March 27, 2007

# MAUI ELECTRIC COMPANY

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## *Investigation of 2006 Maui Island -Wide Power Outage*
## *PUC Docket Number 2006-0431*

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111699

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# Executive Summary

The State of Hawaii experienced a 6.7 magnitude earthquake west of the island of Hawaii at about 0707 hours on Sunday, October 15, 2006 (epicenter). This was the strongest earthquake recorded in Hawaii in 23 years. According to the Hawaii Volcano Observatory (HVO), a second earthquake (6.0 magnitude) occurred approximately seven minutes later. Associated power system events led to island-wide blackouts for Hawaiian Electric Company, Inc. (HECO) on Oahu and Maui Electric Company, Ltd. (MECO) on Maui, although there was little apparent seismic damage to the electric systems on either island. Hawaii Electric Light Company, Inc. (HELCO) on the island of Hawaii maintained partial service with an isolated section, or “island” of generation and customer load in the Hilo area.

MECO had restored service to the majority of its customers by 1315 hours and the remaining customers by 1432 hours on October 15.

POWER Engineers, Inc. (POWER) was retained to investigate the causes of the outage on Maui and provide professional opinions on the reasonableness of the responses of the MECO staff during the event and during power restoration. POWER’s principal investigators, experts in power delivery systems and generation plant design and operation, traveled to Maui on January 8 and 9, 2007 to discuss the events with MECO staff, conduct field visits and gather information relevant to the events of the power outage and restoration on Maui. Additional information was gathered via discussions over phone, through follow up information requests, and analysis of system drawings, relevant Company logs, records, personnel interviews, and other applicable system documentation.

In summary, we find:

- The MECO system was in proper operating condition and appropriately staffed by personnel at the time that the earthquake struck.
- The earthquake causing vibration sensors to trip Maalaea M14 and M16 generators was the direct and proximate cause of the island-wide outage. Loss of these generators set in motion a series of events (through the operation of automatic relays and through operators' actions to protect the equipment) which resulted in sequential loss of generation and eventually led to the system shutdown.
- In POWER's opinion, the MECO personnel reacted to the circumstances in a reasonable, responsible and professional manner. They applied training and experience in reacting properly to the changing system conditions based on the existing system configuration and established MECO operating practices to restore power as quickly as practical.
- Trips of the black start diesel unit at Kahului during the black start process did not impact the system restoration time because the combination and configuration of diesel units at Maalaea Power Plant provided a much faster black start capability.
- Trips of the M5 and M6 diesel units at Maalaea during the initial attempts to re-energize the 69 kV system delayed overall system restoration by approximately 15 minutes. In POWER's opinion, this was a result of attempting to re-energize the system before the transmission and distribution system loads were completely sectionalized.
- In the restoration, MECO operated reasonably and in the public interest by following a systematic, orderly and methodical approach to add priority and customer load to the system as quickly as generators could be started and connected to the bus.
- With the understanding that no system event will ever be identical to the one before it, we do make some specific recommendations which can be found at the end of this Executive Summary and in Section 5 of the report.

<u>Discussion of Findings</u>

The Hawaii Public Utilities Commission issued PUC Order No. 22986, Docket No. 2006-0431 ("PUC Order") requiring an examination of whether HECO, HELCO and MECO acted reasonably and in the public interest prior to and during the power outages. The PUC Order, Section II.C Preliminary Issues, page 8 and page 9, established the scope for this investigation.[1] This report addresses the following issues with respect to MECO.

1. *Aside from the earthquake, are there any underlying causes that contributed or may have contributed to the power outages?*

   We believe that the main underlying cause of the outage was the seismic action of the earthquake triggering vibration alarms and trips on Maalaea unit M14 and M16 generators, due to the shaking of the combustion turbine-generator set. The alarms and trips were valid to protect the equipment, even though the cause was an external event and not equipment damage. In this case, the M14 and M16 generators were tripped simultaneously and the corresponding heat recovery steam generator, M15, also lost its heat source and would soon lose output power. Other generating units were consequently tripped by their protection systems as the loss of M14 and M16 stressed the system.

2. *Were the activities and performance of the HECO Companies prior to and during the power outages reasonable and in the public interest? Specifically, were the power restoration processes and communication regarding the outages reasonable and timely under the circumstances?*

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[1] We understand that the preliminary issues were adopted as the issues for Docket No. 2006-0431 by Order No. 23155 (filed December 21, 2006).

MECO's performance prior to and during the outage demonstrated reasonable actions in the public interest. The investigation found that prior to the outage, the system had all transmission lines in service and the appropriate generation available to supply load and reserves according to the MECO operating practices. MECO had a load shed scheme in operation. They have performed regular training; such as emergency response Incident Command exercises and black start training at the power plants.

The operator trip of Kahului unit 4 was reasonable and in the public interest considering the observations and previous experience of the operator. Power plant alarm logs indicate that the unit alarmed on high vibration two seconds after the operator trip, so K4 would have been tripped by the operator in any case based on the alarm.

The actions of the MECO staff were certainly reasonable and timely and in the best interests of the public. Two cases where responses could have been improved are tripping of the Kahului black start generator by overload from too many auxiliaries left on the bus and trip of the Maalaea diesel units M5 and M6 on overload when attempting to pick up too large of load increments. In POWER's opinion, the trip of the Kahului black start did not affect the duration of the outage because the Maalaea Power Plant is configured to allow fast start from the diesel generators without having to reconfigure auxiliary buses. In other words, the island restoration would not have taken any less time if the Kahului black start process did not encounter the overload trip. We are not aware of any case where actions could be described as imprudent or likely to cause injury, or damage. In our opinion, actions by MECO personnel were reasonable, responsible and conducted in a professional manner.

The system restoration plan developed after the outage by the operations staff was reasonable based on the MECO generation available to restart the system and MECO management's historical knowledge of critical restoration issues. The plan appears to have been well executed by the management, dispatchers, power plant operators and field crews after the system was sufficiently sectionalized to allow Maalaea Power Plant to re-energize the system. Initial attempts to energize the 69 kV system with too large an increment of load connected resulted in two trips of the diesel generators. During the restart time, additional loads were disconnected to dial in an increment that could be picked up while energizing the 69 kV and 23 kV systems. This process took about 15 minutes, successfully restoring power at 0902 hours. The aggressive pace of the restoration was balanced against the risk of tripping the generators restored to service, which would have required the system to be re-sectionalized and then re-started. Coordination between load dispatch and the power plants was set up with a central point of contact at Kahului power plant to relay messages to Maalaea. The generation/load mix was monitored and controlled by the dispatcher and Kahului station supervisor. The plant operator would tell dispatch how much load they could take as generation was brought on line and dispatch would select a feeder which would fit within the load range, based on experience and load readings prior to the outage, and close the breaker. A significant portion of the MECO system can be closed in by SCADA, which allowed the dispatch staff to select and close priority feeders as generation became available that matched the estimated load of the feeder.

Most of the MECO primary internal communication systems initially failed to operate due to a loss of power, but did not contribute to the outage or significantly hamper restoration as communication between the dispatch center, power plants and field crews was established using the MECO short wave radio system and external land-line and cellular telephones. Once auxiliary and utility power was restored, the MECO internal communications system returned to normal operation. Loss of the communication systems was a result of failure of the backup emergency power sources.

3. *Could the island-wide power outages on Oahu and Maui have been avoided? What are the necessary steps to minimize and improve the response to such occurrences in the future?*

In POWER’s opinion, the outage on Maui was unavoidable given the circumstances. The vibration trips of the Maalaea combustion turbine M14 and M16 generators were valid to protect the equipment even though they were initiated by external shaking. At the time of the earthquake the MECO system was carrying a reserve capacity of 36 MW and loss of M14 and M16 dropped 40 MW of generator capacity and also stopped providing heat to the combined cycle boiler for M15, which would soon lose power output and 18 MW of generator capacity. The first load shed block operated as designed when the frequency dropped. With the block 1 load shed and pickup response of the remaining generators, frequency was recovering. Then, M19 automatically tripped on an over-temperature protective trip, and Kaheawa Wind Power (KWP) automatically tripped on an underfrequency protective trip, and K4 was manually tripped, collectively dropping 51.8 MW of capacity. At this point, all remaining load shed blocks operated and there remained a severe load-generation imbalance. The frequency decayed below the EMS measurement threshold of 59 Hz, but protective relay event reports recorded frequencies down to 40 Hz. As the majority of the transmission system remained physically intact, load was disconnected by operation of the automatic load shed scheme. An out of step condition occurred at Puunene and the 69 kV breakers tripped, separating a section of the 69 kV system from Puunene to Kula substations. Operators at Maalaea power plant reported that their remaining generators on line were operating at about 200 rpm when they are designed to run at 450 rpm, indicating a severe overloading and under frequency operation. The M10 and M11 unit auxiliaries had shut down and the operator had to trip them to prevent damaging the machine, resulting in the island-wide outage. POWER could not determine any different actions that could have been taken by the MECO staff that would have clearly prevented a blackout.

With respect to improving responses to future events, POWER offers recommendations 1 and 3 below to improve the MECO communication reliability and reduce the time required to prepare the transmission and distribution system for re-energization.

## Recommendations

The detailed recommendations from Section 5 are summarized below.

1. Evaluate the various internal MECO communication systems and associated emergency and uninterruptible power supplies. Institute recommendations from the evaluation to provide robust and dependable internal communication emergency power supply systems. MECO began this assessment soon after the outage has been implementing the recommendations.

2. Assess the communication protocol between dispatch and power plant operators to determine if they can or should be streamlined to allow closer coordination between dispatch and the individual plants during system restoration.

3. As the MECO system has a significant “fast start” capability, assess the possibility of programming a single button “black system” feature in the SCADA system to automatically open SCADA controlled breakers so that this activity does not become the critical path for system re-energization.

4. Evaluate upgrade of the system frequency and voltage recording equipment to install devices with faster scan rates and wider upper/lower limits to provide better data resolution for evaluating future events.

# 1 Introduction

The State of Hawaii experienced a 6.7 magnitude earthquake west of the island of Hawaii at about 0707 hours on Sunday, October 15, 2006 (epicenter). This was the strongest earthquake recorded in Hawaii in 23 years. According to the Hawaii Volcano Observatory, a second earthquake (6.0 magnitude) occurred approximately seven minutes later. Associated power system events led to island-wide blackouts for Hawaiian Electric Company, Inc. (HECO) on Oahu and Maui Electric Company, Ltd. (MECO) on Maui, although there was little apparent seismic damage to the electric systems on either island. Hawaii Electric Light Company, Inc. (HELCO) on the island of Hawaii maintained partial service with an isolated section, or “island” of generation and customer load on the east side of Hawaii.

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POWER Engineers, Inc. (POWER) was retained to investigate the causes of the outage on Maui and provide professional opinions on the reasonableness of the responses of the MECO staff during the event and during power restoration. POWER’s principal investigators, experts in power delivery systems and generation plant design and operation, traveled to Maui on January 8 and 9, 2007 to discuss the events with the MECO staff, conduct field visits and gather information relevant to the events of the power outage and restoration on Maui. Additional information was gathered via discussions over phone, through follow up information requests, and analysis of system drawings, relevant Company logs, company records, personnel interviews, and other applicable system documentation.

The Hawaii Public Utilities Commission issued PUC Order No. 22986, Docket No. 2006-0431 ("PUC Order") requiring an examination of whether Hawaiian Electric Company, Inc. (HECO), Hawaii Electric Light Company, Inc. (HELCO) and Maui Electric Company, Ltd. (MECO) (collectively "the HECO Companies") acted reasonably and in the public interest prior to and during the power outages. The PUC Order, Section II.C Preliminary Issues, page 8 and page 9, established the scope for this investigation.

The PUC Order identified the following investigation subjects:[2]

1. Aside from the earthquake, are there any underlying causes that contributed or may have contributed to the power outages?

2. Were the activities and performance of the HECO Companies prior to and during the power outages reasonable and in the public interest? Specifically, were the power restoration processes and communication regarding the outages reasonable and timely under the circumstances?

