SAND2009-2042P

ENG 300

Lecture 12 – Case Studies of Interdependencies

9 April 2009

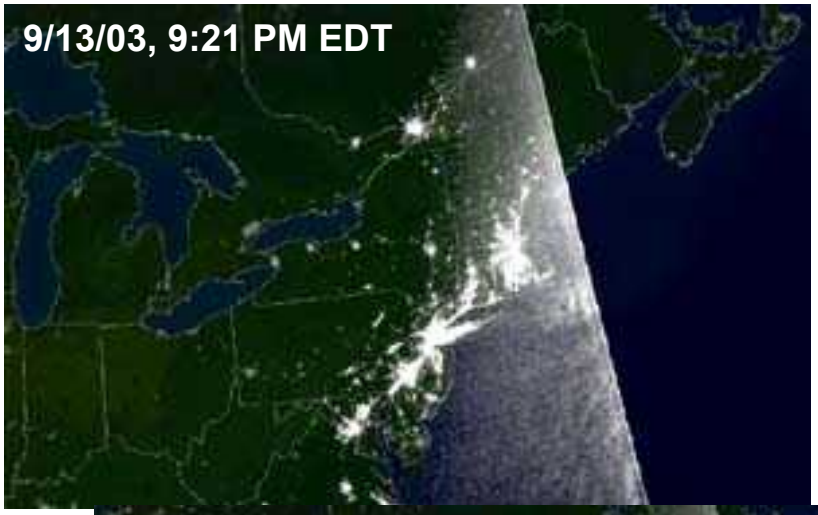
Kevin L. Stamber, Ph. D.
Principal Member of Technical Staff
Systems Research, Analysis & Applications
Sandia National Laboratories
Albuquerque, NM
klstamb@sandia.gov

SAND 2008-2403P

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Summary

- 61,800 MW load lost
  - Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey, and Ontario
  - Estimated 50 million people affected
- $4 to $10 billion impact in the US



Reference: "The Economic Impacts of the August 2003 Blackout," Electric Consumer Research Council (ELCON), February 2, 2004.

Images: NOAA

Sandia National Laboratories

Causes of the Blackout

- Inadequate system understanding
- Inadequate situational awareness
- Inadequate tree trimming
- Inadequate diagnostic support from reliability coordinators

Sandia National Laboratories

Axioms of Interdependencies

- Infrastructure systems are interconnected
- Major (non-binary) heuristic control of infrastructure systems is
  - human
  - functionally specific
  - local
- Binary heuristic control of infrastructure systems is
  - component-specific by design
  - myopically local

