Three Case Studies of High Reliability Power Systems

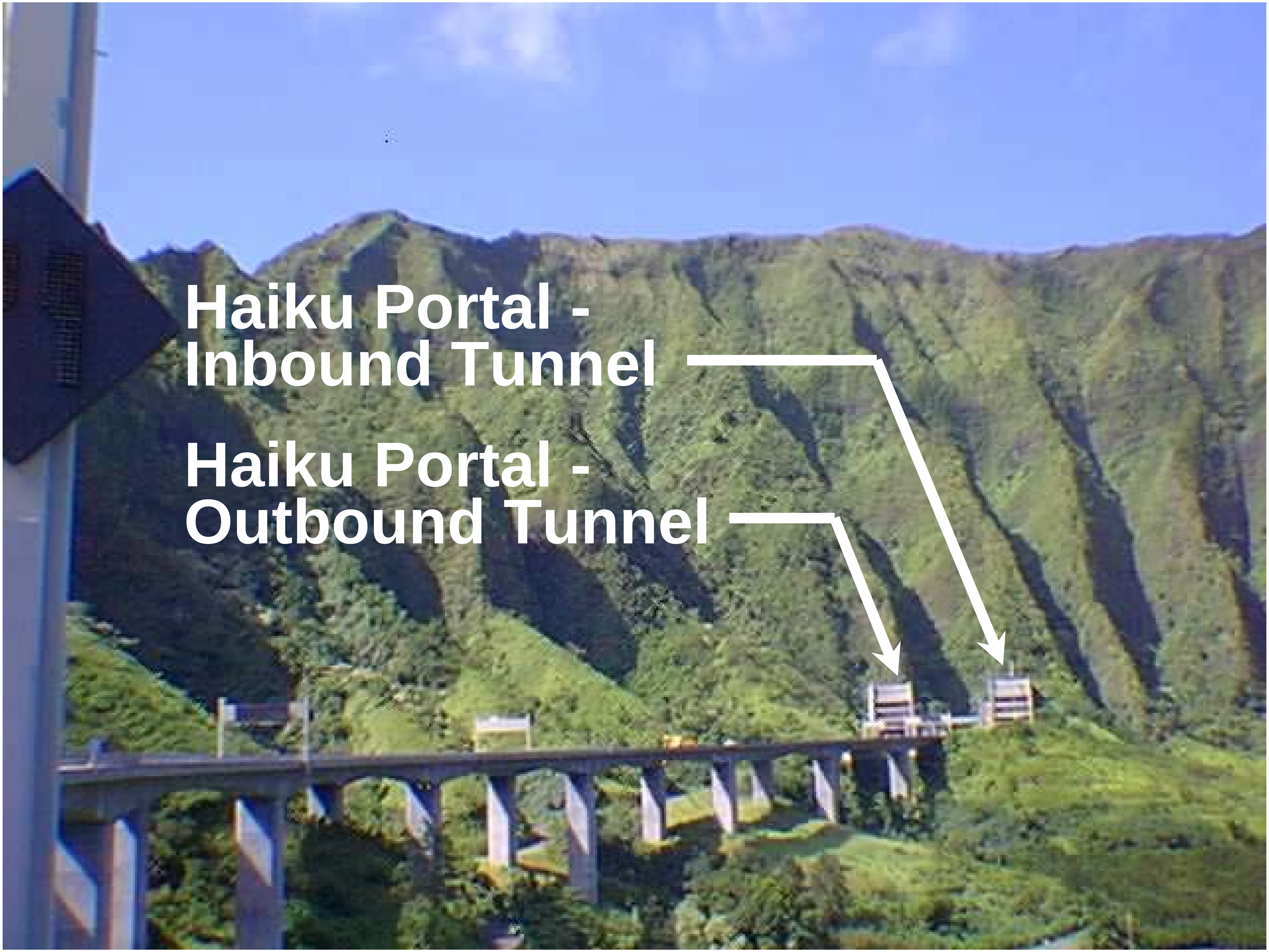
Keene M. Matsuda, P.E.
Senior Member IEEE
IEEE/PES Distinguished Lecturer
ke.matsuda@ieee.org

Buenos Aires, Argentina

June 25 & 26, 2009

Project No. 1: H-3 Tunnel

- 1.6 km (1 mile) long, twin-bore tunnel thru Koolau mountains
- Part of 26-km highway in Honolulu, Hawaii
- Tunnel connects Halawa valley to west and Haiku valley to east
- Cost: $1.3 billion (US) = 90% from FHWA + 10% from HDOT


Haiku Portal -
Inbound Tunnel
Haiku Portal -
Outbound Tunnel


Haiku Cross-
Over Vault

4 Sources of power

- For high reliability, 4 sources:
- 2 utility HV transmission circuits
- 1-500 kW emergency generator
- Numerous UPS and battery/inverter units

Utility power source

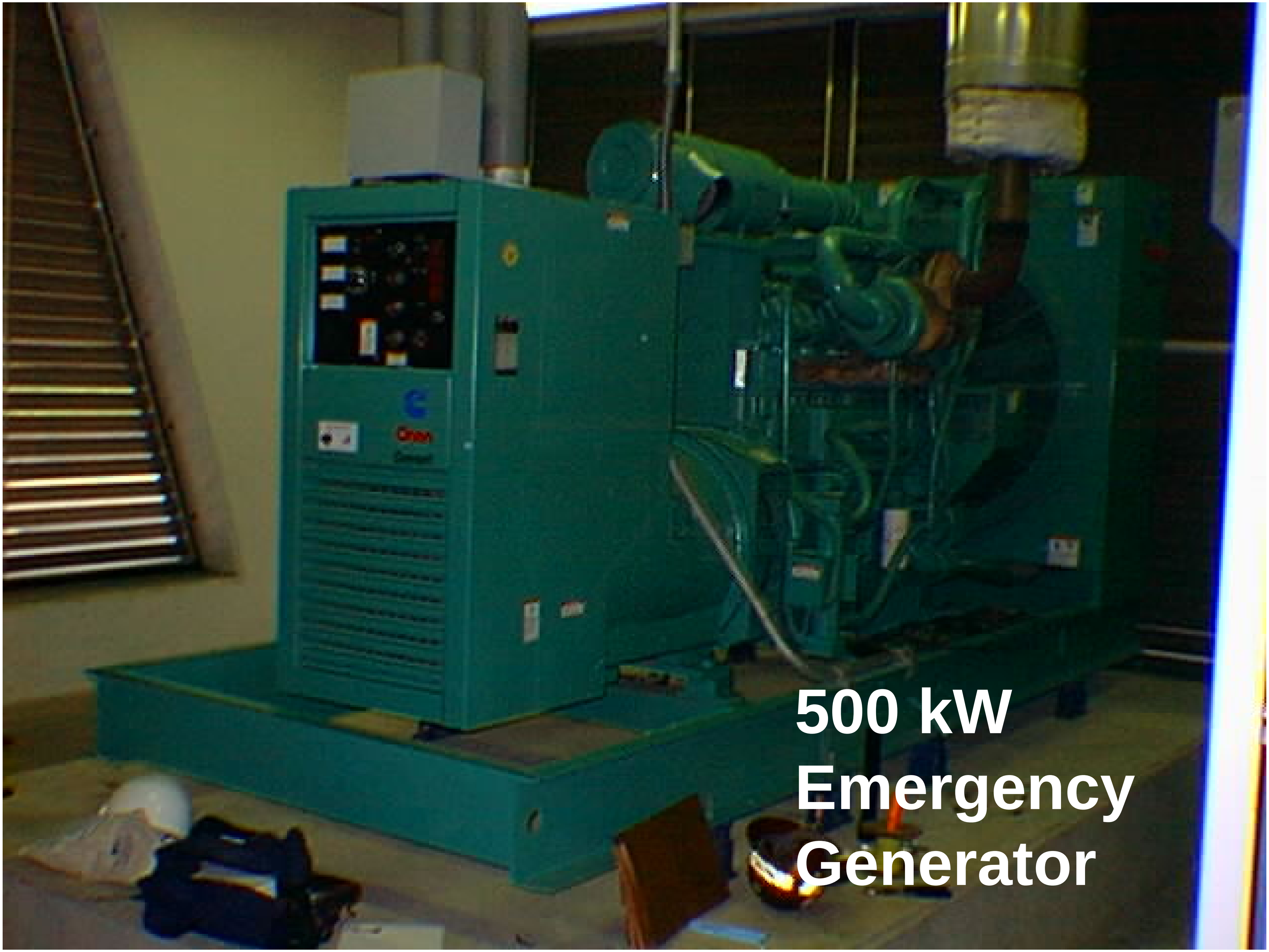
- 2-46 kV HECO transmission lines for high reliability
- Radial circuits terminate at portal substations: Halawa & Haiku
- Separate substations for redundancy
- 10 MVA, 46-12.47 kV transformer, fully sized for redundancy