3. Could the island-wide power outages on Oahu and Maui have been avoided? What are the necessary steps to minimize and improve the response to such occurrences in the future?

4. What penalties, if any, should be imposed on the HECO companies?[3]

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[2] We understand that these four issues were adopted in Order No. 23155 (filed December 21, 2006) in Docket No. 2006-0431.

[3] This report does not address this subject.

In addition, 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." The comparison is presented in the HECO, HELCO, MECO Outage and Restoration Comparison report submitted to the PUC.

From the PUC Order, MECO established the main statement of work for POWER Engineers to investigate and provide expert opinions with respect to the island-wide blackout and restoration on Maui. POWER's investigation focused on four primary topic areas for the MECO transmission system, dispatch center and power plants.

These topic areas are:

- Configuration prior to the event, to include operating procedures and prior training relevant to the event.
- Transmission system, dispatch center and power plant operator actions and automatic protection system action during the interval between the time when the earthquake seismic waves reached Maui and the onset of the island-wide blackout.
- Personnel actions and equipment operations during the interval between the blackout and the return of the first generating units back on the grid.
- Restoration of the power grid from the time the first unit came on line until restoration of service to all customers on October 15.

# 2 Sequence of Events

## *2.1 Background*

<u>Transmission and Distribution System</u>

The MECO transmission and distribution system consists of fifteen 69 kV transmission substations, seven 23 kV substations, thirty-three distribution substations, seventeen 69 kV transmission lines, fifteen 23 kV sub-transmission lines, and ninety-two distribution feeder circuits. The 69 kV and 23 kV circuits are interconnected with redundant circuits that provide multiple options for supplying power to the distribution substations to increase reliability.

MECO has three blocks of automatic load shedding with set-points of 58.7Hz (5-cycle delay), 58.5Hz (no delay), and 58.0Hz (no delay). The set-points are rotated among the three blocks to avoid disrupting the same customers over and over.

- Block 1, approximately 15.4 MW
- Block 2, approximately 10.5 MW
- Block 3, approximately 12 MW

<u>Operations</u>

MECO typically operates with a “regulating reserve”. This means that they have generators on line and running with a total capacity to produce approximately 7 to 10 MW more than the load in order to absorb typical load fluctuations. Generators are brought on line (or taken off line) to anticipate the expected load variations throughout the day and maintain the regulating reserve. The Kahului and Maalaea power plants utilize published unit start up and shut down guidelines for the units but do not have an overall plant or system operating manual. Additional operating guidelines are incorporated in conditional source permit (CSP) documents. This operating philosophy is perfectly reasonable for a relatively small electrical system like that on Maui. It is noted that the system is therefore not operated with a “spinning reserve” sufficient to cover the loss of the largest single generating unit, which is generally the operating philosophy on larger networks. Instead, MECO relies on a combination of fast start diesel engines and underfrequency load shedding to stabilize the system following the loss of the largest unit.

The Dispatch Center has a large wall display to show the status of transmission system, substation circuit breakers and generators and is staffed by the on duty Dispatch Supervisor (DS). This system has an Automatic Generation Control (AGC) function which continuously controls the dispatch of generators that are placed on ACG and displays this information on the wall screen and computer monitors. Units not on AGC control do not participate in load following. One function of the energy management system (EMS) is to record and archive system information such as generator output and frequency. Generating units are brought on line and taken off line daily according to changing load requirements. As load demand increases, the dispatcher coordinates with the Kahului Power Plant operator to dispatch the generation resources. Generator designations, capacities and loading on October 15, 2006 just prior to the earthquake are provided in Table 1.

The Kahului power plant consists of four boiler/steam turbine/generator sets. All four units are operated from one control room that monitors and operates the units. The steam turbine-generator sets are all located on the same floor as the control room.

Maalaea power plant has 15 diesel internal combustion engines (ICE) ranging from 2.5 MW to 12.5 MW generating capacity. The five 2.5 MW ICE units are battery start, while the larger units are compressed air start. Maalaea also has two combined cycle plants with each plant having two combustion turbines (CT) and one heat recovery steam generator (HRSG). One of the HRSG units was in the process of commissioning and was not available on October 15. The ICE and combined cycle plants have separate control rooms.

Each power plant is staffed with a Shift Supervisor who is responsible for the day-to-day operations of the power plant. Kahului power plant has three operators that support steam unit activities. Maalaea power plant has five operators that support diesel and combined cycle plant activities.

Base load units are economically dispatched to meet system requirements, including meeting regulating reserve, and may operate from full output to minimum output on a daily basis. The “base load” terminology in this instance indicates that the machine is connected to the bus and producing power 52 weeks per year, 24 hours per day, unless it is out of service for maintenance. Cycling units are brought on line each day as the load increases and taken off line as load decreases. Cycling units are restarted and synchronized to the system according to the commitment schedule. Peaking units are started when required to supply the system peak load.

Black start procedures are identified in Chapter 11 of the MECO Emergency Restoration Plan (ERP) for Kahului (11.8.1) and Maalaea (11.8.4) power plants.

## Relevant Training

Training of operators at power plants is done when a vacancy in an operating position occurs. The training will involve doubling up with a qualified operator for a period of 2-3 months with a solo period of 1 month to qualify for the position. The shift supervisors are responsible to oversee and follow up with the training. The supervisors go over the training checklists with the operator trainee to ensure that the trainee understands the equipment, and its operation as it pertains to the operation of the plant and its function. Training is also provided with any changes or upgrades to equipment within the power plant. During black start training, the black start generator is synchronized to the auxiliary load center and ran at full load; no change in auxiliary bus configuration is made to match the generator load capacity.

Kahului Power Plant black start training is provided to all crew members by the Shift Supervisors on a regular basis. Junior Boiler Operators and Operator Helpers are trained on starting, synchronizing, operating and shutdown of the black start unit when it is capability tested. Maalaea Power Plant training for black start operation is performed during the training of the operators at the respective units and the procedures are kept at the units (M1, M2, M3, and M14-M16 Control Room). During the training to qualify the operators, the operators manually start the black start units and synchronize the units to the grid. The black start unit at the combined cycle power plant (M14, M15 and M16) is started by the operators on a weekly basis and synchronized to grid to ensure that the unit is available when needed. Combined cycle plant training includes matching the auxiliary bus configuration to the Electro-Motive Division generator and black start generator capacities. The 2.5 MW diesel units (M1, M2, and M3) are used for peaking and are operated as needed.

## 2.2 System Conditions at 7:00 AM Sunday October 15th

On Sunday October 15, prior to the earthquakes, the 69 kV transmission and 23 kV sub-transmission systems were in their normal configuration with all lines in service. No transmission maintenance outages were scheduled for the day. The generation commitments for a Sunday morning were normal. The capacity of MECO and IPP plants in operation immediately before the earthquake was approximately 173 MW, and the system load was 137 MW. The on line capacity exceeded the system load plus the normal regulating reserve in anticipation of morning load increases. The power plant unit status from the EMS archive was as follows:

Table 1:  Generation Status 0708:30 Hours October 15, 2006

| | FUEL TYPE | UNIT TYPE | NTL (GROSS MW) | MODE OF OPERATION | SERVICE DATE | STATUS | OUTPUT (MW) | RESERVE (MW) |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| **MAALAEA GENERATING STATION** | | | | | | | | |
| X1 | No. 2 Diesel | ICE | 2.5 | Peaking | 1987 | OFF | 0 | 0.0 |
| X2 | No. 2 Diesel | ICE | 2.5 | Peaking | 1987 | OFF | 0 | 0.0 |
| M1 | No. 2 Diesel | ICE | 2.5 | Peaking | 1971 | OFF | 0 | 0.0 |
| M2 | No. 2 Diesel | ICE | 2.5 | Peaking | 1972 | OFF | 0 | 0.0 |
| M3 | No. 2 Diesel | ICE | 2.5 | Peaking | 1972 | OFF | 0 | 0.0 |
| M4 | No. 2 Diesel | ICE | 5.6 | Cycling | 1973 | OFF | 0 | 0.0 |
| M5 | No. 2 Diesel | ICE | 5.6 | Cycling | 1973 | OFF | 0 | 0.0 |
| M6 | No. 2 Diesel | ICE | 5.6 | Cycling | 1975 | OFF | 0 | 0.0 |
| M7 | No. 2 Diesel | ICE | 5.6 | Cycling | 1975 | OFF | 0 | 0.0 |
| M8 | No. 2 Diesel | ICE | 5.6 | Cycling | 1977 | OFF | 0 | 0.0 |
| M9 | No. 2 Diesel | ICE | 5.6 | Cycling | 1978 | OFF | 0 | 0.0 |
| M10 | No. 2 Diesel | ICE | 12.5 | Cycling | 1979 | ON - on AGC | 6.9 | 5.6 |
| M11 | No. 2 Diesel | ICE | 12.5 | Cycling | 1980 | ON - on AGC | 8.0 | 4.5 |
| M12 | No. 2 Diesel | ICE | 12.5 | Cycling | 1988 | ON - on AGC | 6.4 | 6.1 |
| M13 | No. 2 Diesel | ICE | 12.5 | Cycling | 1989 | OFF | 0.0 | 0.0 |
| M14 | No. 2 Diesel | CT | 20.0 | DTCC-Baseload | 1992 | ON - on AGC | 19.0 | 1.0 |
| M15 | Exhaust Gas | Steam Turbine | 18.0 | DTCC-Baseload | 1993 | ON - on AGC | 12.8 | 5.2 |
| M16 | No. 2 Diesel | CT | 20.0 | DTCC-Baseload | 1993 | ON - on AGC | 18.5 | 1.5 |
| M17 | No. 2 Diesel | CT | 21.2 | STCC-Cycling | 1998 | OFF | 0.0 | 0.0 |
| M18 | Exhaust Gas | Steam Turbine | 18.0 | STCC-Baseload | 2006 | OFF | 0.0 | 0.0 |
| M19 | No. 2 Diesel | CT | 21.2 | STCC-Baseload | 2000 | ON - on AGC | 12.0 | 9.2 |
| | **Total Maalaea Generating Station** | | 214.5 | | | | 83.6 | 33.1 |

Table 1 Continued:  Generation Status 0708:30 Hours October 15, 2006

|  | FUEL TYPE | UNIT TYPE | NTL (GROSS MW) | MODE OF OPERATION | SERVICE DATE | STATUS | OUTPUT (MW) | RESERVE (MW) |
|---|---|---|---|---|---|---|---|---|
| **KAHULUI GENERATING STATION** |  |  |  |  |  |  |  |  |
| K1 | No. 6 Fuel Oil | Boiler/Steam Turbine | 5.0 | Cycling | 1948 | ON - not on AGC | 2.1 | 2.9 |
| K2 | No. 6 Fuel Oil | Boiler/Steam Turbine | 5.0 | Cycling | 1949 | Overhaul | 0.0 | 0.0 |
| K3 | No. 6 Fuel Oil | Boiler/Steam Turbine | 11.5 | Baseload | 1954 | ON - not on AGC | 11.5 | 0.0 |
| K4 | No. 6 Fuel Oil | Boiler/Steam Turbine | 12.5 | Baseload | 1966 | ON - not on AGC | 12.5 | 0.0 |
|  | **Total Kahului Generating Station** |  | 34.0 |  |  |  | 26.1 | 2.9 |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| **HANA SUBSTATION** |  |  |  |  |  |  |  |  |
| H1 | No. 2 Diesel | ICE | 1.0 | Emergency | 2001 | OFF | 0.0 | 0.0 |
| H2 | No. 2 Diesel | ICE | 1.0 | Emergency | 2001 | OFF | 0.0 | 0.0 |
|  |  | **Total Hana Substation** | 2.0 |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| **IPPs** |  |  |  |  |  |  |  |  |
| HC&S |  | Biomass | 16 | Baseload | 1989 | ON - not on AGC | 9.1 | 0.0 |
| Kaheawa (KWP) |  | Wind Farm | 30.0 | As-Available | 2006 | ON - not on AGC | 18.1 | 0.0 |
| Makila Hydro |  | Run-of-river Hydro | 0.5 | As-Available | 2006 |  | 0.0 | 0.0 |
|  |  | **Total IPP Generation** | 46.5 |  |  |  | 27.2 | 0.0 |
| **TOTAL GENERATION AND RESERVE** |  |  |  |  |  |  | **136.9** | **36** |

The Dispatch Center was properly staffed according to MECO operating procedures. The EMS archive indicated a generation reserve of 36 MW. The dispatcher was conducting routine monitoring of the system conditions and coordinating the startup schedule of generation with the operator at Kahului Power Plant as demand for power began to increase.