Sandia National Laboratories

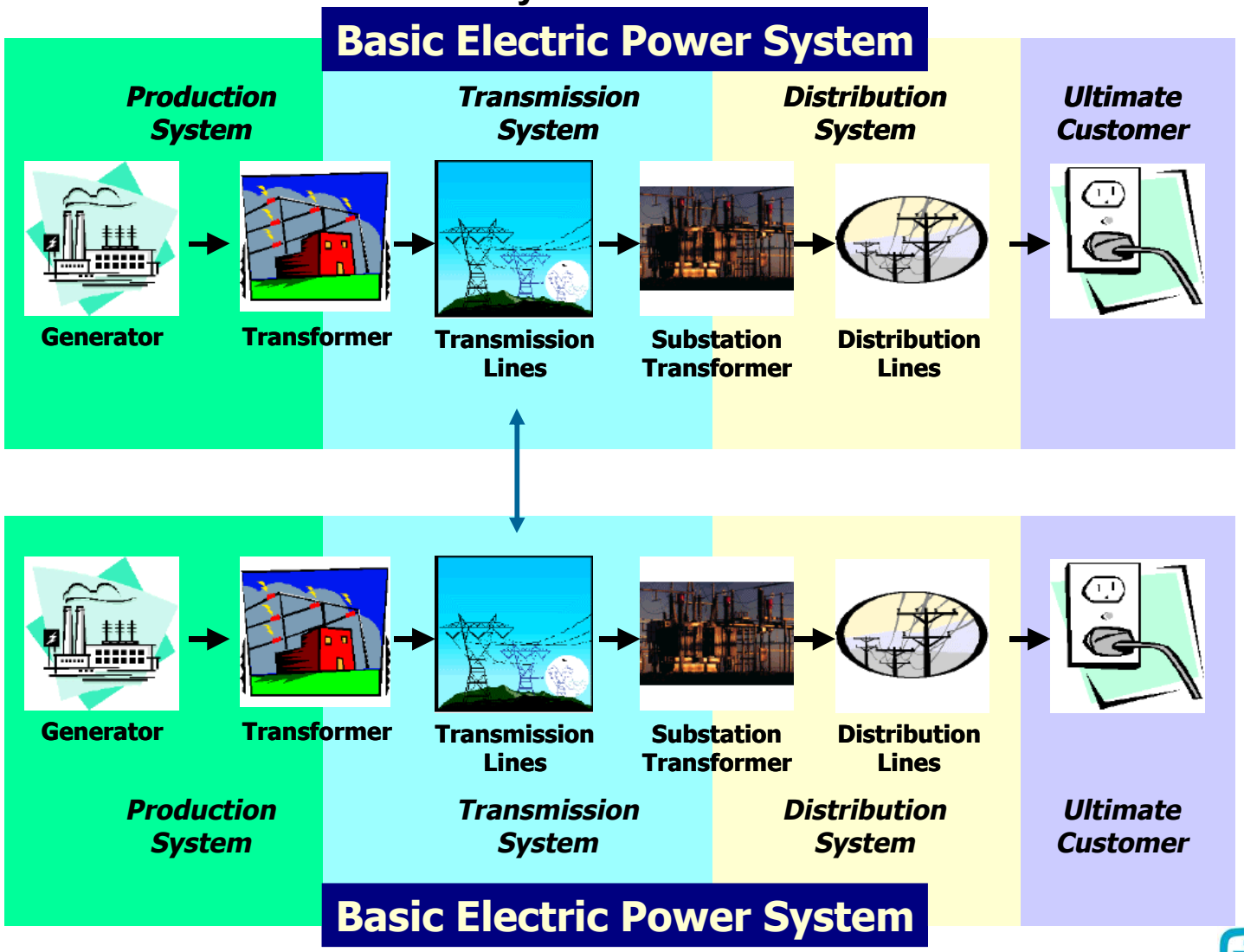
Axioms of Interdependencies

- Time scales of events are important in determining what actions can be taken
- Infrastructure dependencies can and do occur even where there is no physical connection between the infrastructure elements other than a common location
- Interdependencies go far beyond the physical relationships, to include operating rules, regulations, and business decision-making criteria