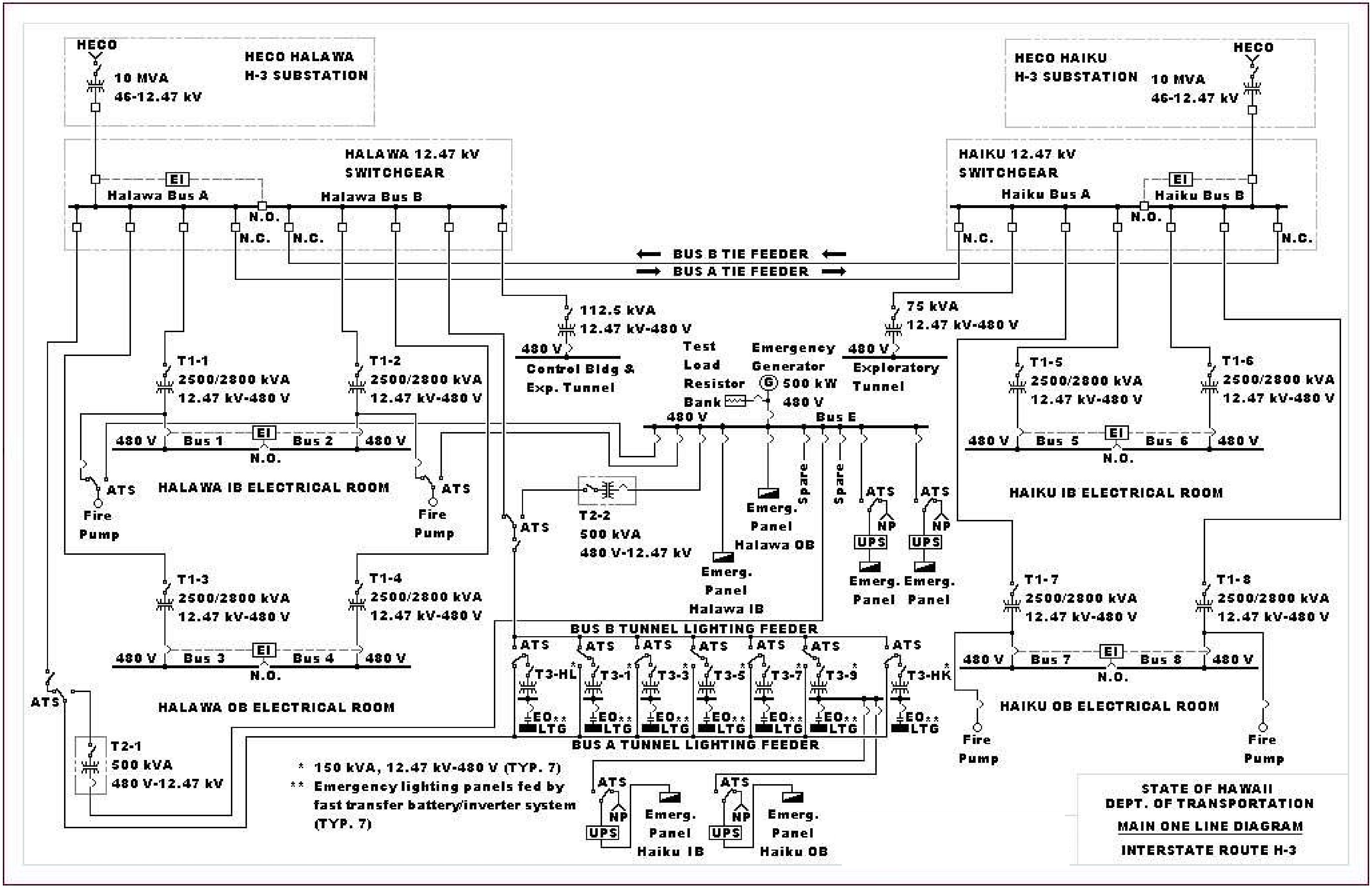

HECO 46 kV
Incoming Ckt

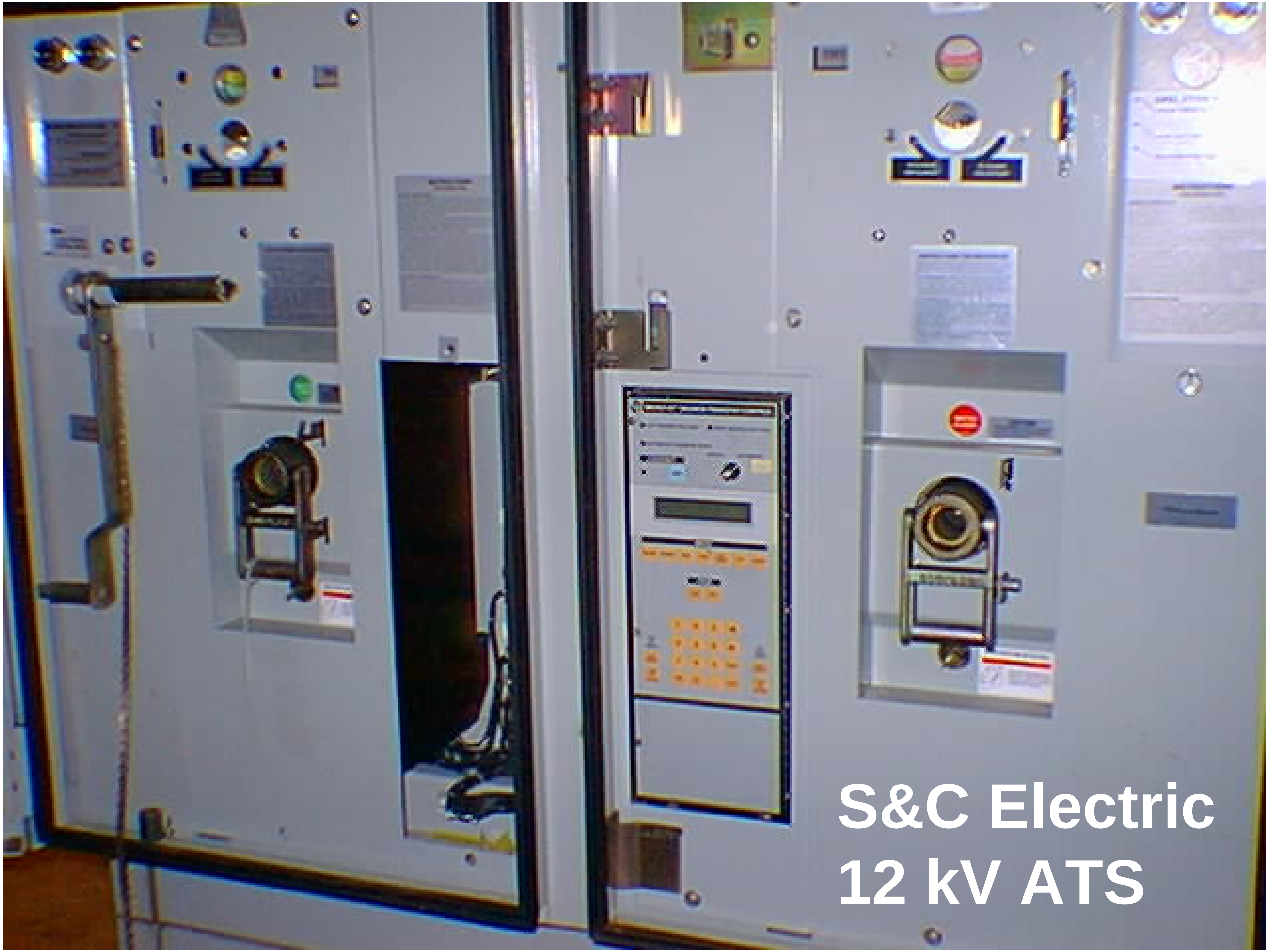

HECO 10 MVA
Substation

Emergency power sources

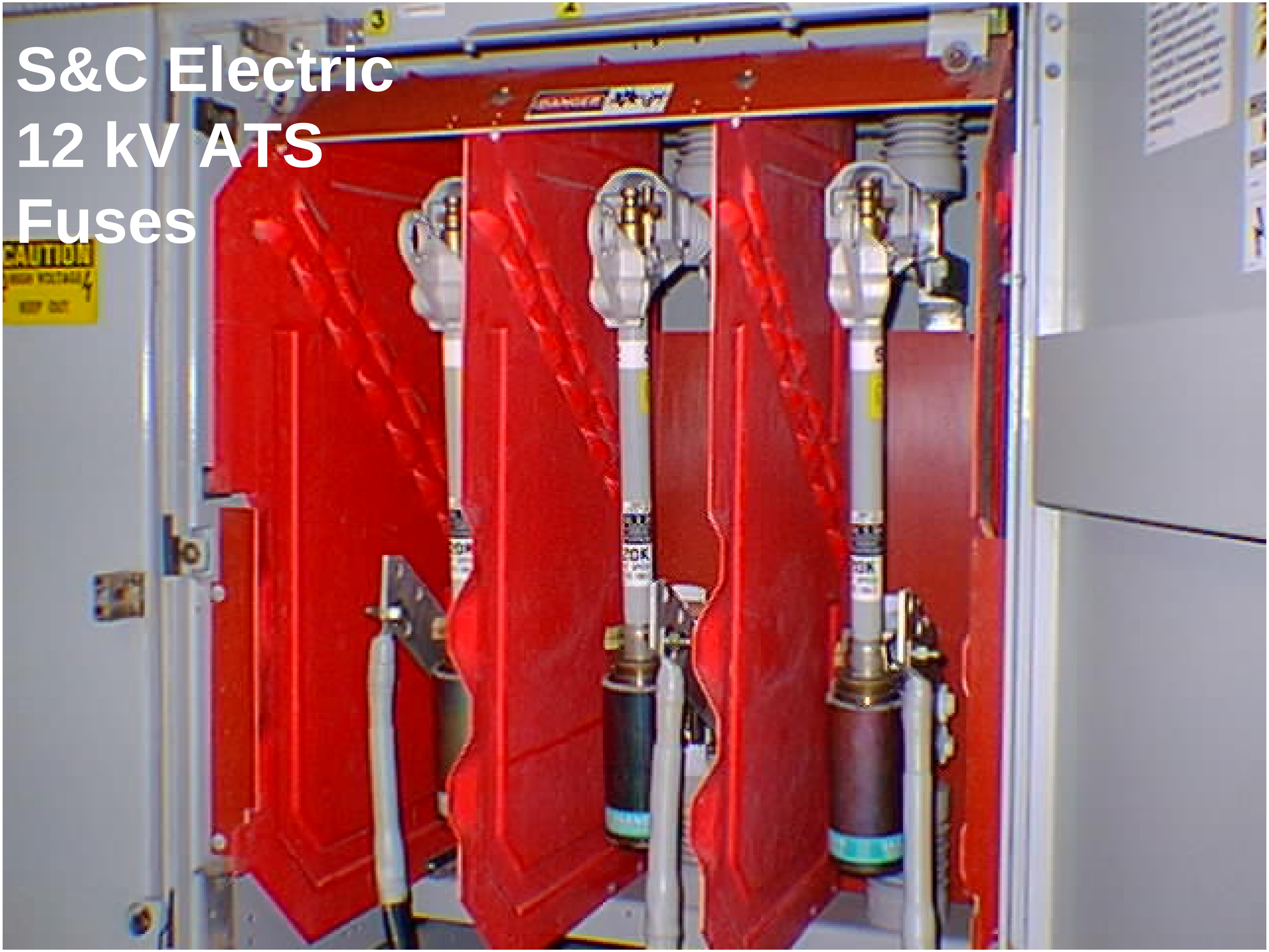
- Emergency diesel engine-generator: 500 kW, 480 V
- UPS units (15 min. battery capacity): computer-type loads
- Fast transfer battery/inverter units (90 min. battery capacity): HID lighting


500 kW
Emergency
Generator

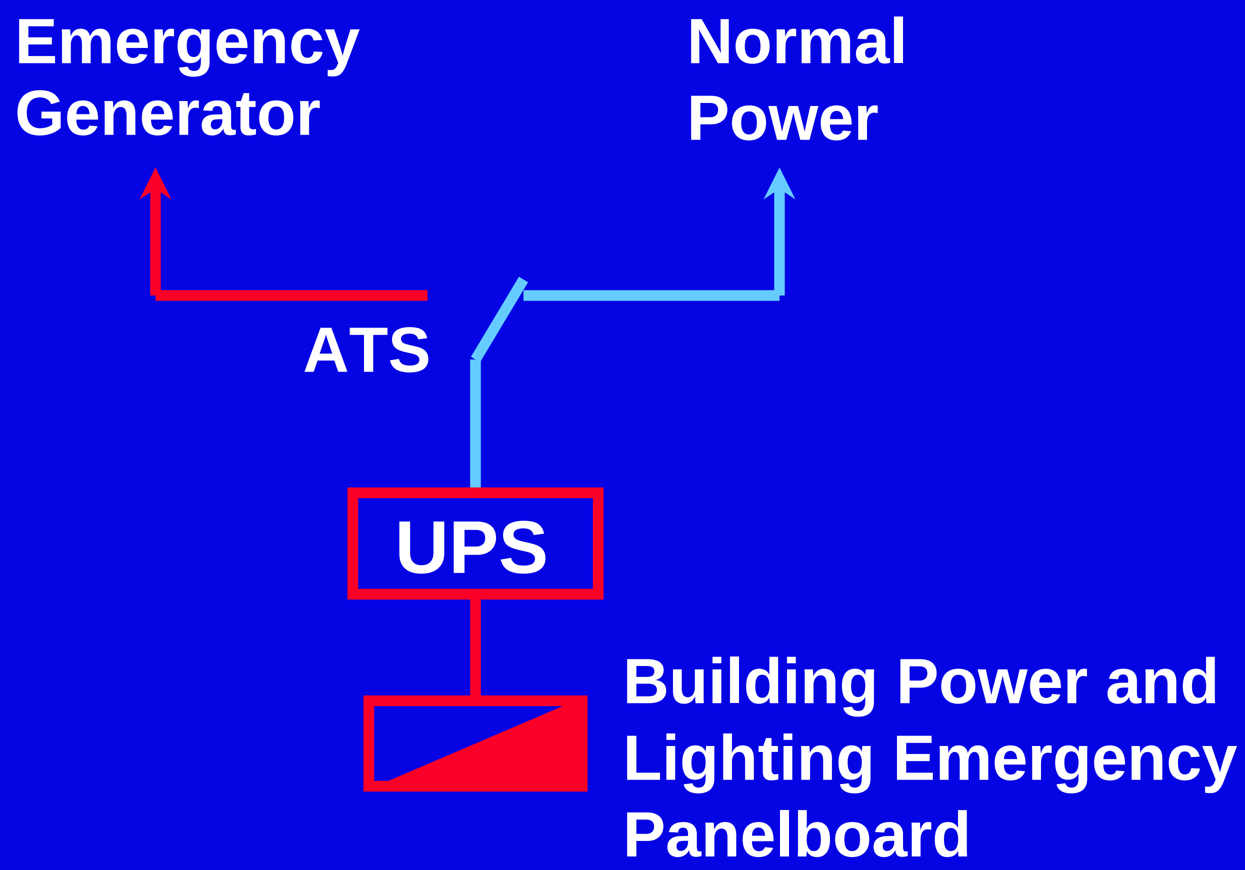

HECO
10 MVA
46-12.47 kV
HECO HALAWA
H-3 SUBSTATION
HECO HAIKU
H-3 SUBSTATION
HECO
10 MVA
46-12.47 kV
HALAWA 12.47 kV
SWITCHGEAR
EI
Halawa Bus A
Halawa Bus B
N.O.
N.C.
N.C.
HAIKU 12.47 kV
SWITCHGEAR
EI
Haiku Bus A
Haiku Bus B
N.O.
N.C.
N.C.
BUS B TIE FEEDER
BUS A TIE FEEDER
112.5 kVA
12.47 kV-480 V
480 V
Control Bldg &
Exp. Tunnel
75 kVA
12.47 kV-480 V
480 V
Exploratory
Tunnel
Test
Load
Resistor
Bank
Emergency
Generator
G 500 kW
480 V
480 V
Bus E
T1-1
2500/2800 kVA
12.47 kV-480 V
T1-2
2500/2800 kVA
12.47 kV-480 V
480 V
Bus 1
EI
Bus 2
480 V
N.O.
ATS
HALAWA IB ELECTRICAL ROOM
ATS
Fire
Pump
Fire
Pump
T1-5
2500/2800 kVA
12.47 kV-480 V
T1-6
2500/2800 kVA
12.47 kV-480 V
480 V
Bus 5
EI
Bus 6
480 V
N.O.
HAIKU IB ELECTRICAL ROOM
Spare
Spare
ATS
NP
UPS
ATS
NP
UPS
Emerg.
Panel
Halawa OB
ATS
T2-2
500 kVA
480 V-12.47 kV
Emerg.
Panel
Halawa IB
Emerg.
Panel
Emerg.
Panel
T1-3
2500/2800 kVA
12.47 kV-480 V
T1-4
2500/2800 kVA
12.47 kV-480 V
480 V
Bus 3
EI
Bus 4
480 V
N.O.
HALAWA OB ELECTRICAL ROOM
ATS
T1-7
2500/2800 kVA
12.47 kV-480 V
T1-8
2500/2800 kVA
12.47 kV-480 V
480 V
Bus 7
EI
Bus 8
480 V
N.O.
HAIKU OB ELECTRICAL ROOM
Fire
Pump
Fire
Pump
BUS B TUNNEL LIGHTING FEEDER
ATS
ATS
ATS
ATS
ATS
ATS
ATS
T3-HL
T3-1*
T3-3*
T3-5*
T3-7*
T3-9*
T3-HK*
EO**
LTG
BUS A TUNNEL LIGHTING FEEDER
T2-1
500 kVA
480 V-12.47 kV
* 150 kVA, 12.47 kV-480 V (TYP. 7)
** Emergency lighting panels fed by
fast transfer battery/inverter system
(TYP. 7)
ATS
NP
UPS
Emerg.
Panel
Haiku IB
ATS
NP
UPS
Emerg.
Panel
Haiku OB
STATE OF HAWAII
DEPT. OF TRANSPORTATION
MAIN ONE LINE DIAGRAM
INTERSTATE ROUTE H-3