Kahului and Maalaea power plant staffing was normal for a Sunday. The personnel were conducting their normal routines of monitoring the plant conditions. The Kahului operator coordinated with the dispatcher to schedule the generation and unit commitment with the operators at Maalaea. Base load units were near capacity and cycling units were increasing their output as the morning load demand increased.

## *2.3 Earthquake and Island-Wide Outage Sequence of Events*

### 2.3.1 Earthquake to Outage

We have developed the sequence of events from just before the earthquake to the outage using information from the EMS, supervisory control and data acquisition (SCADA) reports, power plant distributed control system (DCS) alarm logs, relay event recordings, and employee interviews. This sequence of events coincides with the information displayed in the following figures. Figure 1 shows the system generation/load and frequency with the timing of load shed events on the MECO system from the time of the earthquake until M10 tripped. Figures 2 shows the megawatt output of the individual generating units and the system frequency from 07:08:20 to 07:09:00. Figure 3 shows the megawatt output of the remaining generating units from 07:09:00 to 07:18:00 when all units were off line. Figure 4 shows the system load and frequency from 07:08:20 to 07:18:00 to illustrate that the frequency remained below the 59 Hz.

The EMS, SCADA, DCS and relays are not continuously synchronized to the same clock, so time stamps do not exactly correlate between devices. Time stamps for the sequence of events determined below are primarily derived from the EMS and SCADA reports which are recorded in two second intervals. Information from the power plant DCS is used to better describe the sequence of power plant component operations, but the DCS time stamps are not used as they are out of sync with the EMS and SCADA information. The following time estimates were developed by comparing a specific event between the EMS, SCADA, and DCS time stamps. The EMS was used as the base time. Time stamps for the operator trip of K4 were compared for the EMS, SCADA and Kahului Power Plant DCS. The EMS and SCADA were determined to be in time sync and the Kahului DCS time stamp was plus 58 seconds from the EMS. The point on the EMS graph in Figure 2 for the M16 turbine trip and the Maalaea Power Plant DCS time stamp were compared and the Maalaea DCS was found to be minus 74 seconds from the EMS. All times used in this report are based on the 2400 hour time clock.

- K4 Trip (SCADA = 07:08:43, EMS = 07:08:43, Kahului PP DCS = 07:09:41)
- M16 Turbine Trip (EMS = 07:08:31, Maalaea PP DCS = 07:07:17)

We must also note that the MECO generator breakers do not have a direct open/closed status indicator to the SCADA system – when the SCADA register that power output has gone above/below 0.001 MW, it derives the generator breaker has closed/opened and indicates the status change.

Power plants can be tripped in two ways. First, a trip to “shutdown” where the power reduces over a short time and the generator circuit breaker to the system remains closed until tripped by the operator (power output reduces over more than the 2 second scan interval). Second, a trip by a protective device that opens the generator circuit breaker to the system immediately, thus shutting off the power output (power output reduces to zero within the 2 second scan interval). Both of these type events can be seen in Figure 2.

We also note that the EMS archive continued to record the gross output from HC&S after it separated so this value was manually changed to zero from 07:08:46 in the following figures to reflect that no power was exported to the MECO grid.

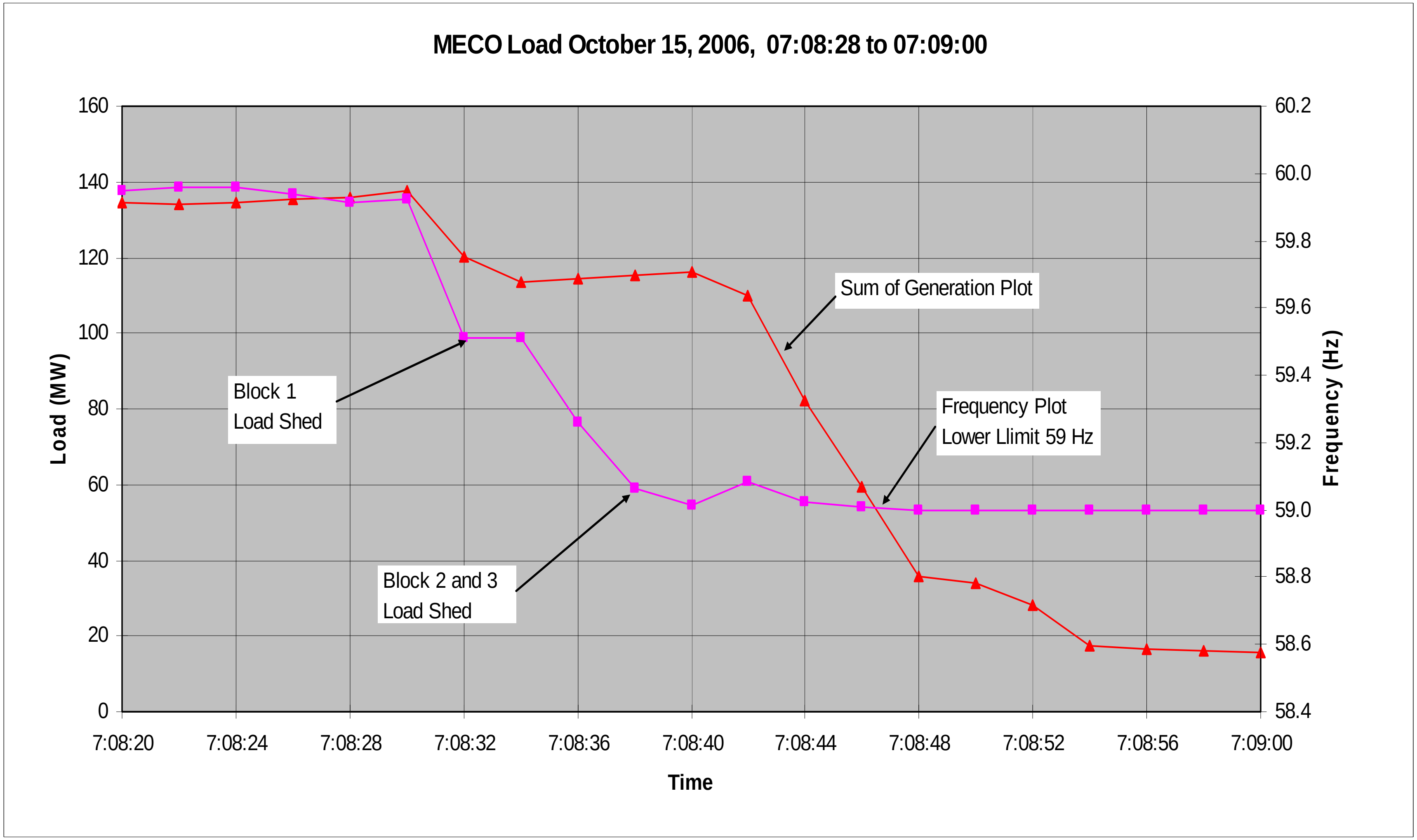

Figure 1: Load versus Frequency Timeline - October 15th, 2006, 07:08:20 to 07:09:00

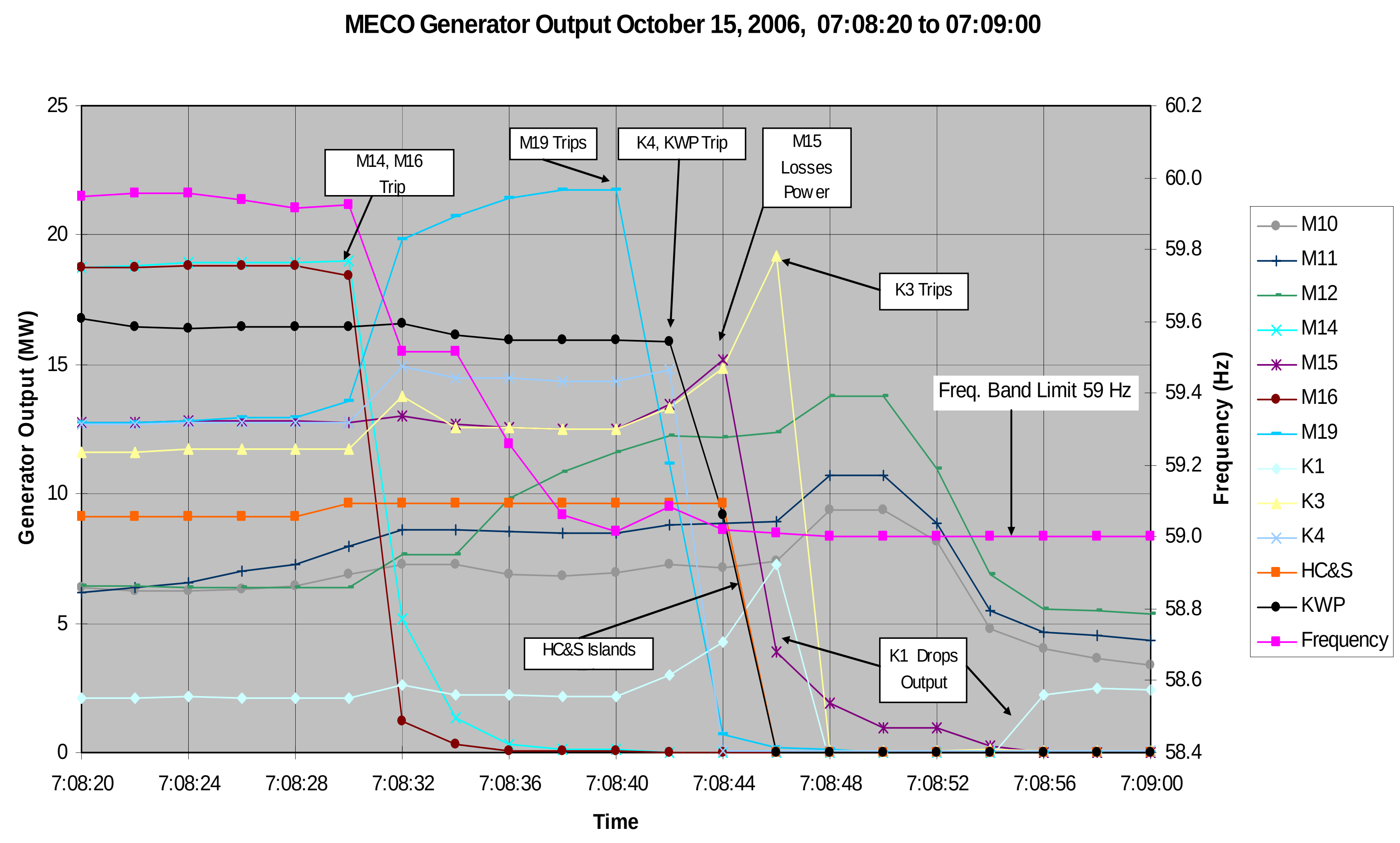

Figure 2: Individual Generator Output Timeline - October 15, 2006, 07:08:20 to 07:09:00

