was not required on Hawaii), in the timeframe beginning with the start of the outage to point when restoration of power was provided to the majority of their customers, HECO restored load at an average of 54 MW/hour compared with MECO's average rate of 23 MW/hour and HELCO's average rate of 27 MW/hour.

- Each utility experienced events which slowed system restorations. For HECO the events that slowed restoration were trips during the black start process and resetting of load shed relays which added a total of approximately 1.5 hours to the restoration time. MECO was slightly slowed as the generation was started and twice tripped on overload as they tried to reenergize the system while continuing to sectionalize the system load. HELCO's restoration was slowed due to the operation of transformer sudden pressure lockout relays and transformer fuses due to the shaking caused by the earthquake. Personnel were required to visit stations and correct the problems before affected transmission breakers and distribution feeders could be energized or generators started. HELCO's system also experienced earthquake damage at two switching stations and 34 kV transmission lines which required repair before the complete transmission system could be restored to western Hawaii. In the process of getting personnel to the stations to reset relays, replace fuses and make repairs, HELCO also had to contend with delays from road closures.