S&C Electric
12 kV ATS

S&C Electric 12 kV ATS Fuses

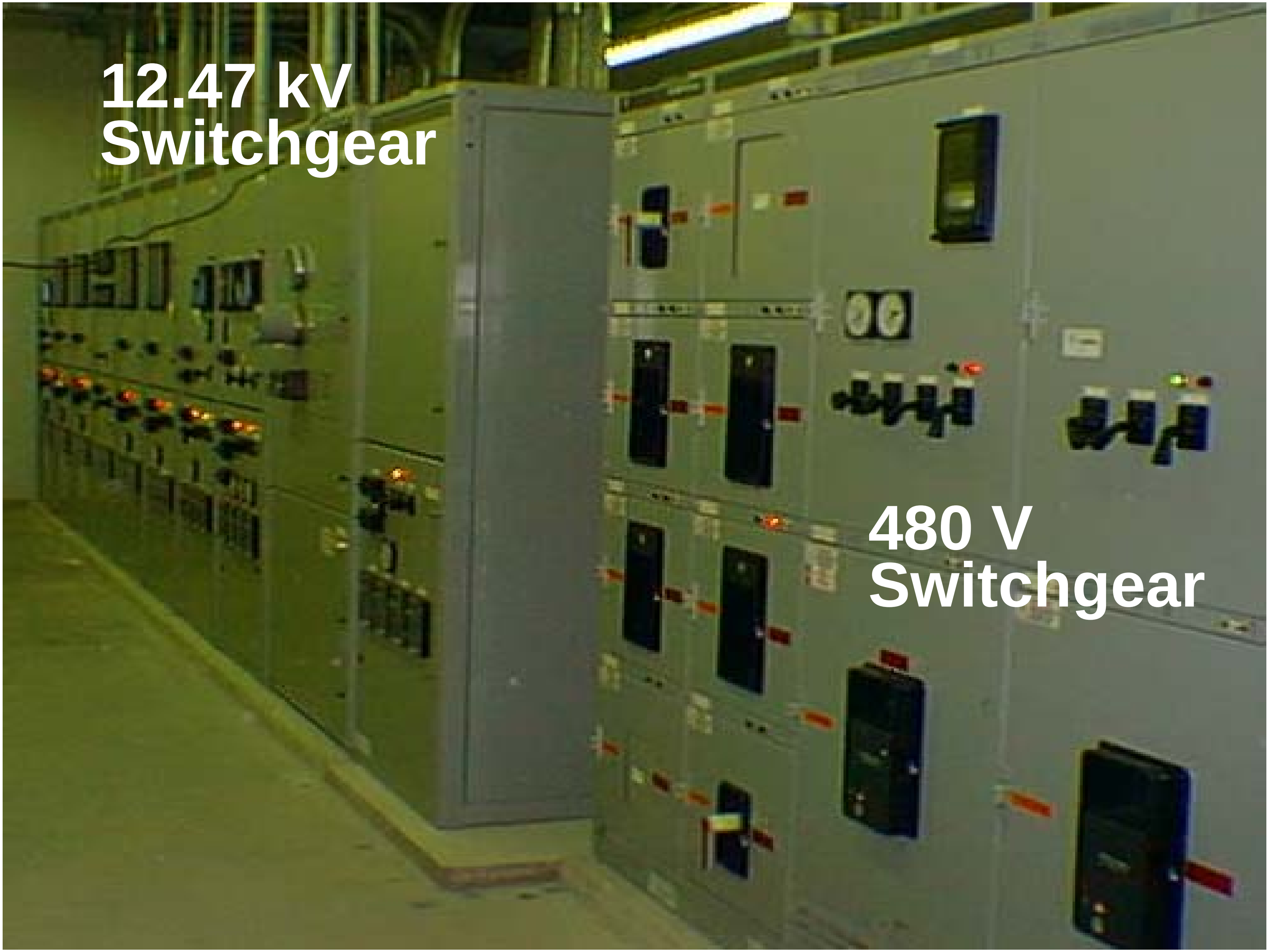


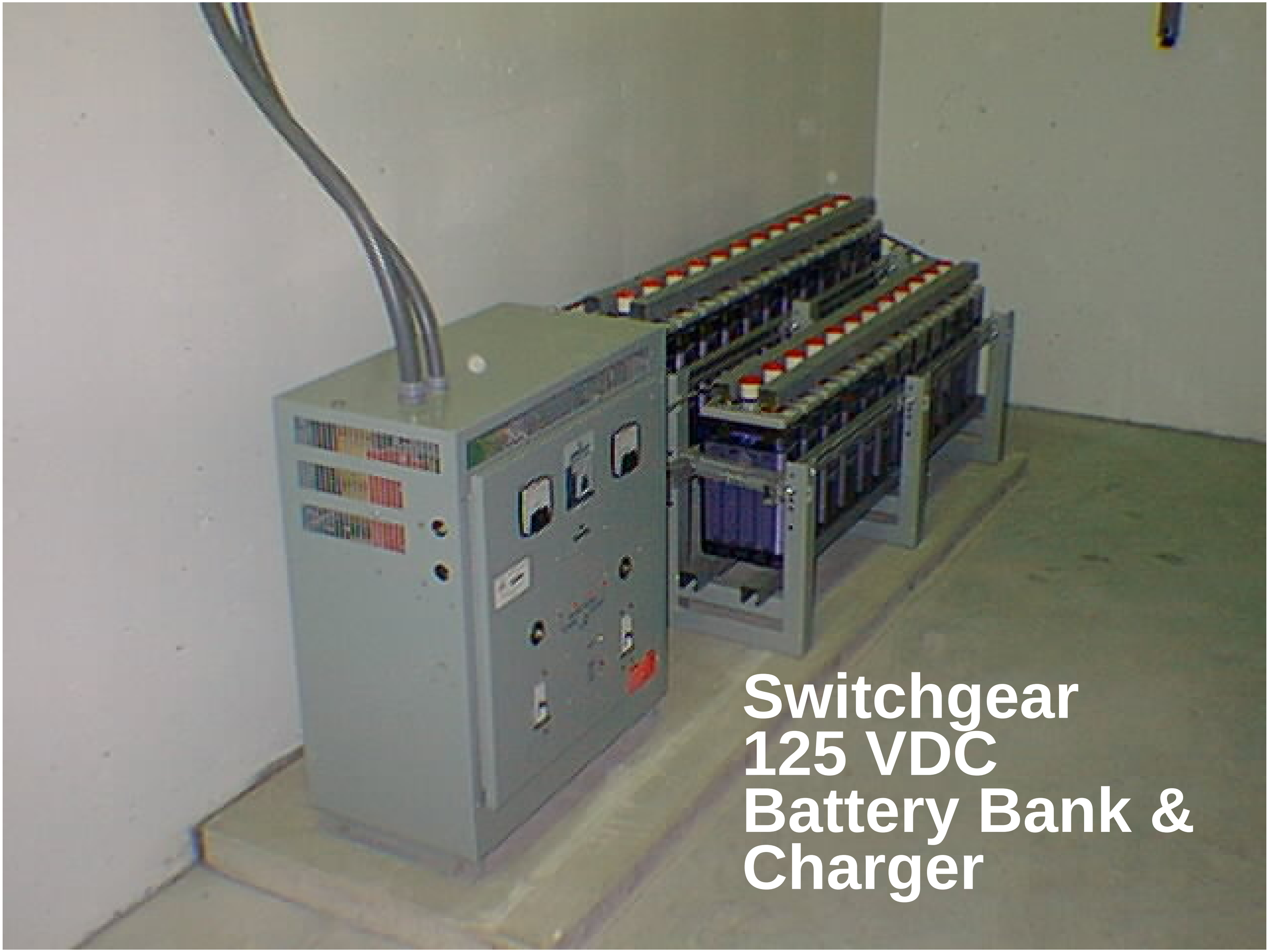
Emergency panelboards



12.47 kV switchgear system

- Metal-clad switchgear
- Vacuum circuit breakers
- Draw-out
- Electrically operated


12.47 kV
Switchgear
480 V
Switchgear

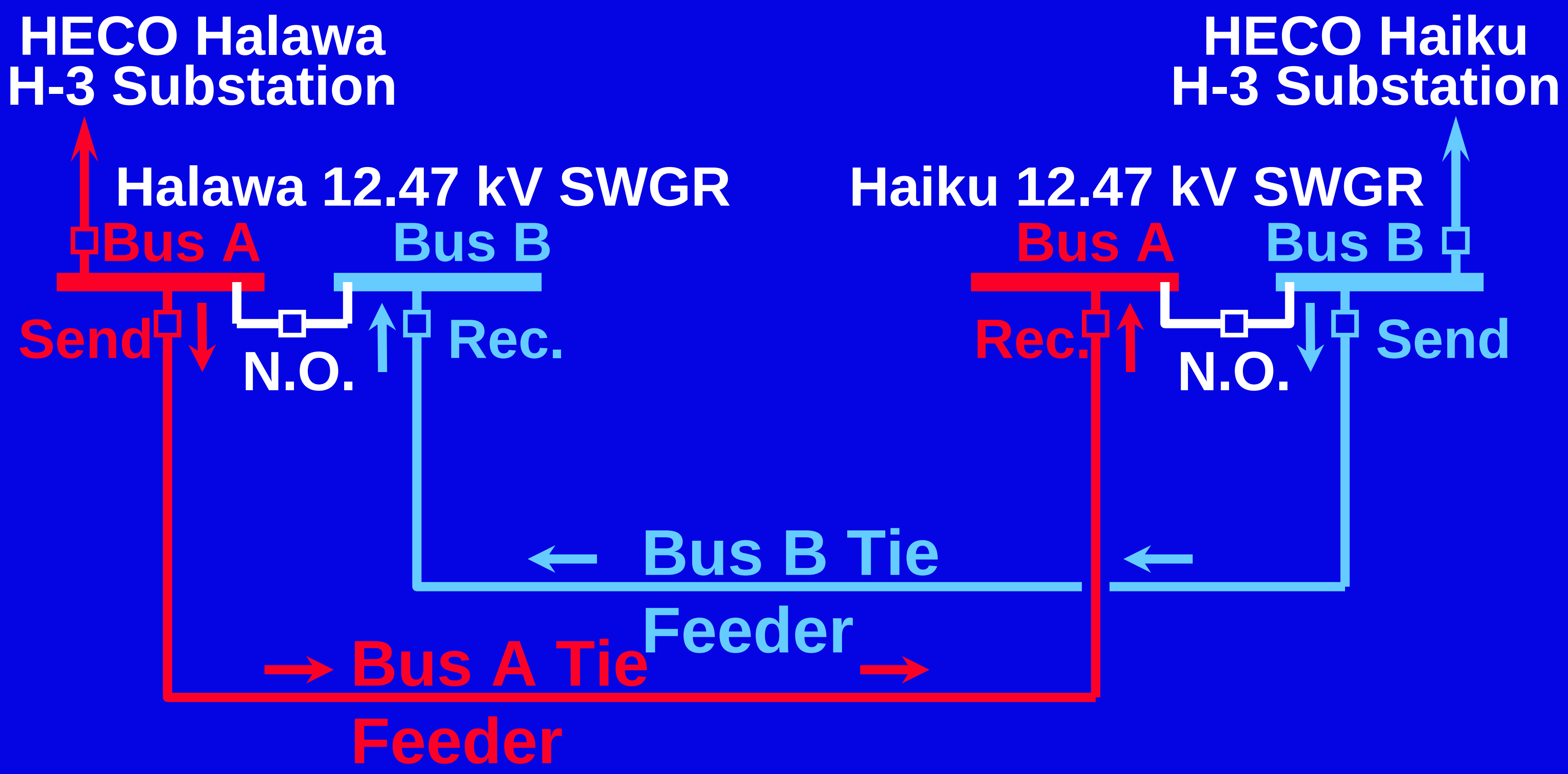


Switchgear
125 VDC
Battery Bank &
Charger

Split bus configuration

- Bus A = HECO Halawa H-3 substation
- Bus B = HECO Haiku H-3 substation
- Bus A tie feeder thru outbound tunnel via concrete duct bank
- Bus B tie feeder thru inbound tunnel via concrete duct bank
- Avoids coincident damage

Split bus configuration

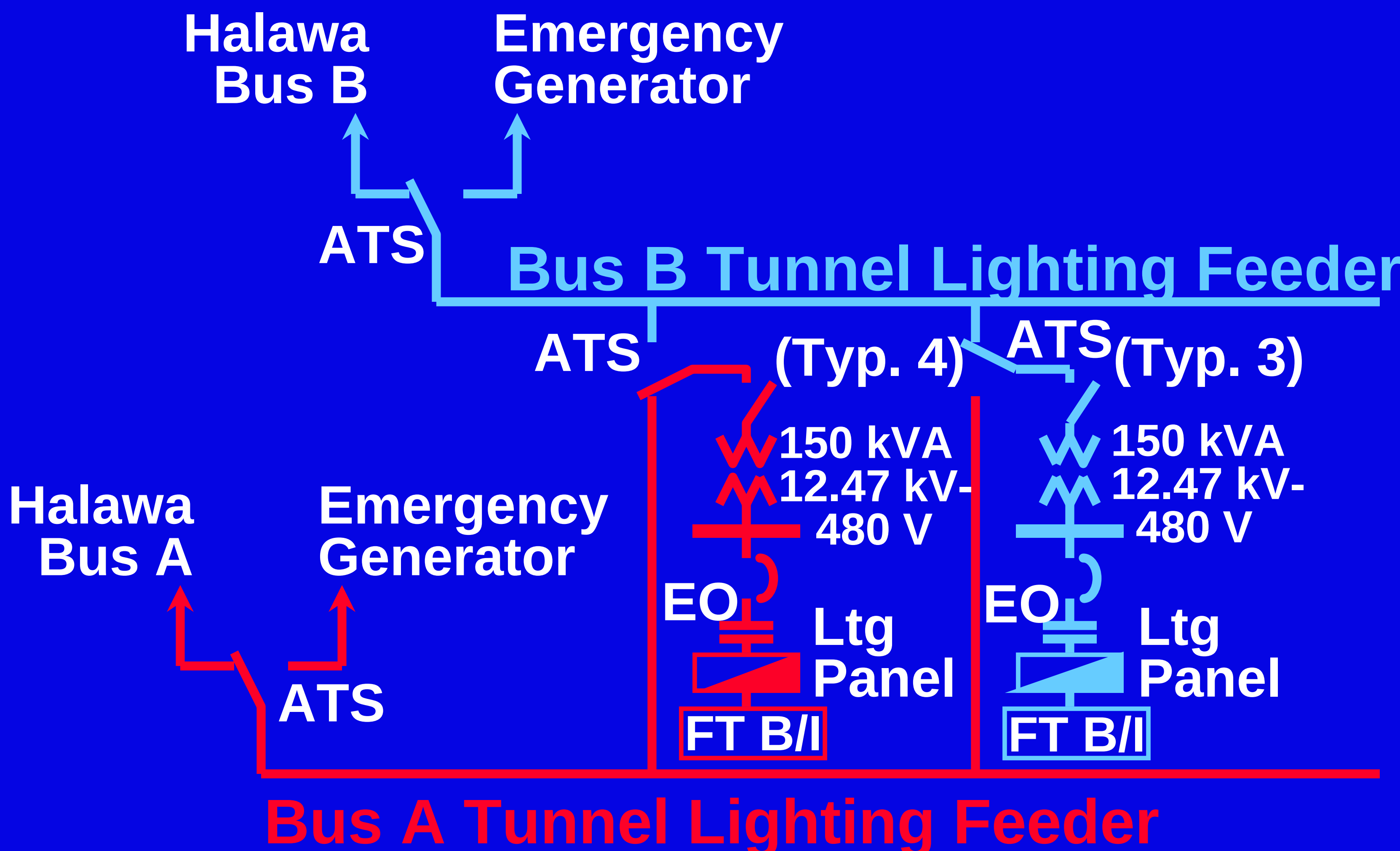


Tunnel lighting feeders

- 2-12.47 kV tunnel lighting feeders
- 7-12.47 kV ATSs and 7-150 kVA, 12.47 kV-480 V transformers:
- 5 cross-passages: 1, 3, 5, 7, 9
- 2 cross-over vaults: Halawa & Haiku
- Electrically-operated contactors, fast transfer battery/inverter units