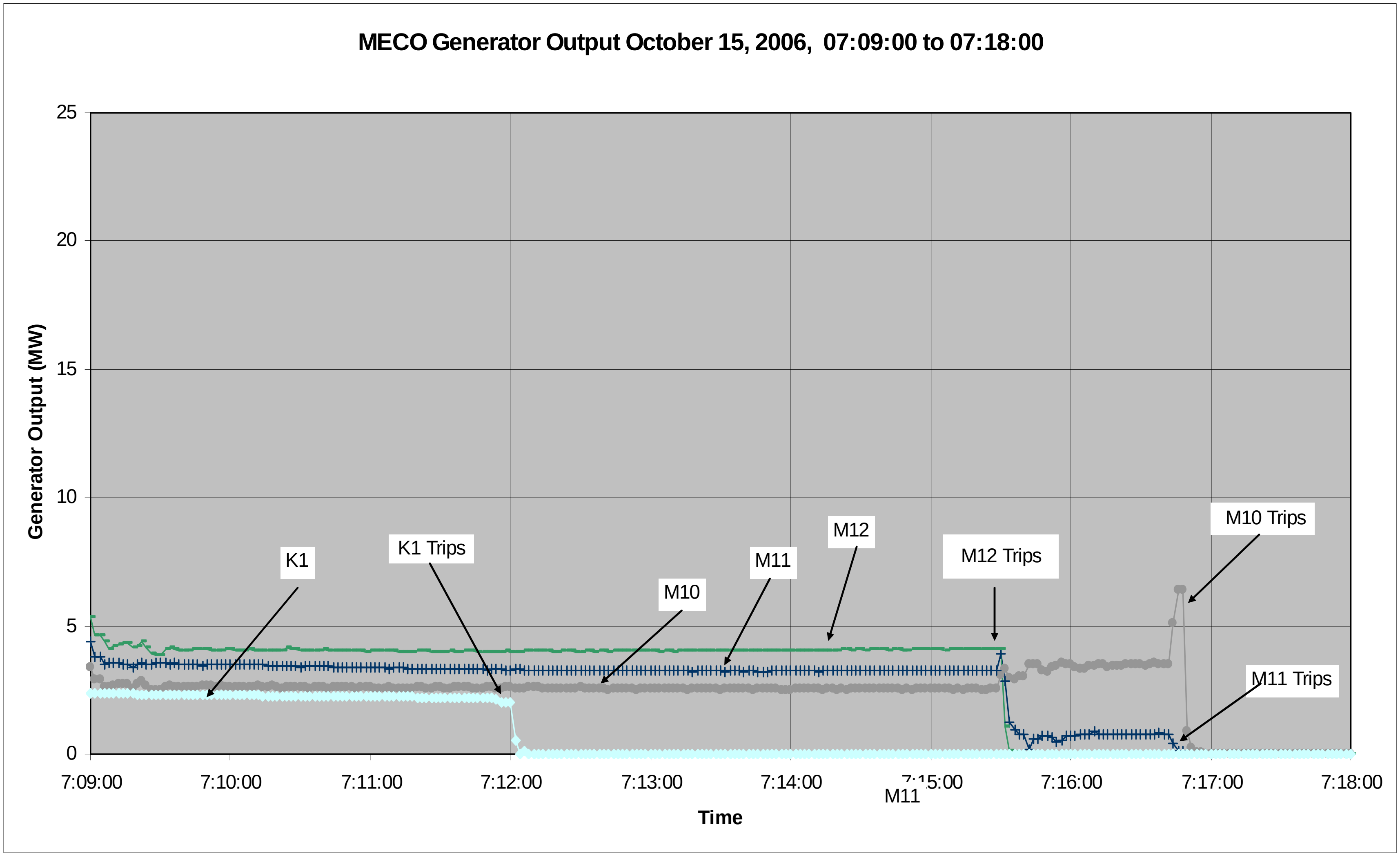

Figure 3: Individual Generator Output Timeline - October 15, 2006, 07:09:00 to 07:18:00

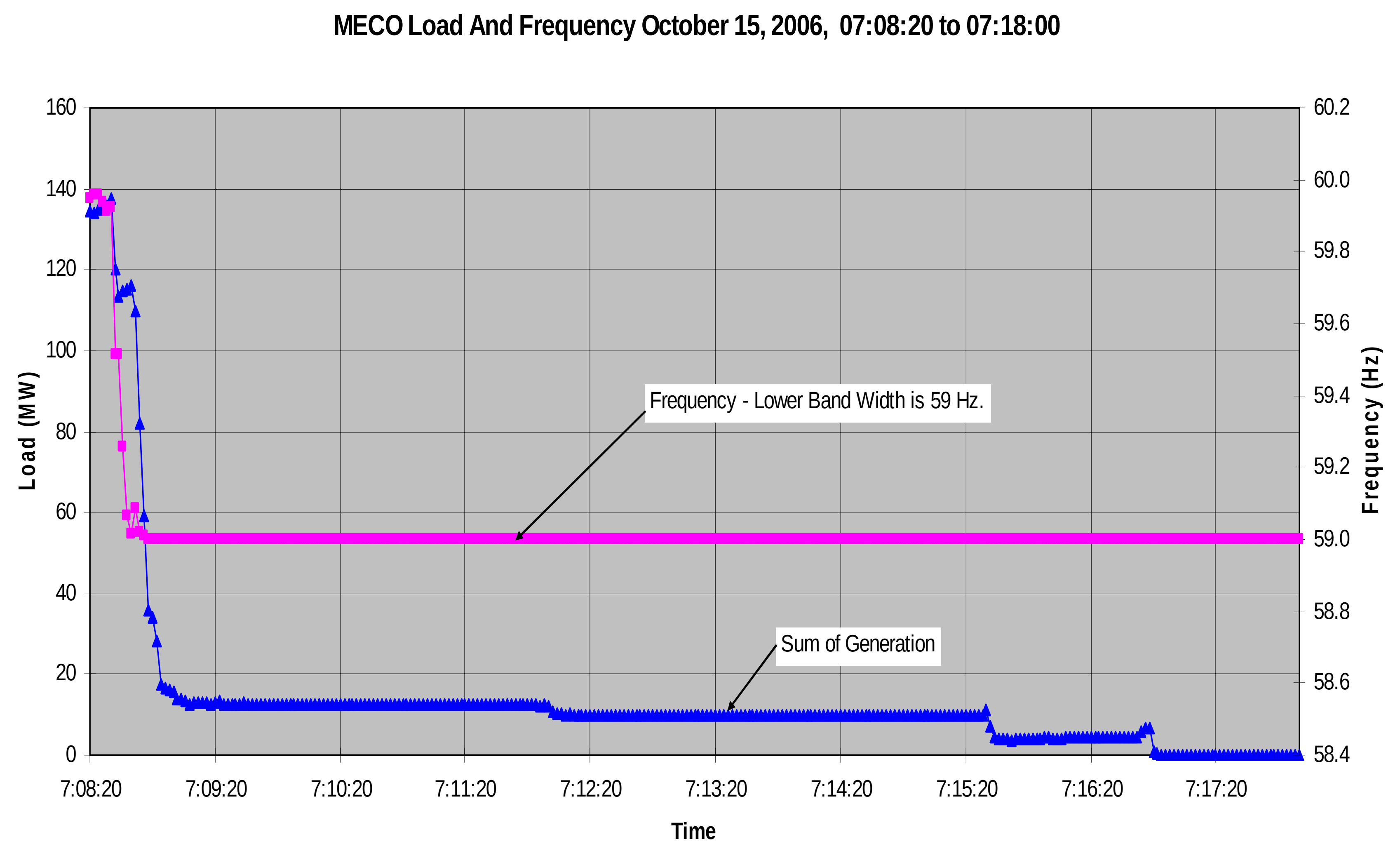

Figure 4: Load versus Frequency Timeline - October 15, 2006, 07:08:20 to 07:18:00

Sequence of Events

7:08:28 – Normal transmission system configuration. EMS indicates 137 MW of generation, 38.9 MW of reserve capacity on line, frequency steady at 60 Hz, and load increasing normally.

7:08:30 – EMS graph shows trip of M14 and M16 (generator vibration).

7:08:31 – SCADA log shows two breakers of load shed block 1 trip.

7:08:33 – SCADA log shows two additional breakers of load shed block 1 trip.

7:08:37 – SCADA log shows M16 breaker open.

7:08:39 – SCADA log shows one breaker of load shed block 2 trips.

7:08:40 – EMS graph shows trip of M19 (turbine over-temp)

7:08:41 – SCADA log shows four breakers of load shed block 2 & 3 trip

7:08:41 – SCADA log shows M14 breaker open.

7:08:42 – EMS graph shows generator trip of K4 (manual – vibration).

7:08:42 – EMS graph shows trip of KWP (07:08:45 SCADA, under frequency trip - 81U).

7:08:43 – SCADA log shows K4 breaker open.

7:08:44 – EMS graph shows reduction of power from M15 (loss of heat from CTs M14 and M16 to the HRSG).

7:08:45 – SCADA log shows eight 69 kV breakers trip (4 tripped by SEL 351A on 81U Sub 97 - KWP).

7:08:45 – SCADA log shows HC&S separated (CB 6848 and 6851 opened at Puunene Out-of-Step)

7:08:46 – EMS graph shows reduction of power from K1. Also shows overload and trip of K3 (86G1 trip of 2252 – static exciter – emergency generator trip).

7:08.48 – EMS graph shows K1 power output near 0 MW.

7:08.50 – EMS graph shows M10, M11 and M12 begin to reduce power output.

7:08:56 – EMS graph shows K1 ramps up to power output to near 2.5 MW.

7:09.30 – EMS graph shows K1, M10, M11 and M12 output stabilizes.

7:12:04 – EMS graph shows trip of K1 (Relay trip – loss of auxiliaries, boiler trip)

7:15:34 – EMS graph shows trip of M12. (Instantaneous overcurrent trip)

7:16:50 – EMS graph shows trip of M11. (Manual trip – loss of auxiliaries)

7:16:52 – EMS graph shows trip of M10. (Manual trip – loss of auxiliaries)

## Summary of the System Dynamics

EMS logs, SCADA reports, and power plant DCS logs were analyzed to summarize the activities and system responses to the events. The EMS data provided in 2 second intervals is plotted in figures 1 through 4 to provide a visual interpretation of the data. At the onset of the earthquake, the system was operating normally with all transmission lines in service and generation properly dispatched to provide sufficient reserve in accordance with the MECO operating procedures. M11 was ramping up output as load was increasing. There were essentially two areas of events. In the first 20 seconds after the earthquake, a majority of the generation tripped and load was shed. In the remaining 8 minutes, generation settled out, but the remaining 4 generators eventually tripped.

At the time of the earthquake, numerous alarms began to register at the power plants and Dispatch Center. Power Plant turbine/generator vibration sensors alarmed at the Maalaea Combined-Cycle 1 Control Room and tripped M14 and M16 instantly, dropping 40 MW of capacity carrying 37.5 MW of load. These two units also supply exhaust heat to the M15 HRSG, which then quickly lost power, dropping an additional 18MW of generation. M10, M11, M12, M19 and K3 ramped up to supply the load dropped by M14 and M16. Load shed block 1 tripped four breakers at 07:08:31-33 and arrested the frequency decay for a moment. At 07:08:40, M19 tripped on high exhaust temperature while carrying 21.8 MW of load. The EMS graph shows that at this point frequency began to improve; indicating that load was being shed and other generators were picking up a larger share of the load. This correlates with the SCADA report indicating blocks 2 and 3 shed five breakers. At 07:08:42 when K4 and KWP tripped, the frequency dipped and then straight-lined on the graph (Figure 1 and Figure 2) indicating it had dropped below the lower metering limit of 59 Hz.

The Kahului power plant Shift Supervisor was walking toward the control room when the earthquake hit and observed K4 turbine shaking violently and water leaking from the K4 boiler. He assumed that the turbine was ingesting water and went into the control room and manually tripped the turbine. At the same time the KWP wind farm tripped. An event report for a relay at Substation 97 Kaheawa (KWP) indicated the frequency had dropped to 56.05 Hz at 07:08:41 and the relay tripped KWP on under frequency. K1, K3 and M15 increased output to compensate for the loss of K4 and KWP. M15 then ran out of steam power and electric power output dropped off. K3 overloaded, recorded static exciter alarms, and tripped. At the same time output from K1 dropped off. Breakers opened at Kula, and Puunene substations due to a relay trip on an out-of-step condition. At 07:08:45 HC&S separated from the MECO system and remained in operation with house load. With the above generation loss, M10, M11 and M12 again responded with increased output to meet load and then power output declined between 07:08:50 and 07:09:00, most likely due to reduced output of auxiliary equipment (pumps and motors) due to the extremely low system frequency. At this time, frequency remained below the EMS metering limit of 59 Hz. Relay event reports recorded frequencies as low as 40 Hz in this time frame.