Sandia National Laboratories

Axioms of Interdependencies

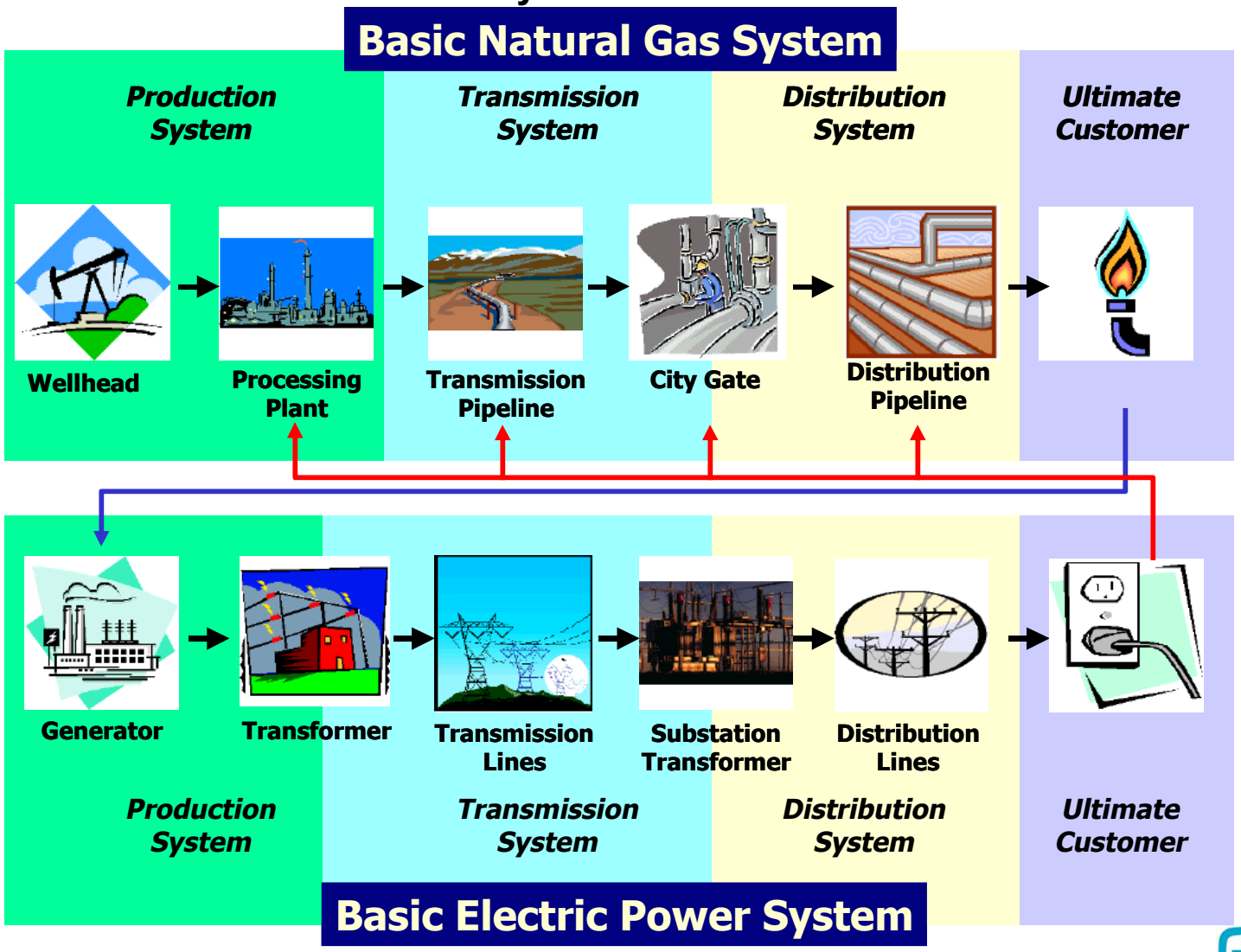
Infrastructure Systems are Interconnected



Sandia National Laboratories

Axioms of Interdependencies

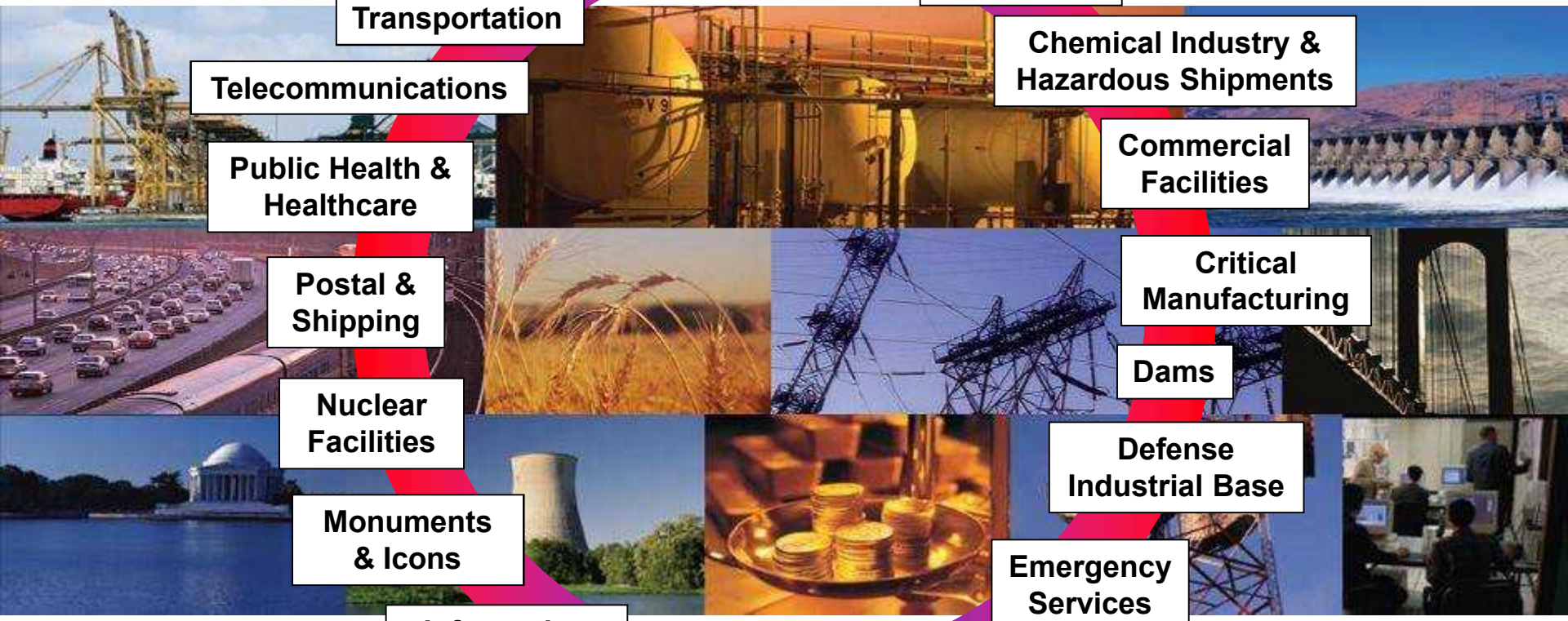
Infrastructure Systems are Interconnected