Batteries for
Emergency
Lighting

Tunnel lighting feeders




Approach from
Halawa Valley


Tetsuo Harano Tunnel

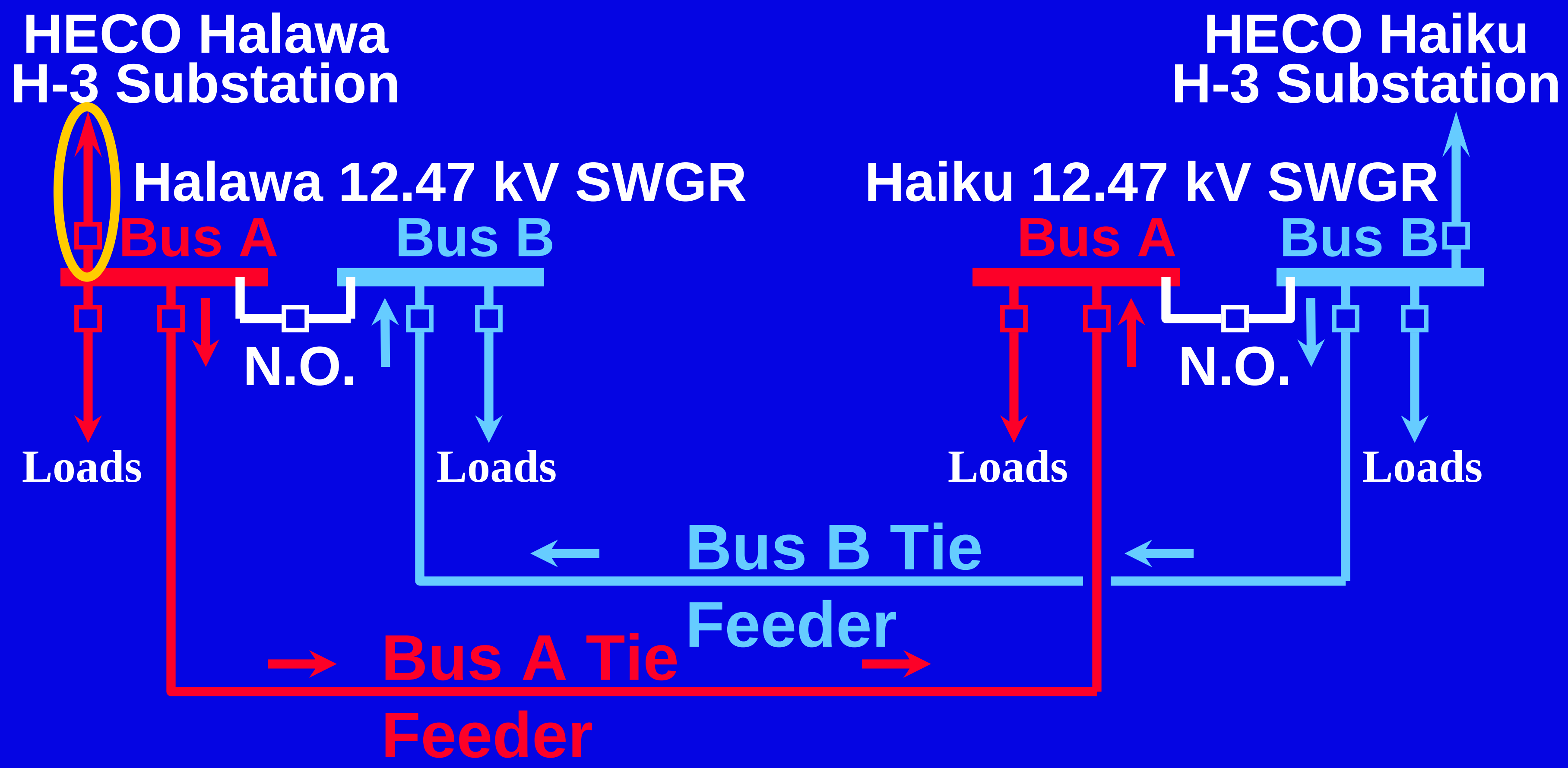

Exit to
Haiku Valley

12.47 kV swgr interlocking

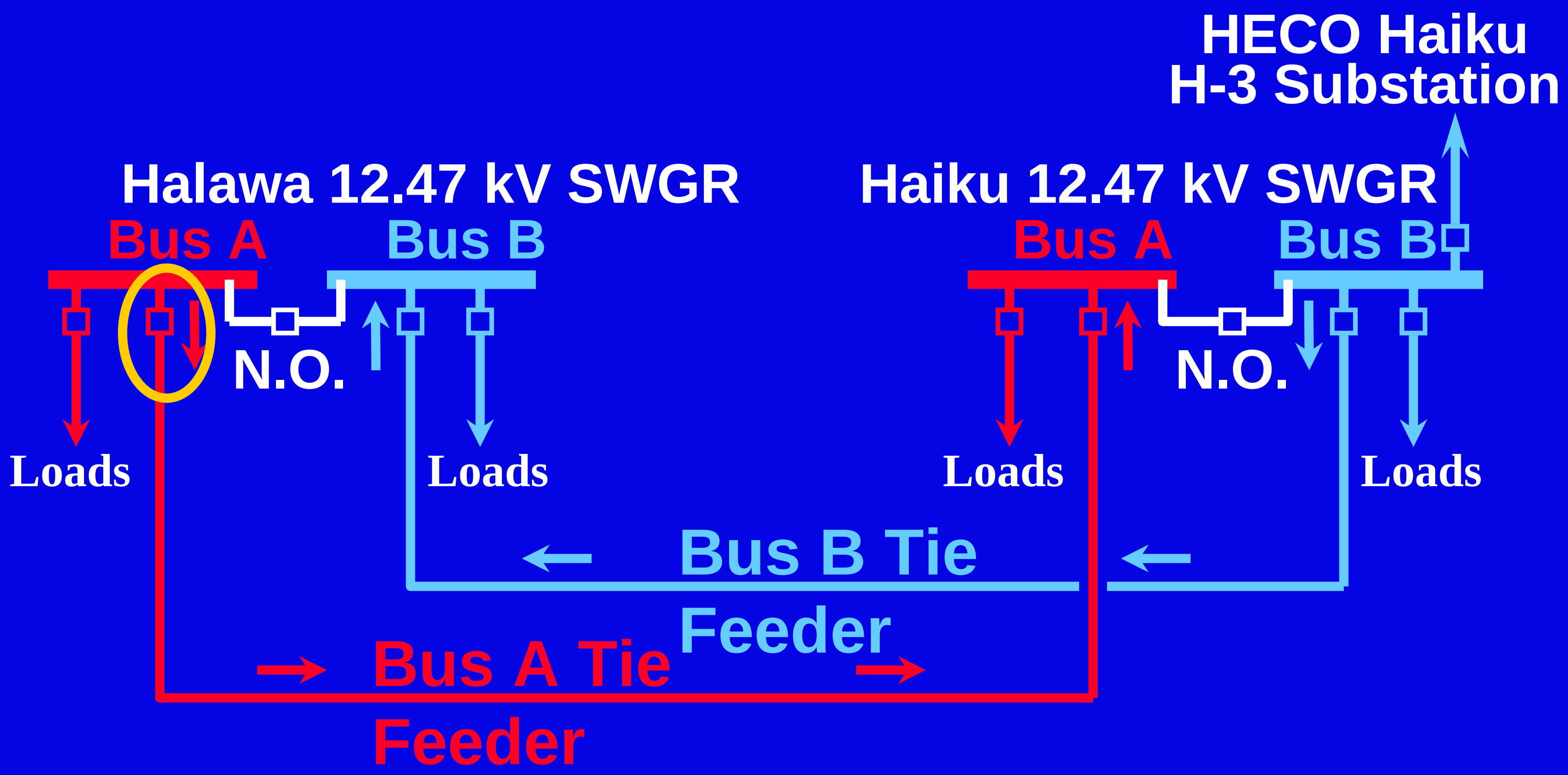
- Most significant reliability feature
- Auto restoration following HECO loss, feeder or bus fault
- Control wiring w/interposing relays between Halawa and Haiku swgr
- Most common failure - loss of one HECO line