About 3.5 minutes after the earthquake, K1 tripped, followed by M12 3.5 minutes later. The K1 trip was attributed to loss of auxiliary power and M12 to an instantaneous overcurrent relay operation. The Maalaea diesel plant operator indicated that the M10 and M11 were running at about 200 rpm (rated 450 rpm) and lost auxiliaries so the operator manually tripped M11 and then M10 at about 07:16:52 to protect these units from damage.

### Load Dispatch Center

At the time of the earthquake, one dispatch supervisor with nine years of dispatch experience at MECO and one dispatcher with less than one year of dispatch experience at MECO were on duty. The dispatchers indicated that when the initial shaking took place, they were immediately aware that it was an earthquake. They reported that the lights, wall display board, computers, phones and radios shut down until the emergency generator came on line. The SCADA alarms were going off continuously and were reported to be too numerous to list. Loss of generation happened too quickly for assessment and intervention by manual load shed.

### Power Plants

Interviews with the power plant staff indicated that most of them were not immediately aware that this was an earthquake.

Kahului operators initially thought the shaking was due to turbine vibrations as they visibly noticed turbines shaking and steel floor plates bouncing. The shift supervisor saw the K4 turbine violently shaking and noted water coming down the east side of the boiler. Believing he had a water injection problem he ran into the control room and manually tripped K4. He stated that he did not notice any alarms prior to tripping K4 but began to receive multiple alarms after the K4 trip on all the units. K3 tripped closely thereafter and the DCS indicated that a relay protecting the static exciter initiated the trip. K1 tripped a few minutes later with the DCS indicating loss of auxiliaries and a boiler trip. The operators then began the procedures to secure the boilers, assess equipment status and prepare for black start.

Maalaea operators also were not immediately aware that this had been an earthquake. CTs M14 and M16 generators immediately tripped offline due to vibration alarms and trips. The combined cycle plant operator indicated the alarms on the control panel were too numerous to quickly evaluate what was happening. M19 power output increased sharply and then shortly the unit tripped on high exhaust temperature. M15 HRSG lost power as it no longer had a heat source from M14 and M16. At this point, the operator indicated that he had lost all controls for the plant. The diesel plant operator received multiple alarms on M10, M11 and M12. The operator noted that M12 had tripped on instantaneous over-current, M10 and M11 rpm had dropped from the rated 450 rpm to about 200 rpm, and that the station had lost auxiliaries. The operator tripped M11 and M10 to prevent damage due to loss of auxiliaries. This resulted in the island-wide power outage.

### Transmission System

The transmission system remained structurally intact with some leaning poles. The only line that showed a fault trip was the Maalaea-Puunene 69 kV line which tripped at about 0855 hours which was clearly during re-energization. The Kaheawa Sub 97 (KWP) underfrequency relay tripped at 07:08:41, which indicated on SCADA at 07:08:45 (set 56 Hz - 2 cycle delay, 57 Hz - 360 cycles delay). The SCADA log indicates between 07:08:30 and 07:17 that there were numerous records of low voltage, closing and opening of shunt capacitors and opening and closing of transformer motor operated disconnect switches.

Load Shed

All indications from the EMS and SCADA are that the automatic Under Frequency Load Shed (UFLS) scheme operated and shed load as designed. Figure 1 would indicate that the load shed block 1 operated above 59.5 Hz, but it is very likely that the frequency dipped low enough to trip load shed block 1 and then recovered to 59.5Hz within the two second EMS frequency scan interval. Load shed blocks 2 and 3 operated just prior to the point where the Kaheawa Sub 97 (KWP) tripped and the relay recorded the frequency at 56.05 Hz, indicating that they tripped within the appropriate frequency range. This load shed along with a ramp up in output from the remaining generators appeared to arrest the frequency decay due to the loss of M14 and M16. On the loss of M19 the remaining attached load overwhelmed the available generation and the system frequency rapidly declined. Unfortunately, the frequency monitoring equipment in place has a lower limit of 59 Hz so we do not have a clear picture of how the frequency behaved after it reached the lower measurement threshold.

### 2.3.2 Outage to System Restoration

The following information is based on interviews with management, the dispatchers, power plant operators, as well as information gathered from various MECO sources including the EMS and SCADA.

Key management personnel quickly responded to the engineering offices on their own volition, when they realized that an earthquake had occurred and the power system had blacked out. As they called in, they were redirected in route to the power plants to establish communications and manage the restoration. The key management personnel traveled to the power plants and found that many of the primary communication systems were out of service due to the power outage and the plant personnel were involved in tasks securing the plant, assessing equipment condition and preparing for restart. Communications were established by telephone and radio backup sources.

Numerous activities were taking place in the power plants as power supply personnel prepared to black start generating units at Kahului and Maalaea. Simultaneously, the dispatchers, trouble men and management personnel were preparing the electrical grid for restoration. In addition to preparing the system for restoration, key operations management personnel were developing a sequence for the restoration process. At that point in time, attention was not yet focused on the detailed customer restoration, but rather on a sequence that had to be followed to re-energize the MECO transmission grid.

The primary objectives of the overall restoration plan were:

1) restore power in a safe manner,
2) avoid damage to customer and utility equipment,
3) restore the transmission grid to provide power to the generating plants (from either Kahului or Maalaea depending on what unit was on line first) so that startup power was available to start additional generating units,
4) ensure that there weren't islanded systems if generating units were started at both Kahului and Maalaea,
5) re-energize the 69 kV and 23 kV grid so that loads around the island could be restored, and
6) provide an energized bus to the HC&S so that they could get their generating unit tied back to the MECO system as quickly as possible.

During the time frame from about 0718 hours to 0834 hours when the first unit (M6) was brought on line on the 69 kV bus, different working groups had to coordinate their efforts by communicating what was happening on the system as they prepared the electrical system restoration. A central point of contact was set up at Kahului Power Plant.

Because Maui had just experienced two earthquakes, the dispatch and power plant personnel could not be certain that the equipment was undamaged. As off duty MECO personnel responded to call out, or voluntarily reported to see if they could assist, they visually inspected as much of the transmission and distribution system as possible as they reported to work. The SCADA log indicates that the operators and T&D personnel began to open system breakers to strip load feeders manually and by SCADA at 0740 and were still in the process at 0840 during the first attempt to re-energize the 69 kV system from Maalaea.

With respect to blackouts, because each outage is different and in each case different parts of the system grid/generators may or may not be available, each restoration plan will be unique. Each restoration plan, such as the one developed on October 15, takes into account the available system components, available MECO staff, and experience gained from previous restorations regarding prudent procedures to maintain system stability during the early stages. In the event of a blackout, MECO generally follows guidelines for black starting the system contained in its Emergency Response Plan (ERP). The ERP includes procedures for assembling an incident command team, onsite response teams, communication protocols, and resources to respond.

## System Restoration

Transmission and distribution system breakers throughout the system were opened by SCADA or manually. About 65 percent of the MECO distribution breakers are able to be operated by SCADA which reduced the time required to prepare the system. An attempt was considered to energize the system from HC&S, which had continued to operate throughout the disturbance. However, HC&S is a private operation not directly controlled by MECO. In order to protect MECO's staff during maintenance work on the transmission system, the protection and control is designed according to typical utility practice and is arranged such that HC&S cannot connect to a dead MECO bus. After some initial consideration, the attempt to reenergize from HC&S was abandoned as Maalaea was quickly coming back on line. The system was re-energized from Maalaea Power Plant.

## Kahului Power Plant

The nature of a steam plant, such as Kahului, is that it takes time and care to "hot" start a boiler and turbine combination. At Kahului a small diesel generator was started up to power auxiliary circuits including the critical turbine turning gear. In addition, steam driven oil pumps were put into operation to use up some of the excess steam in the system and the boilers were stabilized. The auxiliary buses were reconfigured and the turbines put on turning gear. A visual inspection was performed of the fuel system piping and the tank farm. No damage was found. A black start was attempted at Kahului on K1. The initial attempt using the black start generator tripped on overload. Auxiliary air compressors for K3 and K4 were secured from the auxiliary bus and a second attempt was made to start K1. While rolling the K1 turbine the diesel ICE tripped on water jacket over-temperature, due to a problem with the cooling system. At this time, power was restored to the main bus from Maalaea so the auxiliary loads were transferred to the mains, K1 was started and at 1014 hours it was put on line.

Maalaea Power Plant

Diesel internal combustion engines, especially relatively small units, are able to start up and take load within only a few minutes. Maalaea has five diesel ICE units, 2.5 MW each, that are able to start from battery power. The Maalaea 5.6 MW and 12.5 MW units are equipped with an air start system. During and extended outage the air pressure can bleed off. Once station service is restored from the smaller 2.5 MW units, the air system is restored to operating pressure and the larger diesel units perform a blow down and start operation in about 15 minutes.

Combustion turbines can also be started, warmed up, connected to the bus and loaded within 30 minutes, although a key issue for MECO is that the units need to be able to quickly pick up about 8 MW of load to maintain operation within the covered source permit constraints. The LM2500 combustion turbines at Maalaea are equipped with high speed 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 will distort slightly as they cool or the outer case can cool faster than the rotor causing “thermal lock”, and then the unit cannot be re-started until it has cooled down completely. The CT 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 they went into thermal lock which then required a 3 to 4 hour cool-down period before they could be restarted. The combined cycle plant black start generator was put on line at 0753 hours, and provided power to the combined cycle plants auxiliary circuits.

At Maalaea station, unit M1 was put into operation at 0815 hours, and provided power to the station's auxiliary circuits. At 0834 hours, M6 was connected to the 69 kV bus. Transmission breakers 6777 and 6780 were closed at 0846 to energize the line to Puunene and M6 tripped on overload. Additional transmission and distribution system breakers were opened to reduce connected load. At about 0853 hours M6 and M5 were paralleled to the 69 kV bus and the transmission system breaker closed and both units tripped on overload. Additional distribution system breakers were opened to reduce connected load. M5 and M6 were restarted connected to the bus and began to successfully restore load at 0902 hours.

The system was then re-energized from Maalaea, where nine reciprocating engine sets were started up and brought on line between 0902 hours and 0948 hours comprising five 5.6 MW sets (M4, M5, M6, M7 & M8), two 12.5 MW sets (M10 & M11), and two 2.5 MW sets (X1 & X2). Combustion turbine M17 had been shut down at the time of the earthquake and therefore not restricted from starting. M17 was put on line just before 1000 hours when it was able to take load without violating the covered source permit constraints.

Reciprocating unit M12 at Maalaea was next, at 1041 hours. This set operates under a covered source permit constraint which requires the exhaust gas opacity not to exceed 20% for more than 12 minutes in any hour. Higher levels of opacity are generally experienced on reciprocating engines burning No. 2 diesel during start up and when operating on light loads. Unit M12 is started up on bio-diesel, which has proven cleaner burning characteristics during starting and warm-up, and the fuel is changed over to No. 2 diesel when it has warmed up and loaded. Under a controlled stop, the engine fuel is switched to bio-diesel during shutdown so that it is charged with bio-diesel in readiness for the next start up. However, this unit had tripped during the earthquake event and could not be re-started without risking breaching the covered source permit constraints on exhaust opacity. The fuel system was required to be flushed out and filled with bio-diesel before the engine could be re-started Thus M12's start was delayed by an hour or so compared with the other reciprocating sets.

One of the CT mechanics had responded to the plant shutdown and checked the rotation of CT 14 after about 3 hours of cooling and determined that it was free and a start could be attempted. Combustion turbine M14 was connected to the bus at 1111 hours. The KWP wind farm was reconnected after this, then combustion turbine M16 at 1218 hours and M19 at 1251 hours.