Sandia National Laboratories

Axioms of Interdependencies

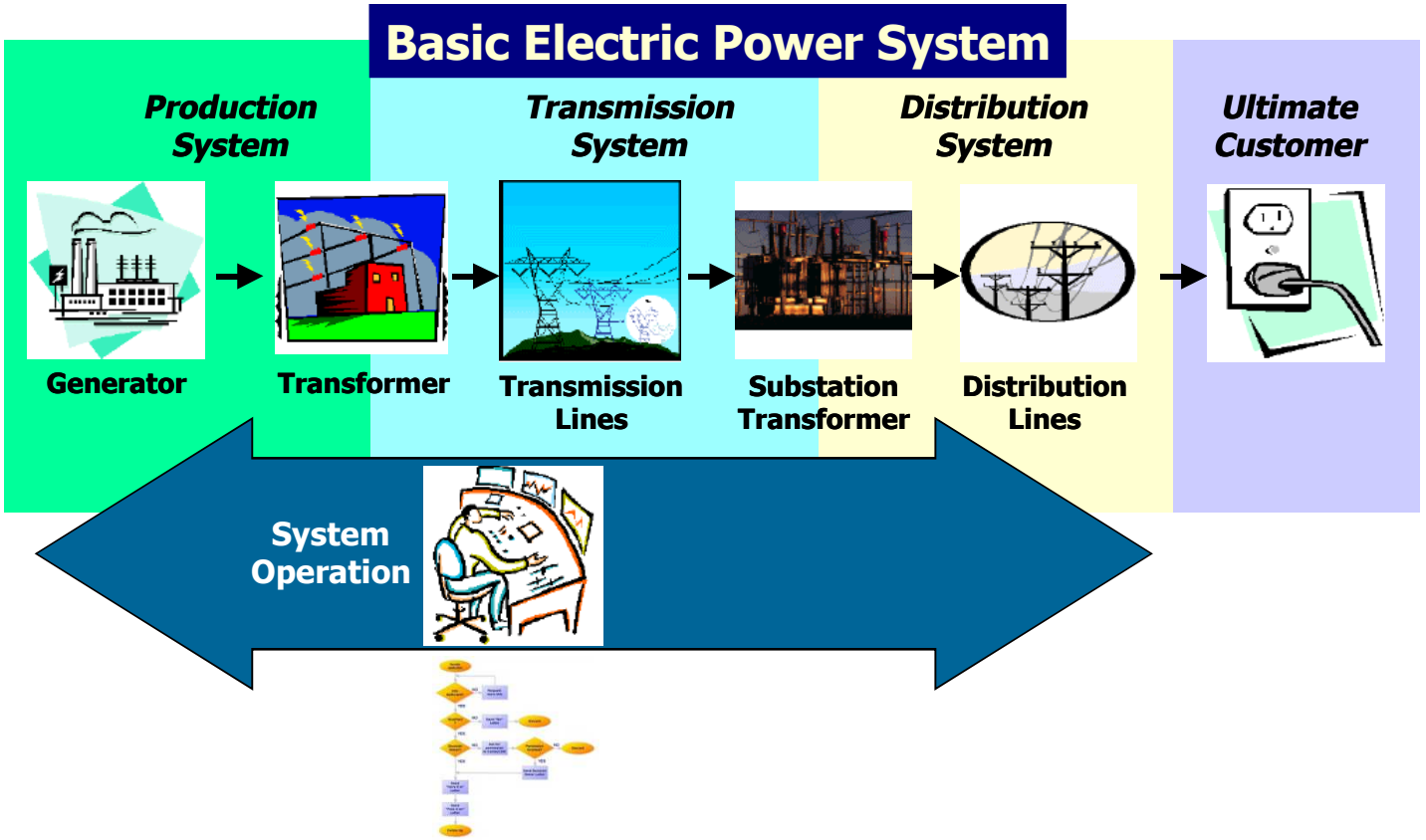
Infrastructure Systems are Interconnected