1 of 32
Tunnel
Vent Fans

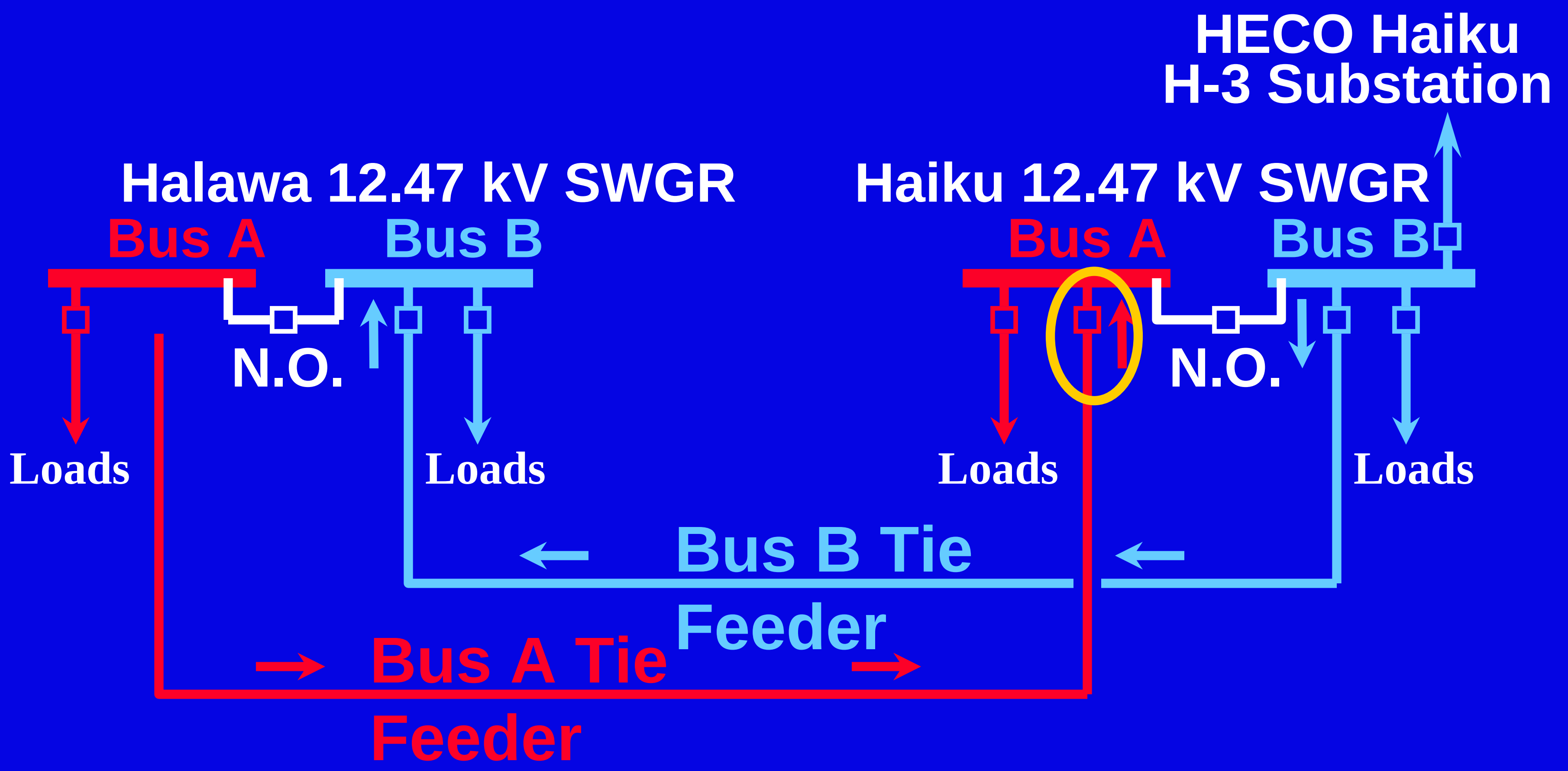
Loss of HECO restoration - 1



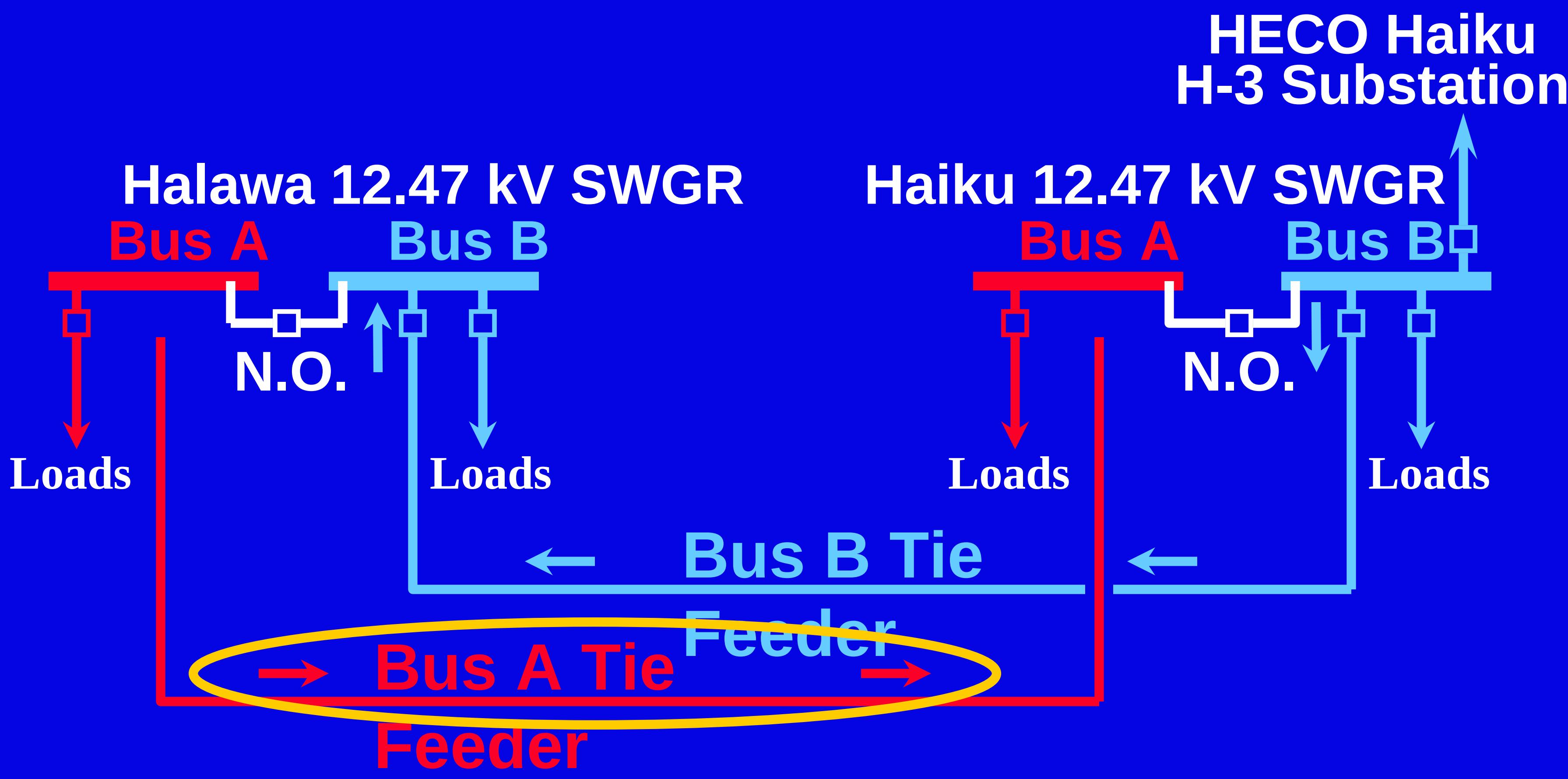
Loss of HECO restoration - 2



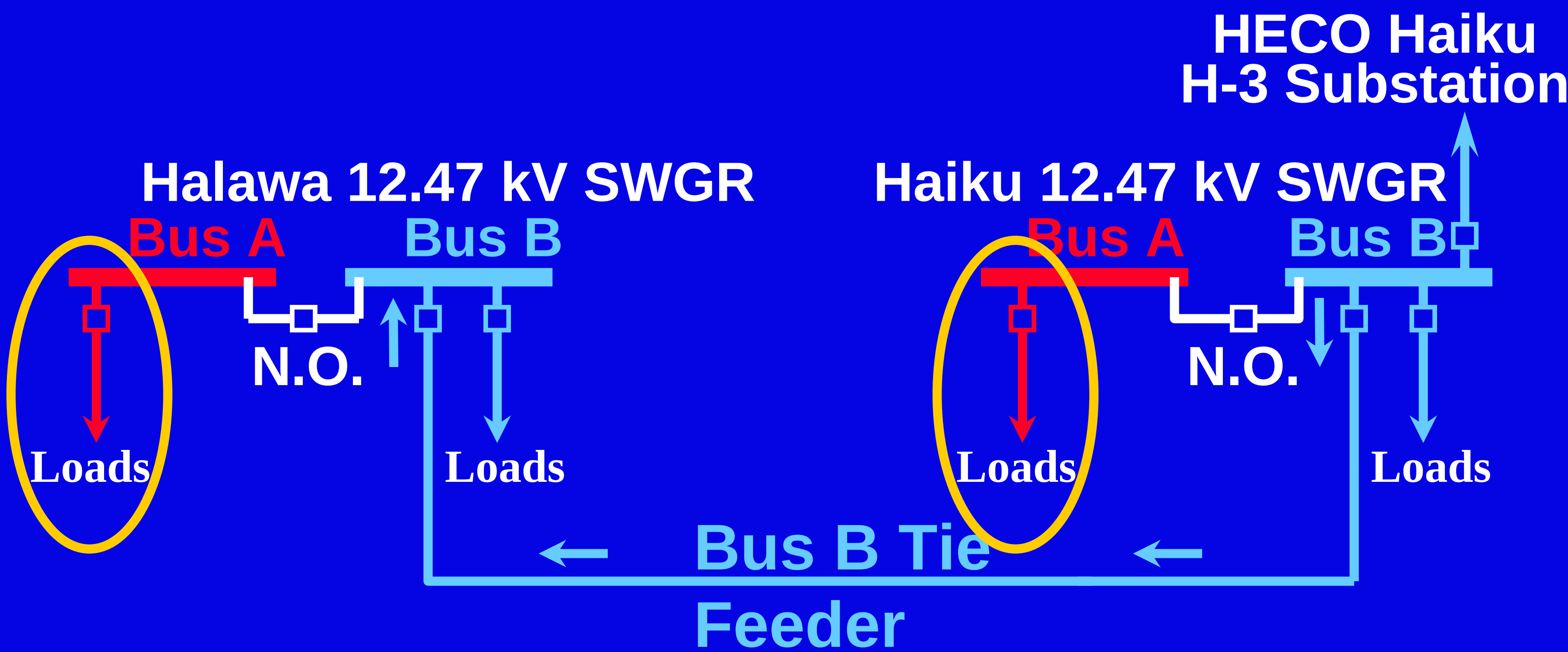
Loss of HECO restoration - 3



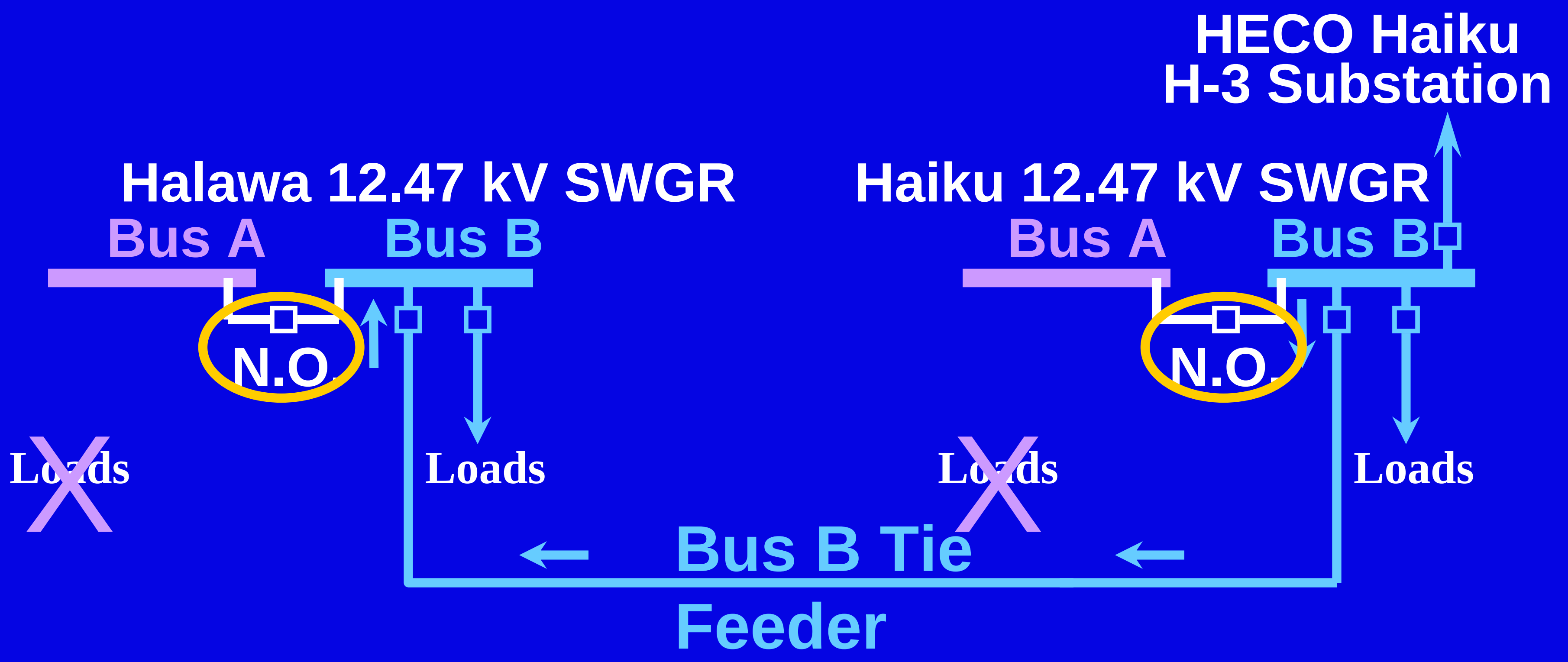
Loss of HECO restoration - 4



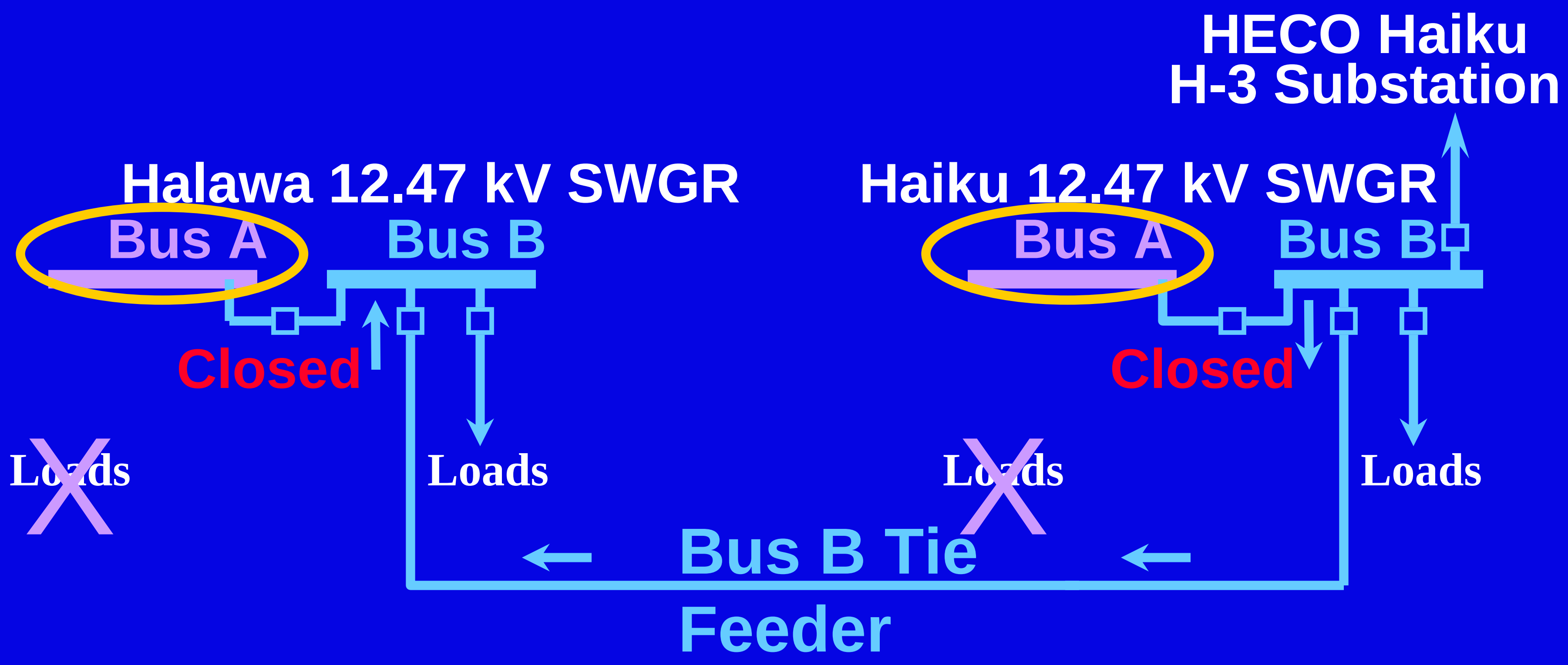
Loss of HECO restoration - 5



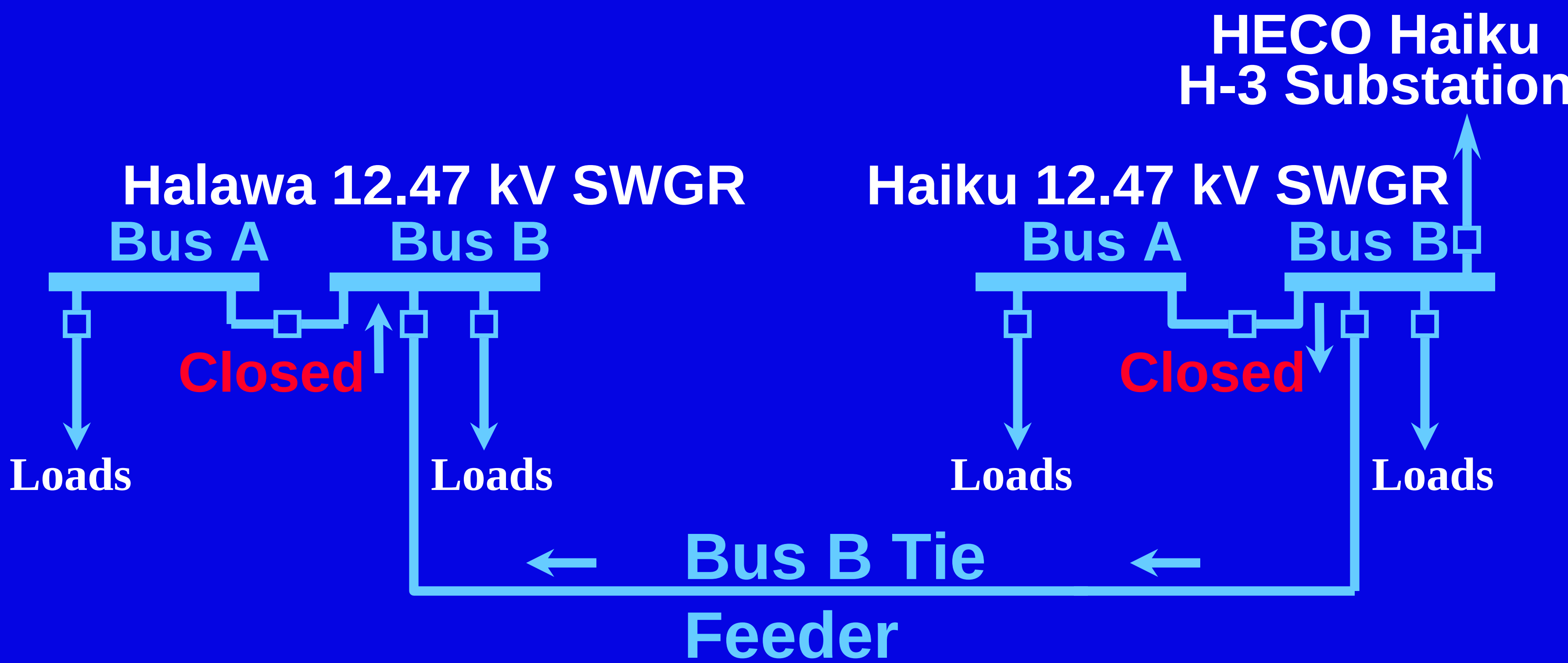
Loss of HECO restoration - 6



Loss of HECO restoration - 7



Loss of HECO restoration - 8



Local manual restoration

- Personnel required at both Halawa and Haiku swgr
- Local auto-manual switch (43AM)
- 43AM in manual to override switchgear automatic features
- Random operations will open and close other breakers