Kahului's unit K3 was brought on line and a very small amount of hydro generation also became available (0.03 MW), bringing the total capacity available by 1432 hours to 217.73 MW.

## Load Restoration

Once M6 and M5 were on line, the plant operators would talk to dispatch to communicate how much load they could take. Dispatch would select a feeder which would fit within the load range, based on experience and load readings prior to the outage, and close the breaker. Load was generally added in 2 MW to 5 MW blocks. Criteria for selection of the load to be closed in was the feeder load magnitude prior to the outage and whether it served critical loads.

Understanding and anticipating the system volatility during restoration, MECO operated in an orderly and methodical manner to add load to the system so that there was adequate opportunity to stabilize the operation of the generating units, and stabilize frequency and voltage on the grid. In some cases a feeder or transmission line was taken back out of service when too large a block of load was closed in. As the length of the outage increased “Cold Load Pickup”[4] began to be a factor that the dispatcher and power plant operators had to contend with when energizing circuits.

MECO also encountered a few problems as they energized circuit such as at Sub 40 (Onehee) where two reclosers powered from internal transformers were damaged, Kula circuits that could not be closed by SCADA and a troubleman had to manually close circuits, and circuit 1285 from Maalaea which required sectionalizing into three sections to isolate a fault caused by vegetation contacting the line. All circuits were restored by 1432 hours.

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[4] Cold Load Pickup is the term used to refer to the fact that the distribution feeders have lost load diversity (all refrigerators, electric water heaters, and air conditioners come on at once) such that the load, when first energized, is temporarily much higher than normal when the equipment is randomly cycling.

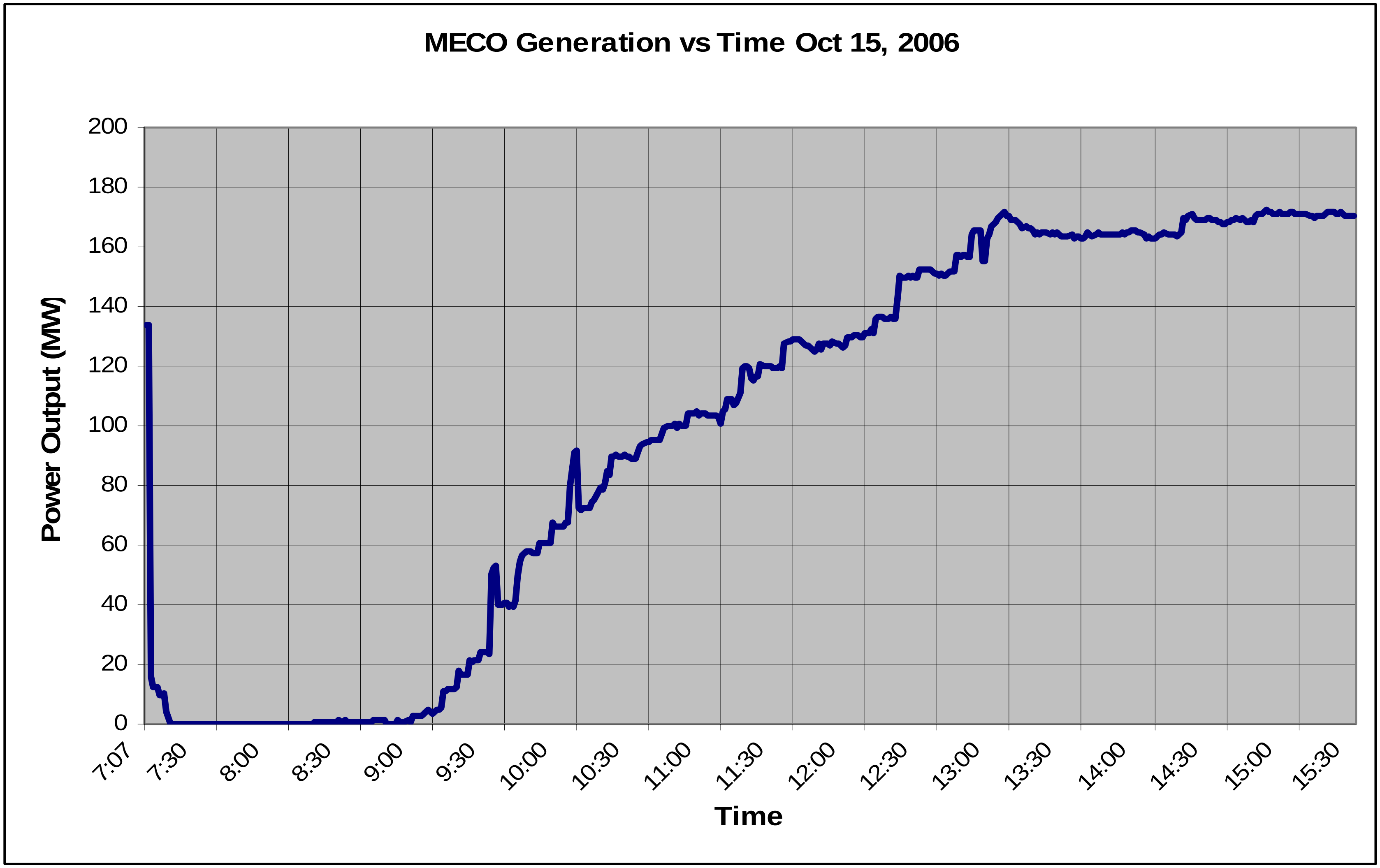

Figure 5: Generation Restoration Megawatts versus Time

# 3 Evaluation

## *3.1 Generation Capacity*

### 3.1.1 Maui Generating Fleet

Approximately 293 MW of generating capacity is currently installed on the island of Maui, with 250 MW owned and operated by MECO and 43 MW by Independent Power Producers (IPPs). The MECO and IPP plant capacities are summarized in Table 1. Note that M18, a heat recovery steam generator (HRSG) rated 18 MW, at the Maalaea Generating Station was commissioned in late October 2006 and therefore was not operable around the time of the earthquake. Furthermore, one of the 12.5 MW diesel engines (M13) and one of the 5.6 MW diesel engines (M9) were not available for operation at the time of the earthquake.

The MECO generating equipment is notable for:

- A split between reciprocating engines (approximately 33%), combustion turbines in combined cycle with steam turbines (approximately 40%) and boilers combined with steam turbines (approximately 12%), supplemented by a small amount of renewable generation (approximately 15%).
- The considerable age of the boiler/steam turbine plant. This was installed at Kahului Generating Station between 1948 and 1966.

## Expected Performance of Generating Plant During Blackouts

Reciprocating diesel engine generators are generally robust under rapidly changing load events. The newer, 12.5 MW generating sets at Maalaea can be expected to withstand the loss of 100% of their load without tripping, and to be able to start quickly and take on load in steps of several MW at a time. The reciprocating engines themselves would not be expected to have been adversely affected by the ground vibrations during the earthquake. Prior to starting a 2.5 MW unit, the 69 kV bus breakers must be opened in order to isolate the Maalaea power plant buses. The 2.5 MW units have battery start capability and can be quickly started and then provide starting power to the rest of the Maalaea plant. Once one of the 2.5 MW units is started and connected to the bus, it takes about 15 minutes to build up system air pressure, blow down one of the larger ICE units, complete the start/warm-up sequence and connect the unit to the bus to begin restoring power to the 69 kV system.

Steam plants can be very valuable in providing frequency stability. However, older designs of plant such as that at Kahului may have difficulty remaining in service following sudden, large load swings. Sudden large load pickup and reduction can take boiler operating parameters, such as drum levels, to the point where control equipment intervenes to protect the plant from damage and automatically trips the unit, to take it out of service. Once the boiler trips, getting a purge of the boiler fuel fumes and re-light, while keeping the turbine generating, is very difficult and is not often successful. When a plant is suddenly tripped off line, there are numerous steps required to secure the plant, assess equipment conditions, and proceed through the startup sequence. To complete these sequences requires between 2 and 4 hours depending on the residual steam pressure/temperature of the boiler.

Combustion turbine combined cycle plants of the type installed at Maalaea are able to respond well to rapidly changing loads and can be brought on line relatively quickly. The Maalaea combustion turbines are manufactured by General Electric, type LM2500. The LM2500 is based on an aero engine that has been modified for use as a land-based generating set. It is typically used, as in this case, in combined cycle mode whereby the heat in the turbine's exhaust gas is used to generate steam for a steam turbine (HRSG). Maalaea Generating Station uses two combustion turbines feeding heat to one HRSG – again a typical and proven arrangement for a cost effective and efficient installation. As previously described, on shutdown the CTs are required to be put on high speed turning gear within 7 to 10 minutes to properly cool the unit to prevent thermal lock. In normal operation with the auxiliary power available, this is not an issue. When the plant goes black, the auxiliary bus must be properly configured to allow start up of the combined cycle plant 600 kW black start unit to provide auxiliary power. This process takes time, which can lead to the operating CTs going into thermal lock requiring about a 3 to 4 hour cool down time before the unit can be safely restarted. Each CT also requires a minimum load of about 8 MW in order to operate within the covered source permit constraints. The associated HRSG steam turbines take longer to bring on line and are less able to accept significant load changes. However, the combustion turbines can operate in "simple-cycle" mode, i.e. without the HRSG steam turbines running, until sufficient exhaust heat is available to bring the steam turbines on line.

On October 15, the HC&S biomass steam turbine separated from the system and remained in operation. The HC&S plant would have been available to export power to black start the MECO system. However, as is quite normal practice to ensure safety of the MECO system and personnel, the protection and control system is configured to prevent back-energization of a “dead” MECO bus connection by the HC&S unit. The ability of the Maalaea plant to quickly black start using the battery start diesel 2.5 MW ICE units, with no time requirement to reconfigure the auxiliary buses, significantly reduces the value of using HC&S to black start the MECO system.

### 3.1.3 Operational Generating Capacity on October 15

The system conditions on the morning of October 15 are discussed in sub-Section 2.2 of this report, and the status of the generating units, as of 0708 hours that morning, are shown in Table 1. The capacity of plant operating at that time was 173 MW, 36 MW in excess of total customer demand of 137 MW. The 36 MW of excess operating capacity was substantially greater than the 7 MW to 10 MW regulating reserve normally carried by MECO.

Considering the installed and operationally-available generating capacity and the customer demands on the island of Maui on the morning of October 15, 2006, the black-out of the system was not connected with any shortcomings in the MECO processes for the long-term planning of generating capacity, or the timing of the startup of cycling units, or the selection of generating units to operate that morning.

## *3.2 Outage*

### 3.2.1 Operator Generator Trips

Units K4, M10 and M11 were tripped manually by their respective operators.

Unit K4 is a steam turbine in Kahului Power Plant. This power station is constructed in the traditional way, with the control room located at the turbine floor level, one floor up from ground level. The main floor comprises steel plates over a framework of structural steel, built around the turbines which are mounted on concrete foundations formed into the ground below. Thus, the turbines and the steel floor are not physically connected at this level. The K4 turbine is located about 10 feet from the control room. When the earthquake struck, the shift supervisor noticed water coming down one side of the boiler of unit K4 and also saw that the turbine was shaking. He did not realize that there was an earthquake in progress, and thought that the boiler had a fault which had caused water to carry over to the turbine, thus causing it to vibrate severely. This would be a potentially very serious problem which could cause major turbine damage, so the shift supervisor went into the control room and hit the emergency stop switch for K4. Another operator on the floor at that time indicated that he observed steel floor inspection plates bouncing up and down around K4 turbine at that time. Two seconds after the manual trip signal was initiated, the DCS recorded vibration alarms on K4, which would have led to a trip of the unit if the shift supervisor had not already done so. We must also note that K2, which was off line for overhaul, registered a vibration alarm two seconds after the K4 vibration alarm.