Sandia National Laboratories

Axioms of Interdependencies

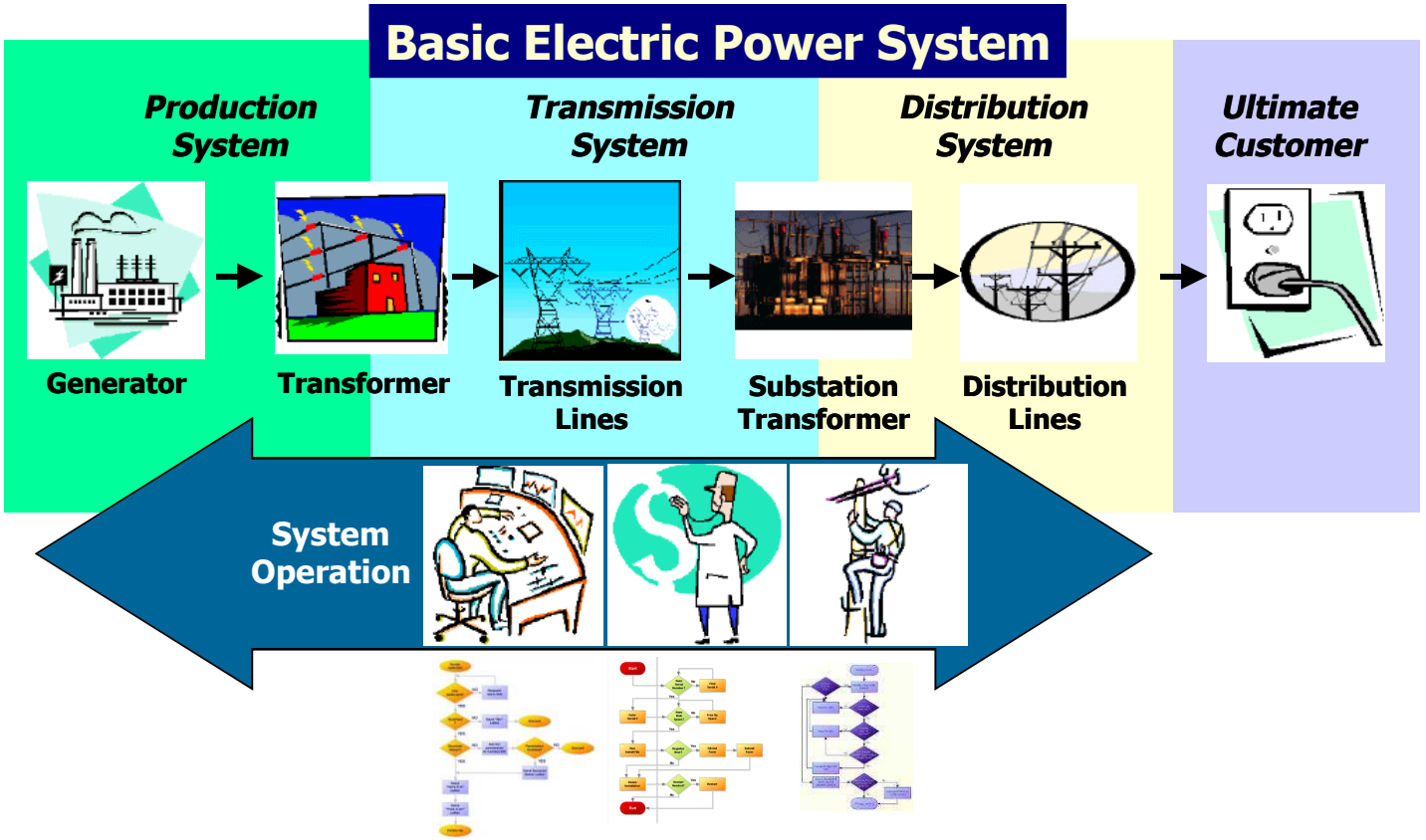
Non-Binary Heuristic Control of Infrastructure Systems is Human