Remote manual restoration

- Through control room computer
- 43COMP is similar to local 43AM switch
- 43COMP is a control relay
- Energize 43COMP relay = manual


Control
Room

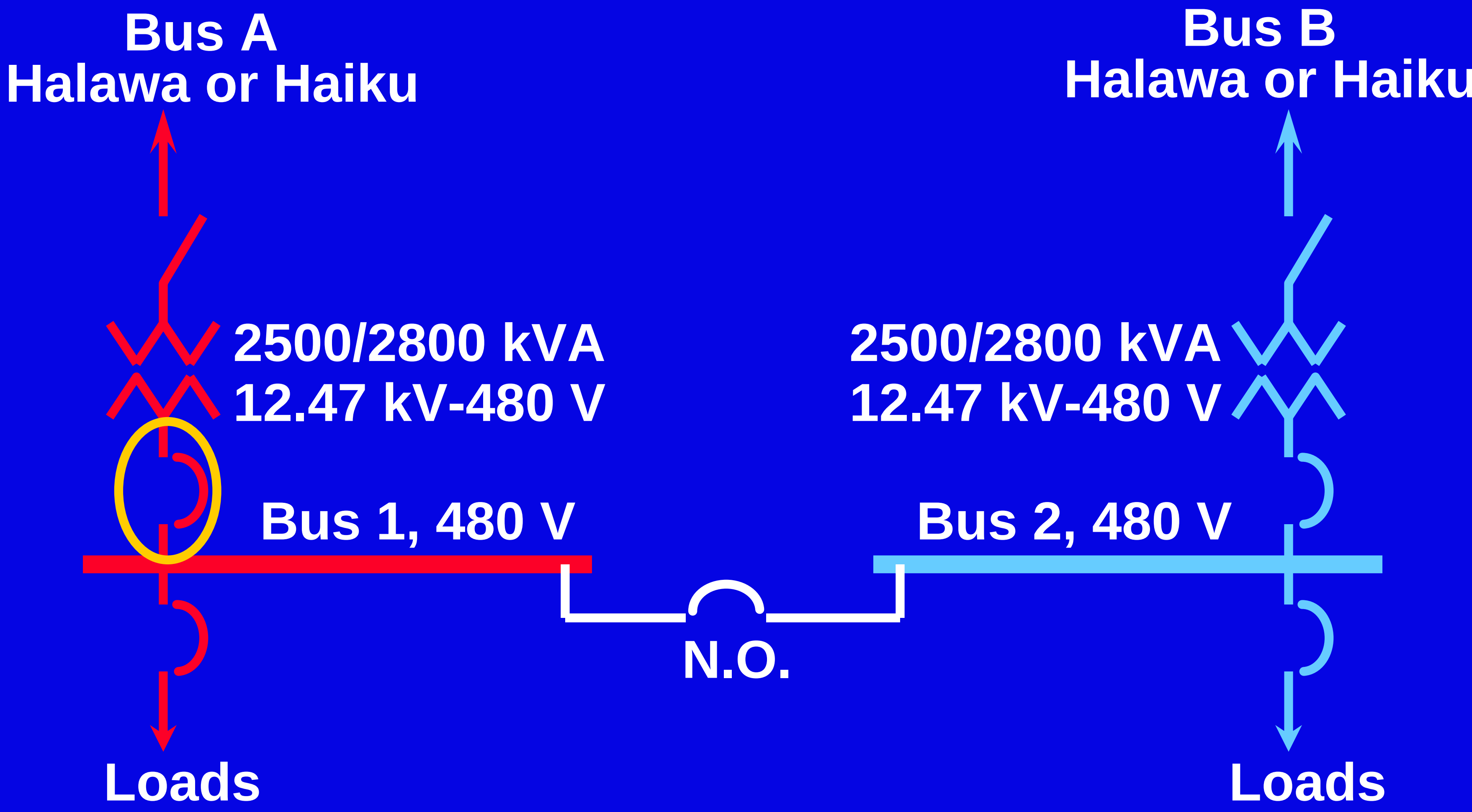
12.47 kV relay settings

- Very inverse OC relays set for max loading
- Coordination very difficult, many combinations
- Special setting for instantaneous relays
- Large inrush current from many transformers

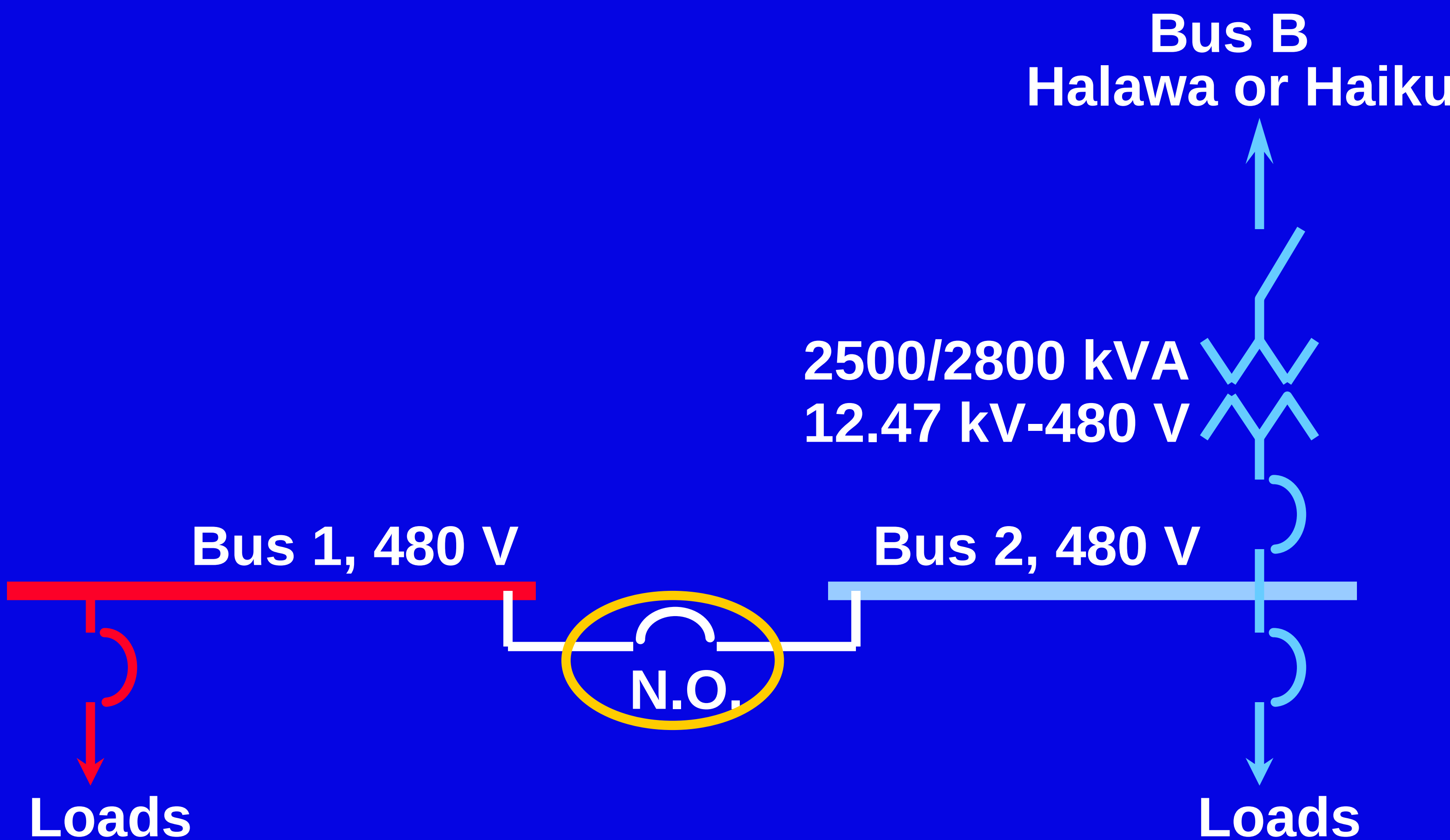
480 V load centers

- Two 2,500 kVA, 12.47 kV - 480Y/277 V transformers
- Fully-sized, all 4 portal buildings
- Also split-bus configuration w/automatic restoration
- Restoration via local or remote