By 0716 hours, only units M10 and M11 were still generating. The SCADA log indicates between 07:08:45 and 07:16:50 numerous alarms were logged for low voltage, loss of bus potentials and loss of station AC. Under low voltage conditions, motor contactors would open and cause auxiliaries to shut down. The Maalaea diesel plant operator indicated that M10 and M11 were operating at about 200 rpm (rated for 450 rpm) and that the auxiliary systems were off line. The diesel plant operator notified the control operator that the M10 and M11 generator breakers were still closed with the engines running 200 rpm, they were showing about 2 MW output and no auxiliaries were operating. At this point it became evident that it would be impossible to safely maintain operation of these engines, and the control operator manually tripped the generator breakers and shut down the diesel engines to protect the systems from overheating and improper lubrication.

### 3.2.2 Generator Relay and Control Trips

Units K1, K3, M12, M14, M15, M16, and M19 were tripped by their respective protection and control systems.

Trips Due to High Vibration

High vibration caused units M14 and M16 generators to trip just after 0708 hours. These combustion turbine-generator sets are equipped with vibration sensing devices which detect the relative positions of shafts and housings to determine if vibration is occurring which the manufacturer considers could damage the machine. The DCS indicated that both units received a “Combustion Turb High Vibration” alarm followed by “CT Emergency Stop” and “Combustion Turb Trip By Shutdown” alarm. The turbine and generation vibration alarms and trips are common to the DCS, thus it is difficult to determine which vibration element tripped the units. In MECO’s discussion with vendors and other plant personnel, it suspected that the generator proximity probe initiated the trip signal. The proximity probe trip on the generator directly trips the generator breaker and the combustion turbine fuel valve to the unit at approximately the same time. The loss of these two units, which were carrying 37.6 MW or 28.5% of the island's load, precipitated the island wide blackout. Without M14 and M16 exhausting heat into the HRSG to produce steam for steam turbine M15, M15 was unable to continue carrying load and lost power output capability some 14 seconds later.

K2 registered high vibration alarms even through it was off line for maintenance. We expect that the earthquake was shaking the generator sufficiently to trigger the proximity probe monitor. M19 did not alarm for high vibration. In review of the CT operation to try to explain why M19 did not trip on vibration, we noted that M17 and M19 are equipped with different models of generators, different models of vibration monitors, they are physically located in a different section of the yard and they are oriented 90 degrees from the layout of M14 and M16. Any of these factors could reduce the effect of the earthquake shaking on the generator bearing clearances.

The vibration monitoring equipment installed is as follows:

- K1-K4: Bently-Nevada model 3500 System
- M14 and M16: GE LM2500 CT with Brush Electrical Machines, LTD generators and Bently-Nevada 3500 System vibration monitors
- M17 and M19: GE LM2500 CT with Dresser Rand/Electrical Machinery generators and Vibro-Meter ABE 022 MMS System vibration monitors

## LM2500 COMBUSTION TURBINE VIBRATION MONITORING

When used in a power generation application, LM2500 combustion turbine-generator sets, such as the four units at Maalaea, are equipped with vibration sensing equipment on both the turbine and generator as follows:

Accelerometers – the combustion turbine is fitted with two accelerometers, one on the gas generator at the air inlet end, the other on the power turbine. These sensors detect vibrations in the combustion turbine casing. The aim is to detect vibrations at normal shaft speeds to provide an alert if a shaft becomes unbalanced. The LM2500 has high background noise (vibration) levels, so a speed signal is taken from each shaft (gas generator shaft and power turbine shaft) in order to filter out vibrations which do not occur at shaft speeds. Alarm and trip levels are set for each accelerometer for vibrations at each shaft speed. Thus, the accelerometers on the combustion turbines are not designed to detect vibrations due to external forces, only vibrations at much higher frequencies due to shaft unbalance problems. In common with most aero-derived combustion turbines it is fitted with rolling element bearings which are resistant to externally applied vibrations.

Proximity probes – the electric generator, which is a separately manufactured component from the LM2500, is fitted with proximity probes which detect the distance between the bearing housings and the shaft. There are four probes, two at each machine bearing (i.e. at each end of the generator). Each pair of probes is arranged at 90°, one in a vertical orientation and one horizontal. The purpose of these probes is to detect relative lateral movement between the generator stationary and rotating parts, which will occur in the event of bearing or lubrication failure, shaft unbalance or other types of internal damage. In fact, these are not truly vibration sensors at all, but are, as the name says, proximity detectors. Proximity detectors are used because the bearings in the generator sets are, in common with generators of this size world-wide, plain journal bearings which rely on a hydrodynamic film of oil for lubrication. Significant vibration from any source and at any frequency can cause the film of oil to be disrupted which would lead to bearing failure and possible shaft damage. The proximity probes detect the relative shaft/housing clearances; changes to which may indicate loss of oil film lubrication.

When the earthquake struck, we believe that the proximity probes on the bearings of the generators of combustion turbines M14 & M16 detected movement between the bearing housings and the shafts in excess of the "trip" threshold and caused the machines to shut down. The threshold levels are: lower level alarm at 3.5 mil peak to peak; trip level at 6.5 mil peak to peak. These levels are consistent with the commonly accepted standard design practice of one thousandth of an inch clearance per inch of shaft diameter. Furthermore, the levels are specified by the generator manufacturer to protect the equipment from damage. Though the generator manufacturer can be approached to ascertain if higher vibration levels can be accepted, we consider it highly unlikely that it will do so.

### Trips By Other Plant Relays

Following the loss of M14 and M16, the combustion turbine M19 picked up load. The Maalaea DCS recorded several alarms at 07:07:29 (07:08:43 EMS/SCADA). The senior operations supervisor and combined cycle operator interviews indicated that M19 then tripped on PT (power turbine) Inlet Temp. Dev. (T54DLT) or high exhaust temperature.

After trying to hold onto the system until about 07:15:30 hours, M12 was reported to have tripped on overload by an instantaneous overcurrent relay.

HC&S separated from the MECO system and islanded with their local load. KWP was tripped off line by the Sub 97 – Kaheawa under frequency relay. At this point M12, K3 and K1 attempted to pick up the load. At 07:09:45 DCS, (07:08:45 EMS/SCADA) K3 recorded “Generator Emer. Trip” and “K3 Gen. Backup Protection” alarms. Prior to these events K3 had recorded alarms for auxiliary power loss and static exciter trouble. The Maalaea diesel plant operator recorded a device 50-instantaneous overcurrent relay and primary Volts/Hertz 59p/81/X1 trip switch activated on M12.

Trips Due to Loss of Auxiliaries

After a duration where Kahului steam unit K1 and Maalaea reciprocating engines M10 and M11 attempted to hang onto the remaining load and seemed stabilized, they lost auxiliary power and were shut down. The SCADA log records numerous low voltage alarms but does not indicate any additional breakers opening to separate load. It can be surmised that the system remained with a severe load-generation imbalance between 07:09:00 and 07:17, which would significantly distress the connected generators and their auxiliary systems. DCS logs for K1 indicated at 07:12:56 (07:11:58 SCADA/EMS) that the unit lost auxiliary power and the boiler tripped on “Low Fuel Pressure”. Approximately 1 minute later the SCADA system recorded CB 2252 open.

### 3.2.3 Dispatch Center Event Response

After the initial tremor, it was clear to Dispatch Center personnel that Maui had experienced an earthquake. M14 and M16 had immediately tripped off line and breakers had tripped for load shed block 1. The SCADA began logging multiple alarms. The lights were reported to have flickered and then the display board, computers, phones and radios shut down. By the time the earthquake was over, reported to be 15 to 20 seconds by the Hawaii Volcano Observatory, the majority of the system generation was off line and the K1, M10, M11 and M12 were trying to support the system. System frequency remained below the minimum EMS recording level of 59 Hz. The Kahului Baseyard emergency generator was reported to have been slow to come on-line.

With the temporary loss of primary communications the dispatch personnel were not able to communicate or participate in the events over the next few minutes before total system blackout. However, given the amount of generation that was lost as a result of the earthquake, it appears that the dispatchers did not have sufficient time to assess the unfolding events and take actions that could have maintained some portion of the system energized.

### 3.2.4 Load Shed

The frequency scan rate of the EMS is two seconds. It is surmised in this evaluation that the frequency decayed below load shed relay set points, triggered the relays and frequency recovered within the 2 second scan window.

From Figures 1 and 2, it appears that the generator trips of M14 and M16 caused the frequency to quickly decay below the 58.7 Hz trigger-point of the UFLS block 1. UFLS block 1 operated along with a ramp-up in power output from the other generators; the frequency recovered to above 59.5 Hz and then began to decay again as the power output from M14 and M16 finally dropped to zero at 07:08:38.

At this point it again appears that during the next 2 second interval that the frequency decayed below 59 Hz and then recovered as the remaining generation ramped up and load shed blocks operated. Block 2 and 3 seem to have operated at about 7:08:41 which corresponds to a dip below 59 Hz and then a slight rebound. However, one relay of block 2 is reported to have a 10 second delay so it did not operate. Breakers on the 69 kV system operated on Out-of-Step and de-energize the 69 kV transmission system from Puunene to Kula. Relays outside the UFLS recorded frequencies about 47 Hz in this time frame, which would have triggered all of the UFLS relays. The UFLS that operated was unable to compensate for the loss of M14, M16 and M19 with an aggregate generation capacity of 61.2 MW.

## *3.3 Restoration*

### 3.3.1 Black Start

Plant personnel formulated the black start plans and identified the units to be started first. Under the circumstances, extra caution was required to assess equipment possibly damaged by the earthquake that could endanger additional equipment or personnel safety during operation. The process was started in parallel at Kahului and Maalaea power plants.

It was realized that HC&S was still operating and about 30 minutes was spent trying to determine a way to connect them to the dead MECO system to provide starting power. It soon became clear that this could not be accomplished safely before one of the MECO plants came back on line and the effort was abandoned.

At Kahului, the first K1 start attempt tripped the black start generator on overload. The K3 and K4 auxiliary air compressors were then stripped from the auxiliary buses to reduce the load to within the capability of the black start diesel. As they were beginning to roll K1 for the second start attempt, the diesel generator tripped on water jacket temperature, due to a cooling system problem. At this point power was restored from Maalaea, auxiliaries were transferred to the main bus, and K1 was restarted. This delayed restart of Kahului, but did not affect the restart of the system. If Kahului and Maalaea had both restarted and began to pick up islands of load, one plant would have to shut down and have power restored from the other plant.

At Maalaea Power Plant, the first order of business after assessing the plant condition was to open all of the breakers on the 69 kV bus, which is required to start a 2.5 MW diesel unit and connect to a dead bus. At this time the Maalaea plant SCADA was not functioning due to failure of the backup power supply so the breakers had to be opened manually. MECO staff reporting to the station immediately after the outage realized this action was necessary and began the process to manually open the breakers, which minimized the impact to the overall restart time. The SCADA report indicates that it took about 22 minutes before the 69 kV breakers stripping was initiated after the blackout and it took about 10 minutes to complete. Once the 69 kV bus was cleared, diesel unit M1 was started and began to supply station auxiliary power about 58 minutes after the plant went dark. The battery start 2.5 MW diesels are too small to pick up initial customer load so one of the larger 5.6 MW or 12.5 MW diesels needed to be started. These units (M6 to M12) use compressed air for starting, instrumentation and controls. Once the auxiliary power was restored, it took about 15 minutes to build up sufficient air pressure, perform blow down to purge any water from the combustion chambers and start M6.

### 3.3.2 Transmission and Distribution Load Restoration

The restoration plan developed was based on MECO’s past experience with the frequency and voltage stability conditions of the system during restoration. Numerous activities were taking place in the power plants as personnel prepared to black start generating units at Kahului and at Maalaea. Simultaneously, the dispatchers, trouble men and management personnel were preparing the electrical grid for the first unit to come on-line. In addition to preparing the system for restoration, key operations management personnel were developing a sequence for the restoration process. A significant portion of the MECO system can be closed in by SCADA, which allowed the dispatch staff to select and close priority feeders as generation became available that matched the estimated load of the feeder.