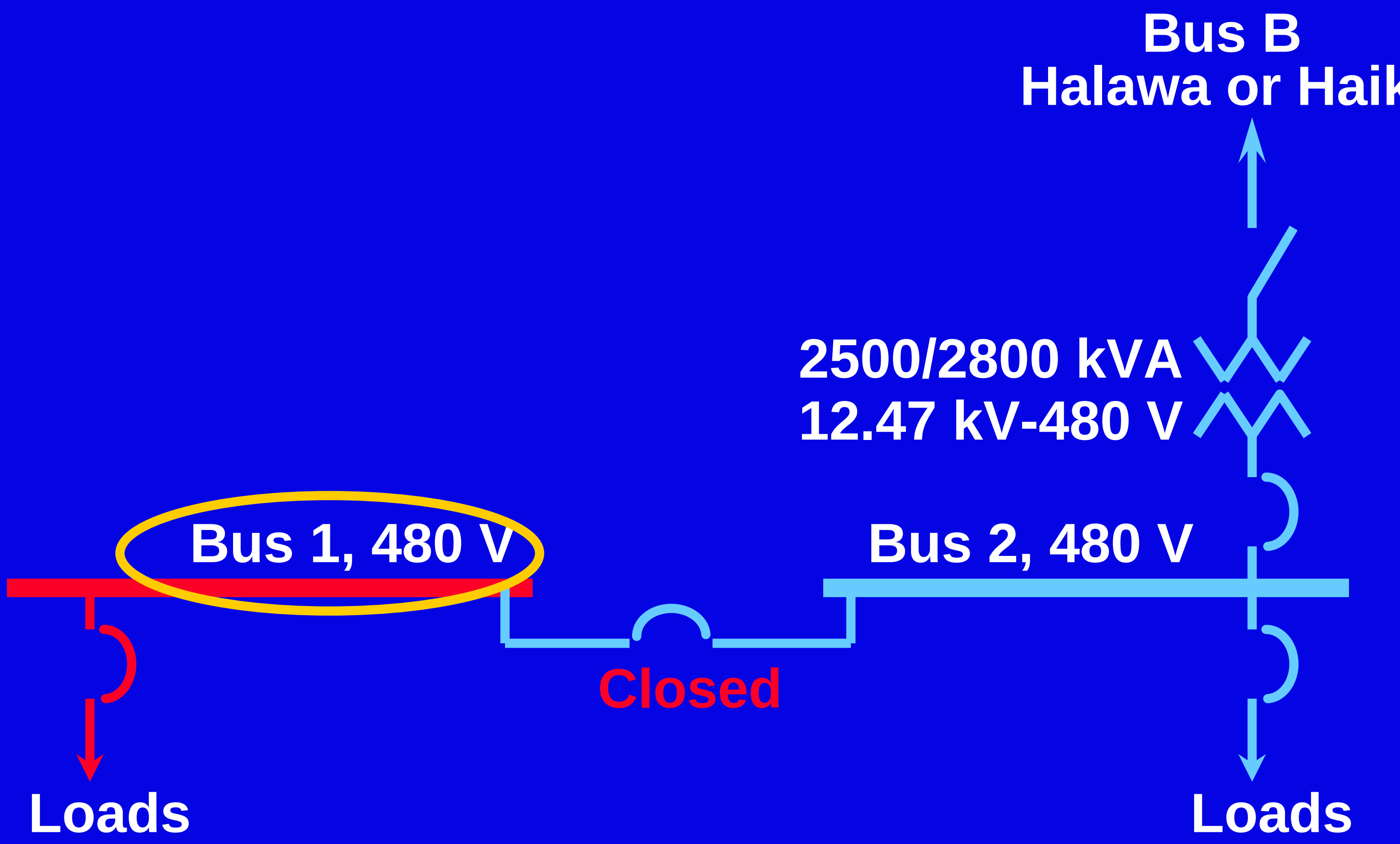
480 V restoration - 1



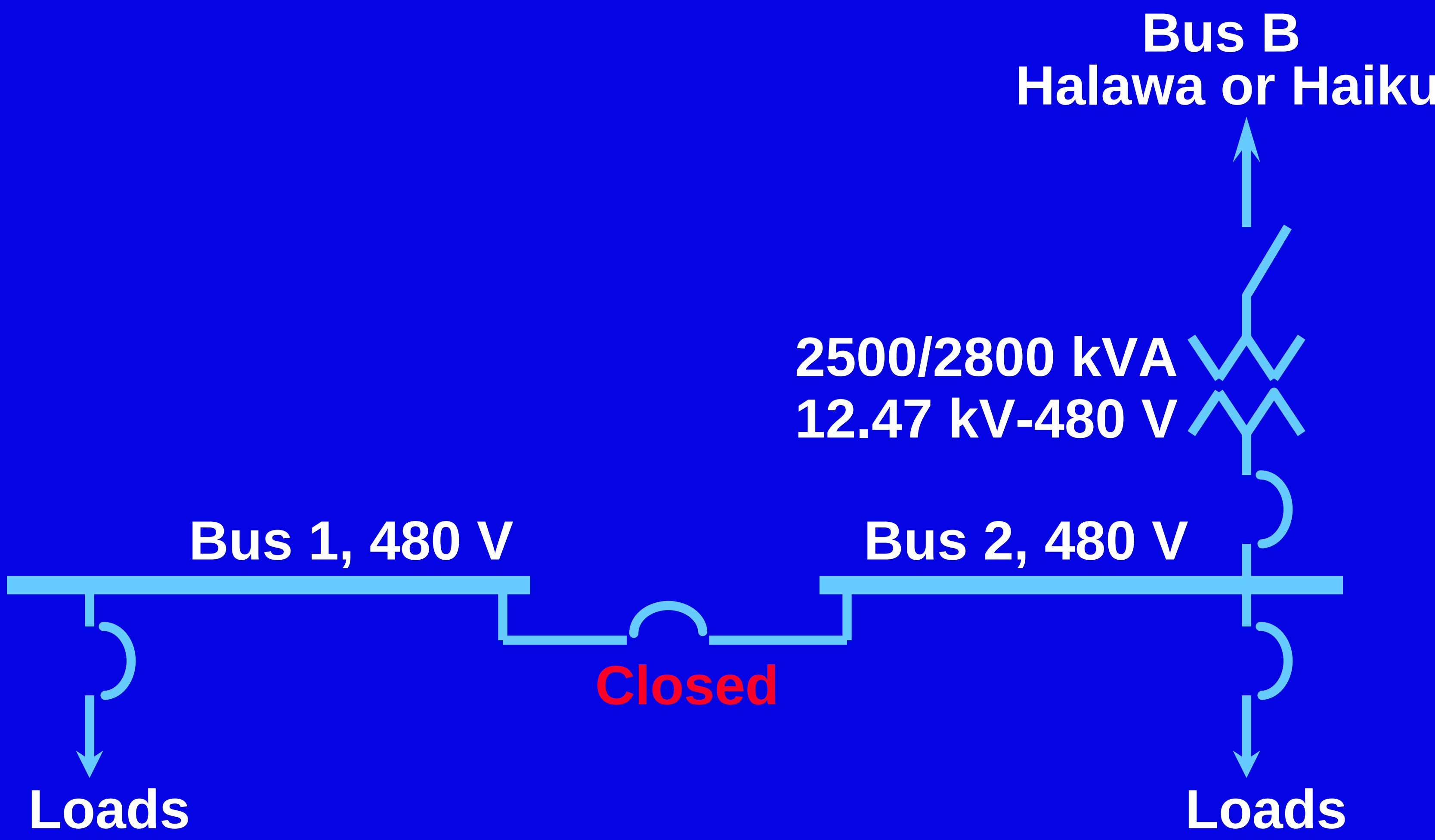
480 V restoration - 2



480 V restoration - 3



480 V restoration - 4

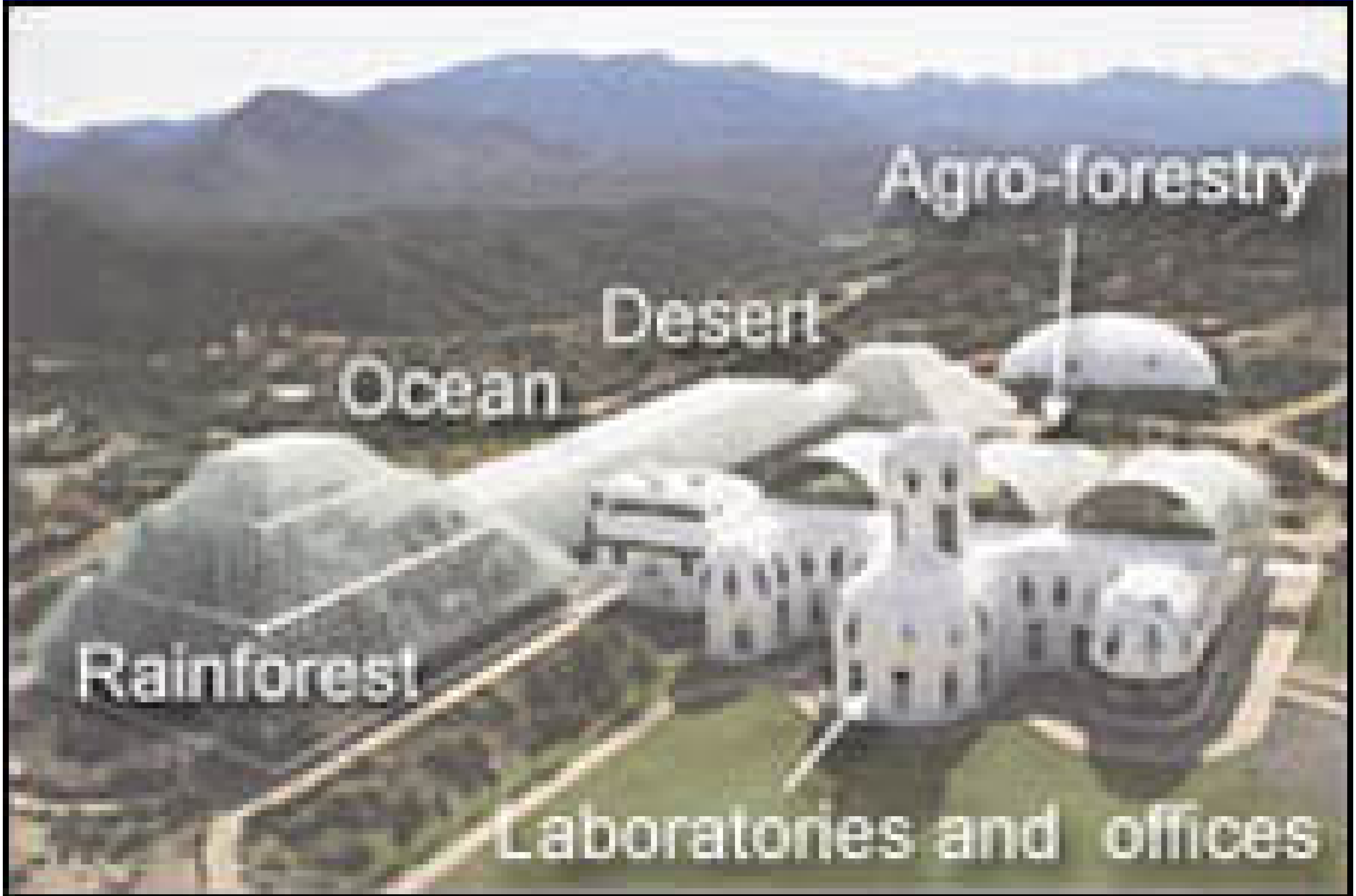


Project No. 2: Biosphere 2

- Biosphere 2 is a 3.15 acre closed ecosystem with 5 biomes:
- 1. Desert
- 2. Marsh
- 3. Savannah
- 4. Rainforest
- 5. Ocean

Project No. 2: Biosphere 2

- Original intent: experimentation for space travel
- Learn from sealing 8 people in closed system
- 1^{st} mission: 2 years, September 1991
- Mission-critical: requires high reliability power system


Agro-forestry
Desert
Ocean
Rainforest
Laboratories and offices

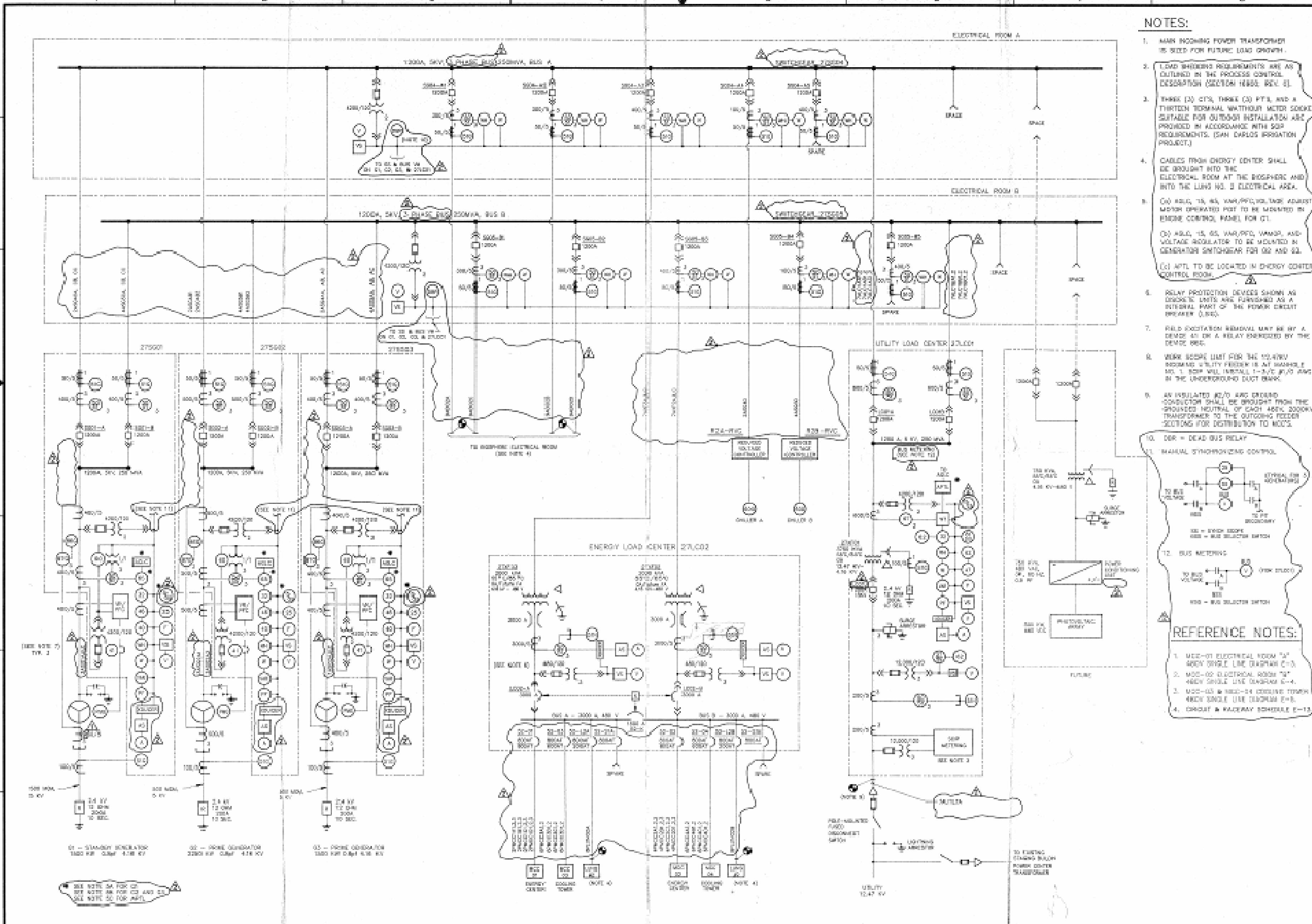
Cogeneration power plant

- Biosphere 2 cogeneration power plant produces:
- Electrical energy
- Hot water for heating
- Cold water for cooling
- Waste heat from engine captured to run absorption chiller


COLUMBIA UNIVERSITY'S
BIOSPHERE 2 CENTER
Academic Village
Hotel Front Desk
Catalina Conference Room
Rm. 1-8
Rm. 18-27
Rainforest Biome
Faculty Offices
Rm. 9-17
Main Entrance
Parking
Habitat
Martin Education Bldg.
Suffolk House
Lion's Den Cafe
Picnic Plaza
West Lung
Agro-forestry Biome
Ocean Biome
Analytical Labs
Botanical Exhibits
Cañada del Oro Restaurant
Energy Center
Desert Biome
Outreach Offices
Visitor Center
Biosphere 2 Observatory
South Lung
N

4.16 kV double bus swgr

- Heart of electrical system is 4.16 kV double-bus system
- Bus A & Bus B with metal-clad swgr
- Two buses located in separate electrical rooms
- Prevent coincident damage


ELECTRICAL ROOM A
1200A, 5KV, 3 PHASE BUS, 250MVA, BUS A
SWITCHGEAR 275G04
ELECTRICAL ROOM B
1200A, 5KV, 3 PHASE BUS, 250MVA, BUS B
SWITCHGEAR 275G05
UTILITY LOAD CENTER 27LC01
ENERGY LOAD CENTER 27LC02
CHILLER A
CHILLER B
SPARE
FUTURE
PHOTOVOLTAIC ARRAY
POWER CONDITIONING UNIT
SURGE ARRESTOR
LIGHTNING ARRESTOR
UTILITY 12.47 KV
G1 - STAND-BY GENERATOR
G2 - PRIME GENERATOR
G3 - PRIME GENERATOR
NOTES:
1. MAIN INCOMING POWER TRANSFORMER IS SIZED FOR FUTURE LOAD GROWTH.
2. LOAD SHEDDING REQUIREMENTS ARE AS OUTLINED IN THE PROCESS CONTROL DESCRIPTION (SECTION 16900, REV. 0).
3. THREE (3) CT'S, THREE (3) PT'S, AND A THIRTEEN TERMINAL WATTHOUR METER SOCKET SUITABLE FOR OUTDOOR INSTALLATION ARE PROVIDED IN ACCORDANCE WITH SCIP REQUIREMENTS. (SAN CARLOS IRRIGATION PROJECT.)
4. CABLES FROM ENERGY CENTER SHALL BE BROUGHT INTO THE ELECTRICAL ROOM AT THE BIOSPHERE AND INTO THE LUNG NO. 2 ELECTRICAL AREA.
5. (a) ASLC, 15, 65, VAR/PFC, VOLTAGE ADJUST MOTOR OPERATED POT TO BE MOUNTED IN ENGINE CONTROL PANEL FOR G1.
(b) ASLC, 15, 65, VAR/PFC, VAMOP, AND VOLTAGE REGULATOR TO BE MOUNTED IN GENERATOR SWITCHGEAR FOR G2 AND G3.
(c) APTL TO BE LOCATED IN ENERGY CENTER CONTROL ROOM.
6. RELAY PROTECTION DEVICES SHOWN AS DISCRETE UNITS ARE FURNISHED AS A INTEGRAL PART OF THE POWER CIRCUIT BREAKER (LSG).
7. FIELD EXCITATION REMOVAL MAY BE BY A DEVICE 41 OR A RELAY ENERGIZED BY THE DEVICE 86G.
8. WORK SCOPE LIMIT FOR THE 12.47KV INCOMING UTILITY FEEDER IS AT MANHOLE NO. 1. SCIP WILL INSTALL 1-3/C #1/0 AWG IN THE UNDERGROUND DUCT BANK.
9. AN INSULATED #2/0 AWG GROUND CONDUCTOR SHALL BE BROUGHT FROM THE GROUNDED NEUTRAL OF EACH 480V, 2000KVA TRANSFORMER TO THE OUTGOING FEEDER SECTIONS FOR DISTRIBUTION TO MCC'S.
10. DBR = DEAD BUS RELAY
11. MANUAL SYNCHRONIZING CONTROL
TO BUS VOLTAGE
TO PT SECONDARY
SS = SYNCH SCOPE
BSS = BUS SELECTOR SWITCH
12. BUS METERING
BSS = BUS SELECTOR SWITCH
REFERENCE NOTES:
1. MCC-01 ELECTRICAL ROOM "A" 480V SINGLE LINE DIAGRAM E-3.
2. MCC-02 ELECTRICAL ROOM "B" 480V SINGLE LINE DIAGRAM E-4.
3. MCC-03 & MCC-04 COOLING TOWER 480V SINGLE LINE DIAGRAM E-5.
4. CIRCUIT & RACEWAY SCHEDULE E-12.