MECO personnel have indicated that during the outage and initial stages of restoration, the loss of primary communications between the dispatch center and power plants provided challenges to the operating personnel. Personnel resorted to backup sources (radios, landline, cell phones) to re-establish communications. Once utility and auxiliary power was restored to the plants, the communication system returned to normal operations. Coordination between load dispatch and the power plants was set up with a central point of contact at Kahului power plant to relay messages to Maalaea. The generation/load mix was monitored and controlled by the dispatcher and Kahului station supervisor. The plant operator would tell dispatch how much load they could take as generation was brought on line and dispatch would select a feeder which would fit within the load range, based on experience and load readings prior to the outage, and close the breaker.

Once M6 was on the bus, the first circuit closed was the 69 kV line to Puunene. The system had not been sufficiently sectionalized at Puunene and M6 tripped on overload. M6 was restarted and additional feeders were opened at Maalaea and Puunene. M6 paralleled to the bus and began picking up load. M5 started, paralleled with the bus and began picking up load. M5 and M6 tripped on overload and the process was restarted. At 0902 hours, the re-energization sequence was again initiated with M6 and progressed successfully to energize the 69 kV system, parallel with HC&S, start Kahului Power Plant and pick up priority and customer load. The majority of the load was restored by about 1315 hours with the last feeder breaker closing at 1432 hours.

MECO staff indicated that they took a fairly aggressive approach to restoring load and in some cases overloaded the generator(s) or had to reopen lines when load sections were larger than expected. The early trips of M6 and M5 in the loading sequence added about 15 minutes to the overall restoration time. Based on the timing of the startup and loading of the Maalaea CTs, it appears that the thermal lock of the units had released prior to them being required for the next increment of load and did not delay restoration.

### 3.3.3 Communications

MECO utilizes SCADA, an Avaya phone system, Maalaea Power Plant Gai-tronics phone system, interdepartmental Gai-tronics phone system, intra-company shortwave radio, Maalaea short wave radio, inter-company email, and external land lines and cell phones. Reports from personnel interviews indicate that primary internal communication systems failed on loss of utility or auxiliary power. SCADA, phone and radio communications were restored at the Kahului Baseyard Dispatch Center when the emergency generator came on line. Soon after the loss of primary communications, communications were re-established between the dispatch center and the power plants using backup communications sources including use of shortwave radios, external land line and cell phone service. Once auxiliary power was restored to the power plants, internal MECO communication mediums returned to normal.

# 4 Conclusions

After evaluating information provided by MECO, the data logs and other automatically generated information and information discussed throughout this report, along with the interviews of the operators on duty during the event and restoration, we conclude:

1. The main underlying cause of the island-wide outage was that the earthquake induced the operation of vibration sensors when generator minimum mechanical clearance tolerances were exceeded during the seismic shaking on M14 and M16. These were in fact valid alarms caused by exterior forces, rather than from actual equipment faults, which could still result in machine damage. The loss of these two units which were carrying 37.6 MW or 28.5% of the island's load, precipitated the island-wide blackout. Loss of M14 and M16 led to a cascade of operation of protective equipment on the remaining generators, such as high exhaust temperature on M19, under frequency on KWP, and static exciter trouble and low fuel pressure on K3. Loss of M19 appears to have been the event that overwhelmed the system's ability to recover frequency by shedding load and ramping up remaining generation. Without M14 and M16 exhausting heat into the boiler producing steam for the HRSG steam turbine M15, M15 was unable to continue carrying load and lost power output capability some 14 seconds later. The loss of the above generators resulted in very low frequency on the remaining generators (K1, M10, M11, and M12), that eventually led to their trip and system wide blackout. The equipment operated as designed to protect the generators and POWER has no recommendation for further evaluation.

2. The manual trip of K4 was reasonable and prudent. Considering the shift supervisor's observations and experience, it was reasonable for him to conclude that the K4 turbine was the source of the vibrations and act expeditiously to minimize damage. In fact, the vibration alarm received immediately after the manual trip would have prompted the operator to trip the turbine in any case. In the time line, K4 was tripped slightly after M19 tripped and the system was already in severe distress. When the earthquake struck, the Kahului shift supervisor noticed water coming down one side of the boiler of unit K4 and also saw that the turbine was shaking. He had not realized that there was an earthquake in progress, and thought that the boiler had a fault which had caused the turbine to ingest water causing it to vibrate severely. This would be a potentially very serious problem which could cause major turbine damage, so the shift supervisor hit the emergency stop switch for K4. Two seconds after the manual trip signal was initiated, the DCS recorded vibration alarms on K4, which would have led to a trip of the unit if the shift supervisor had not already done so. POWER concludes that the operator's actions were reasonable under the circumstances and that protective equipment would have operated in the next couple of seconds to protect the generators. POWER has no recommendation for further evaluation.

3. The sequence of load shed operation indicates that the UFLS operated as designed. The scheme was not designed for contingencies and multiple events which result in the percentage of generation lost due to the October 15th earthquake (45% of the system load at the time of the earthquake). From the EMS and SCADA data it appears that on the generator trips of M14 and M16, the frequency quickly decayed to below the 58.7 Hz trigger-point of the UFLS Block 1, and the load shed block operated. Then frequency recovered to above 59.5 Hz, but began to decay again as the power output from M14 and M16 reduced to zero. When this occurred, the frequency decayed below 59 Hz and then recovered as the remaining generation ramped up and load shed blocks 2 and 3 operated. One breaker of block 2 did not operate

because other breakers on the 69 kV system operated before the 10 second delay had elapsed to de-energize the 69 kV transmission system that fed this circuit. We do note that the frequency data provided from the EMS has limited value in assessing the system response to an underfrequency event as the frequency monitoring equipment has a lower limit is 59 Hz which is above the settings for the UFLS relays. Concluding that the UFLS operated as designed, no recommendations are forthcoming for evaluation of the UFLS, but we do recommend examining the EMS frequency recording capability.

4. HC&S separated from MECO but remained on line, supplying local load for some time. The interconnect scheme is set according to common utility practice and does not allow HC&S to close on a dead MECO bus. In the case where this unit continues to operate following a system disturbance and “island” to local load, it might be used to restart the grid, if the substation equipment is reconfigured to allow HC&S to close on the “dead” MECO bus. The ability to make these changes, however, will be impacted by other factors such as safety considerations, permitting limitations, control and other technical limitations of the equipment, and contractual agreements between MECO and HC&S that define requirements and obligations of both parties in such a restart situation. As MECO has a very quick black start capability with the Maalaea diesel units and CTs, an option to use HC&S to black start the system has a much reduced value. Thus, POWER is not proposing any recommendation with respect to use of HC&S for black start of the MECO system.

5. Loss of several of the internal MECO communication systems and SCADA between the dispatch center and plants impeded coordination during the outage, but did not contribute to the outage and does not appear to have delayed the restoration. MECO has SCADA, an Avaya phone system, a Gai-tronics phone systems and shortwave radios along with external land line and cell phone communications. MECO personnel have indicated that the many of the internal communication systems initially failed on loss of utility or auxiliary power and external systems were congested. Communications were established between the dispatch center and the power plants using the radios, external land line and cell phone service. Once auxiliary power was restored to the power plants, internal MECO communication mediums returned to normal. MECO's present communication protocol is for the dispatcher to coordinate with the plant operator at Kahului, who then dispatches the generation from Kahului or Maalaea. This adds an additional leg to traverse and could be problematic when communication systems are stressed. In this event, however, communications were restored quickly enough to not hamper the coordination between the dispatch center and the power plants.

6. The power plants, Dispatch Center and transmission system were properly configured, dispatched and staffed for normal operations the morning of Sunday October 15, 2006 at 0700 hours. The Dispatch Center was properly staffed according to MECO operating procedures. The dispatcher was conducting routine monitoring of the system conditions and coordinating the startup schedule of generation with the operator at Kahului power plant as demand for power began to increase. Kahului and Maalaea power plant staffing was normal for a Sunday. The personnel were conducting their normal routines of monitoring the plant conditions. The Kahului operator coordinated with the dispatcher to schedule the generation and coordinated unit commitment with the operators at Maalaea. POWER is not proposing any recommendation with respect to MECO dispatch or staffing.

7. The actions of the MECO staff were reasonable and in the best interests of the public. In POWER's opinion, the MECO personnel reacted to the circumstances in a reasonable, responsible and professional manner. The dispatch and power plant staff did not have time to respond to the major loss of generation over a 20 second period. After the major loss of generation, the data indicates that the system was experiencing severe low frequency which eventually resulted in the trip of the four remaining generators by protective relay action or operator intervention. They applied training and experience in reacting properly to the changing system conditions based on the system condition and established MECO operating practices to restore power as quickly as practical. We have considered data logs of the dispatch center, power plant units, and transmission system following the earthquake on the morning of October 15. We also reviewed statements of power plant operators and conducted direct interviews of dispatchers, power plant operators, engineers and management staff. Our assessment has found only two issues that could perhaps have been handled differently, and neither significantly extended the outage. First, additional stripping of the K3 and K4 auxiliaries would have avoided the trip of the Kahului black start unit on overload. Second, trips of the Maalaea M6 and M5 units occurred on overload as the plant attempted to pick up load increments that were too large in the early stages, due to the fact that stripping the load from the transmission and distribution system had not been completed by the time the plant was in the position to re-energize the 69 kV system. As Maalaea power plant can fast start with ICE and CT generation that is better adapted to reenergizing the system, we conclude that the black start trip of K1 essentially did not have any effect on the duration of the outage. We are not aware of any case where actions could be described as imprudent or likely to cause injury, or damage or have materially improved restoration time. The senior staff that reported in after the earthquake were directed to respond to the power plants to assist in establishing communications and managing the system restoration. The MECO personnel

acted professionally throughout the outage and restoration applying their training and experience to their assigned tasks during a distinctly extraordinary event. The system restoration plan developed by the operations staff was prioritized, reasonable and well executed; and generally followed the procedures outlined in the Emergency Response Manual. As noted above, the pace of the restoration was initially aggressive which resulted in tripping the generators while additional sectionalizing was in progress and then re-start of the unit. In the MECO case, with the magnitude of diesel generation available, this is not as large a risk in the early stages as restart can be performed in five to ten minutes as additional load is stripped until the remaining system load matches the generation on line.

8. The power plant staff exercised reasonable judgment in the planning and execution of the black start procedures. The black start process was slowed at Kahului due to overload trip when K3 and K4 auxiliary air compressors remained connected and overheating of the black start generator due to a cooling system fault. However, these events did not impact the start outage duration as this was occurring in parallel with other activities. It appears that the black start of Maalaea Power Plant was only impacted by the time required to strip loads on the transmission and distribution system to match the generation brought on line. Both of the initial trips of the Maalaea occurred because the connected system load remained above the generator capability. As the Maalaea diesel plant can theoretically be restarted in 30 to 60 minutes, sectionalizing the transmission and distribution system to disconnect load could become the critical path for the system restoration.

# 5 Recommendations

In this section of this report we provide recommendations, which, if implemented, are not likely to reduce the likelihood of a repeat of the system blackout of October 15, 2006 due to similar circumstances, but they could speed up the restoration of electricity to consumers in the event of a system blackout. We recommend the following:

1. Evaluate the various internal MECO communication systems and associated emergency and uninterruptible power supplies. Institute recommendations from the evaluation to provide robust and dependable internal communication emergency power supply systems. MECO began this assessment soon after the outage has been implementing the recommendations.

2. Assess the communication protocol between dispatch and power plant operators to determine if they can or should be streamlined to allow closer coordination between dispatch and the individual plants during system restoration.

3. As the MECO system has a significant “fast start” capability, assess the possibility of programming a single button “black system” feature in the SCADA system to automatically open SCADA controlled breakers so that this activity does not become the critical path for system re-energization.

4. Evaluate upgrade of the system frequency and voltage recording equipment to install devices with faster scan rates and wider upper/lower limits to provide better data resolution for evaluating future events.