Redundant 4.16 kV feeders

- Four 4.16 kV feeders total
- Bus A: two feeders, A1 & A2
- Bus B: two feeders, B1 & B2
- Only one feeder required to run Biosphere 2 experiment

Engine-generators, 4.16 kV

- 3 engine-generators, dual-fuel
- Standby & prime: 5,250 kW total
- G1, standby generator, 1,500 kW
- G2, prime generator, 2,250 kW
- G3, prime generator, 1,500 kW
- 2 generator breakers to Bus A & B

480 V double-ended subs

- Power plant parasitic loads from load center 27LC02
- Double-ended substation
- Two 2,000 kVA, 4160-480 V transformers, fully-sized
- Split bus configuration: main-tie-main

Utility as back-up

- Energy center generators provide primary power
- Electric utility serves as back-up
- One 3,750 kVA, 12.47-4.16 kV transformer
- Import of 50 kW, APTL controller

Future solar PV array

- Provisions for 3rd power source:
- 500 kW solar photovoltaic array
- DC to AC inverter
- 750 kVA, 480-4160 V step–up transformer

Project No. 3: Motorola

- HV Distribution System Upgrade
- Design/build for Motorola plant in Plantation, Florida
- 30-year-old electrical system
- Failures: Al feeder cables and transformer


MOTOROLA

Project No. 3: Motorola

- Prime directive: keep production lines running
- Downtime costs: $300,000 per hour
- Motorola required highly reliable power system

Old 13.2 kV utility

- Two FP&L services at 13.2 kV
- Shared with other customers
- 1. Vault with transformers & 480 V feeders
- 2. 13.2 kV fused switches & 13.2 kV feeders
- Radial feeders to transformers

New 23 kV distribution

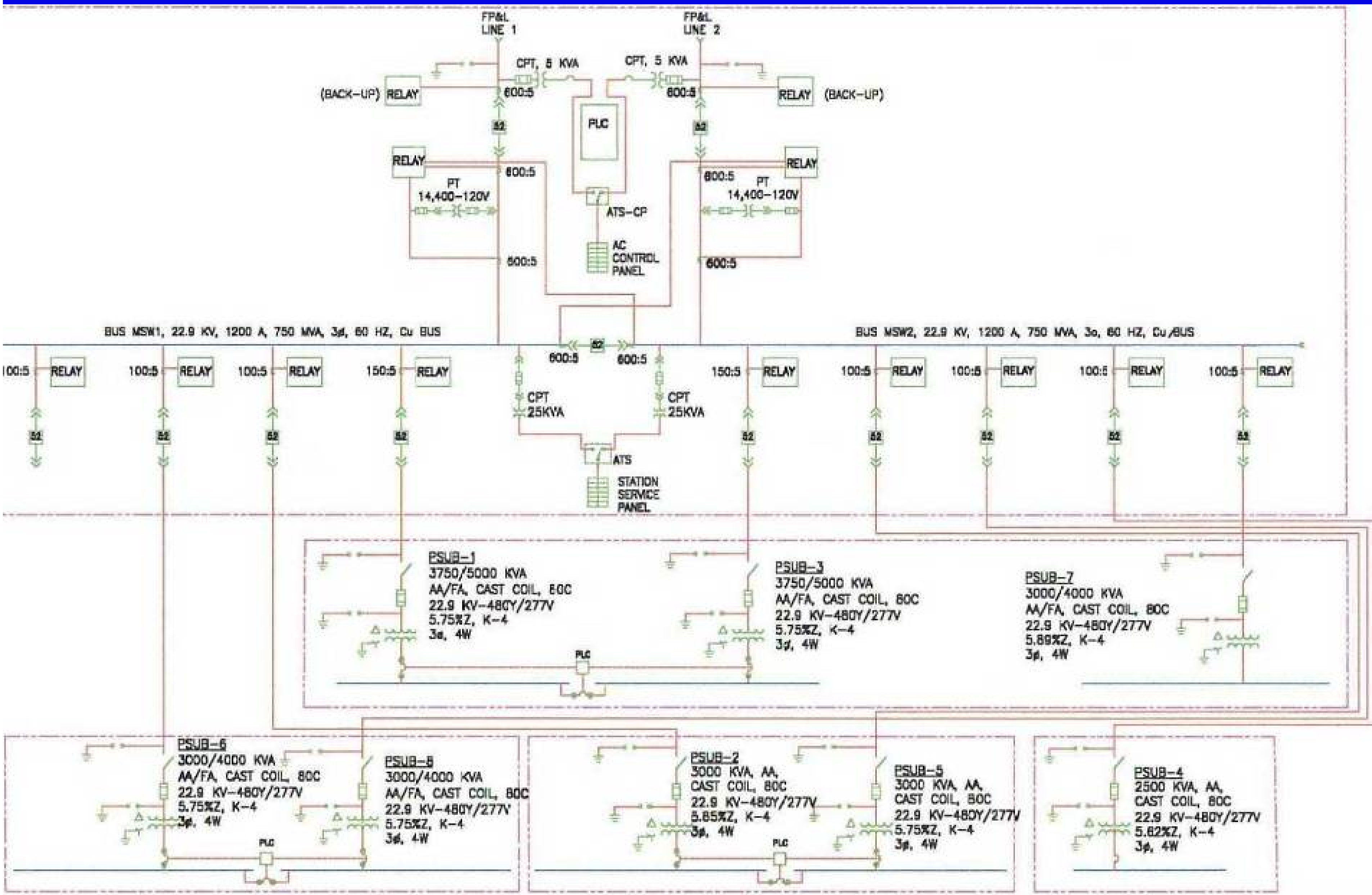
- New 23 kV substation for two 23 kV FP&L feeders
- 23 kV permits higher power transfer
- Peak demand = 10 MW
- Dedicated feeders from FP&L substation


25 11:07AM


25 11:08AM

23 kV substation

- Dedicated electrical room
- Metal-clad swgr, 27 kV class, 750 MVA, 3 cycle, vacuum breakers
- Split-bus configuration: main-tie-main, fully redundant
- Provisions for 3rd bus for >15 MW load


FP&L LINE 1
FP&L LINE 2
CPT, 5 KVA
(BACK-UP) RELAY
600:5
52
PLC
RELAY
PT 14,400-120V
ATS-CP
AC CONTROL PANEL
BUS MSW1, 22.9 KV, 1200 A, 750 MVA, 3ϕ, 60 HZ, Cu BUS
BUS MSW2, 22.9 KV, 1200 A, 750 MVA, 3ϕ, 60 HZ, Cu BUS
100:5
150:5
CPT 25KVA
ATS
STATION SERVICE PANEL
PSUB-1
3750/5000 KVA
AA/FA, CAST COIL, 80C
22.9 KV-480Y/277V
5.75%Z, K-4
3ϕ, 4W
PSUB-3
3750/5000 KVA
AA/FA, CAST COIL, 80C
22.9 KV-480Y/277V
5.75%Z, K-4
3ϕ, 4W
PSUB-7
3000/4000 KVA
AA/FA, CAST COIL, 80C
22.9 KV-480Y/277V
5.89%Z, K-4
3ϕ, 4W
PSUB-6
3000/4000 KVA
AA/FA, CAST COIL, 80C
22.9 KV-480Y/277V
5.75%Z, K-4
3ϕ, 4W
PSUB-8
3000/4000 KVA
AA/FA, CAST COIL, 80C
22.9 KV-480Y/277V
5.75%Z, K-4
3ϕ, 4W
PSUB-2
3000 KVA, AA,
CAST COIL, 80C
22.9 KV-480Y/277V
5.85%Z, K-4
3ϕ, 4W
PSUB-5
3000 KVA, AA,
CAST COIL, 80C
22.9 KV-480Y/277V
5.75%Z, K-4
3ϕ, 4W
PSUB-4
2500 KVA, AA,
CAST COIL, 80C
22.9 KV-480Y/277V
5.62%Z, K-4
3ϕ, 4W

23 kV FP&L vault

- Adjacent FP&L vault: HV switches, relays, meters
- Fiber optic link from FP&L substation
- Direct communication for breaker & relay status


FIBER OPTIC CABLE

Electronic relays

- All relays: electronic solid-state
- Two main breakers had back-up relays
- RS-232 link permitted uploading of settings


27 12:55PM

Switchgear control power

- Combination of AC and DC power
- AC: close vacuum circuit breakers
- DC for critical loads:
- 1. Trip circuit breakers
- 2. PLC
- 3. Relays

Control power from PTs

- AC control power from 2 PTs at both 23 kV buses
- One bus may be unavailable
- ATS to select either bus

DC power from batteries

- DC power from battery banks
- 2 battery banks for increased reliability
- ATS selects either battery bank
- Primary: gel cell batteries
- Secondary: sealed cell batteries

PLC

- PLC used to control swgr
- Actuates local annunciator board
- Sends automatic alarm to electrical personnel, pager on weekends


MSW1-BT
BUS-TIE
BREAKER

PLC alarms (partial list)

- PLC internal failure
- Switchgear battery ground fault
- Switchgear DC bus failure
- Switchgear battery charger failure
- Main breaker relay failure
- Closed transition failure
- Air conditioner failure

PLC high output cards

- Increased reliability with direct tripping of breakers
- Use PLC high output cards
- Advantages: less time to trip, less component failure
- Old method: interposing relay

Closed transition transfer

- Unique: closed transition transfer (i.e., make-before-break)
- No interruption to plant
- Usually not allowed by utility
- Restrictions: 1 second, frequency check, synch check

Closed transition transfer

- Normal configuration: split-bus, open bus-tie
- If: loss of one FP&L feeder
- Then: close bus-tie
- Then: open main
- Reverse upon return

Ground grid

- Highest quality ground: electrolytic ground rods
- Copper-clad steel ground rods at intermediate points
- Interconnected with bare copper conductors

Halo ground

- Added safety feature: halo ground
- Solid copper ground buses
- At ceiling, front & behind 23 kV swgr line-up
- Attach ground leads during maintenance, rack-out breakers


27 12:57PM


27 12:58PM

HV cables

- For 23 kV circuit, standard cable rating would be 25 kV
- Decrease HV stresses, next rating of 35 kV
- Shielded, EPR insulation, 100%, MV-105, copper


aggreko
30 4:27 PM

HV terminations

- Increased reliability: HV molded elbows
- Superior connection: cable to bus w/metal insert
- Contains HV corona
- Old method: stress cone terminations with exposed energized surfaces


625-50
25 KV
1 8:08 AM


8 7:56PM

480 V double-ended subs

- Improved reliability, 480 V double-ended substations
- Split-bus: main-tie-main
- Fully-rated transformers, 23 kV-480 volts


12 9:44AM


12 9:44AM


GREENLEE
12 9:44AM

Best cast coil transformers

- No spill containment
- No liquid (fire or environmental)
- Better surge capability, epoxy cast over coils
- Less space required, no fins
- Fewer maintenance tests (e.g., no dissolved gas-in-oil)


LIFT
20 11:24AM

Closed transition transfer

- 480 V swgr repeats closed transition transfer function
- Could parallel 23 kV lines at 480 V swgr
- Safeguard: control wires as permissive in 480 V swgr PLC
- Check for status of 23 kV breakers

Transformer HV switch

- Transformer directly coupled to 23 kV fused air switch
- Fuse provides internal transformer fault protection
- Local disconnecting means for maintenance

Lightning arresters

- HV lightning arresters: transformer primary
- Metal-oxide, 15.8 kV
- Protects from damaging HV spikes & surges
- Added reliability: 2^{nd} set of arresters, line side of switch


6:45AM

Summary: H-3 Tunnel

- 4 sources of power for critical loads
- Features: redundancy and flexibility
- Significant: 12.47 kV swgr interlocking
- Immediate auto restoration of power
- High reliability power system

Summary: Biosphere 2

- 4.16 kV dual-bus
- Separate electrical rooms
- Redundancy in 4 feeders
- 3 engine-generators
- Utility as back-up
- High reliability power system

Summary: Motorola

- Increase distribution voltage from 13.2 to 23 kV
- Split-bus 23 kV & 480 V swgr
- Double-ended substations
- PLC for closed transition transfer

Summary: Motorola

- Cast-coil transformers
- 35 kV cables for 23 kV circuits
- Molded elbows for HV terminations
- Dual lightning arresters
- High reliability power system

Questions?