Sandia National Laboratories

Axioms of Interdependencies

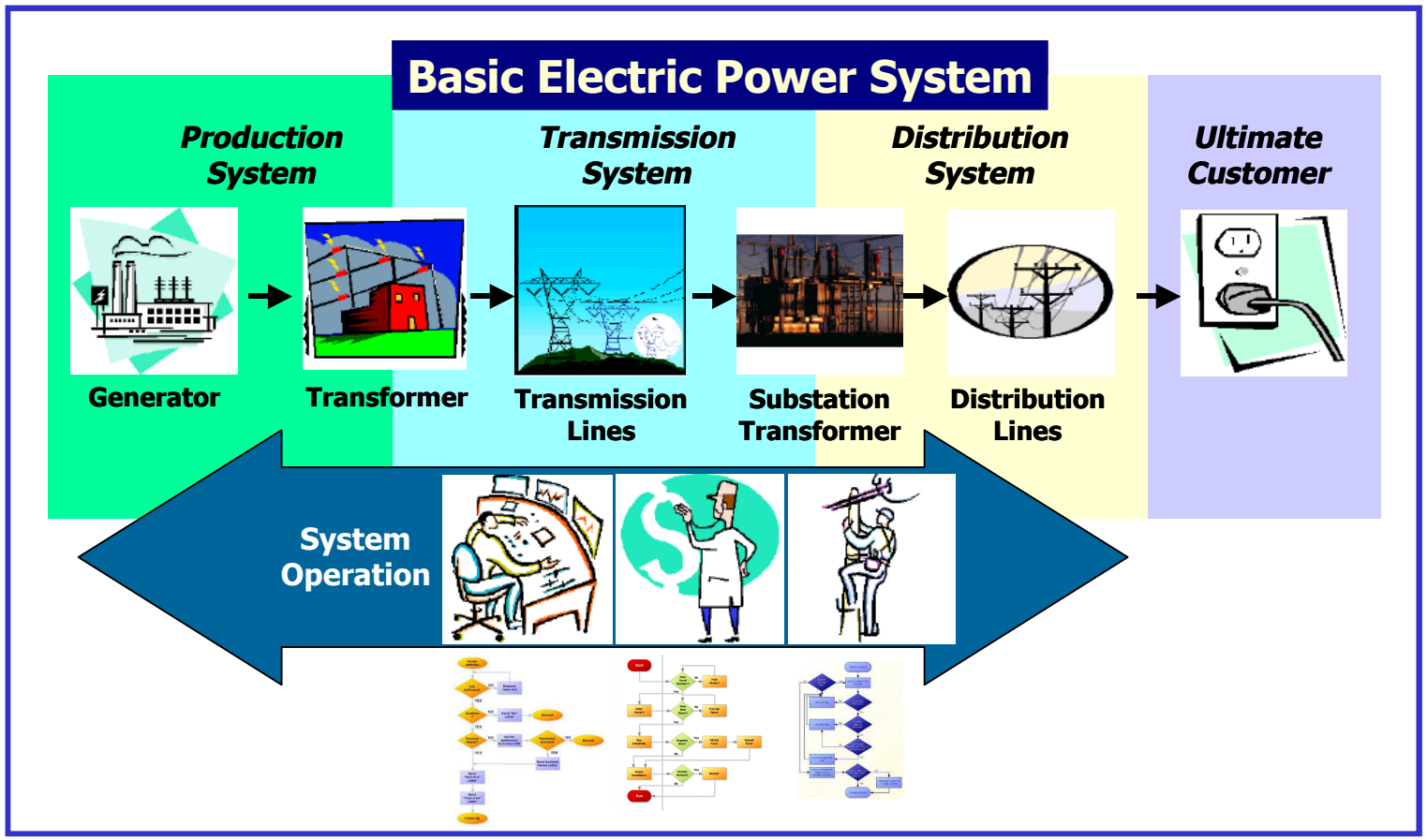
Non-Binary Heuristic Control of Infrastructure Systems is Functionally Specific



Sandia National Laboratories

Axioms of Interdependencies

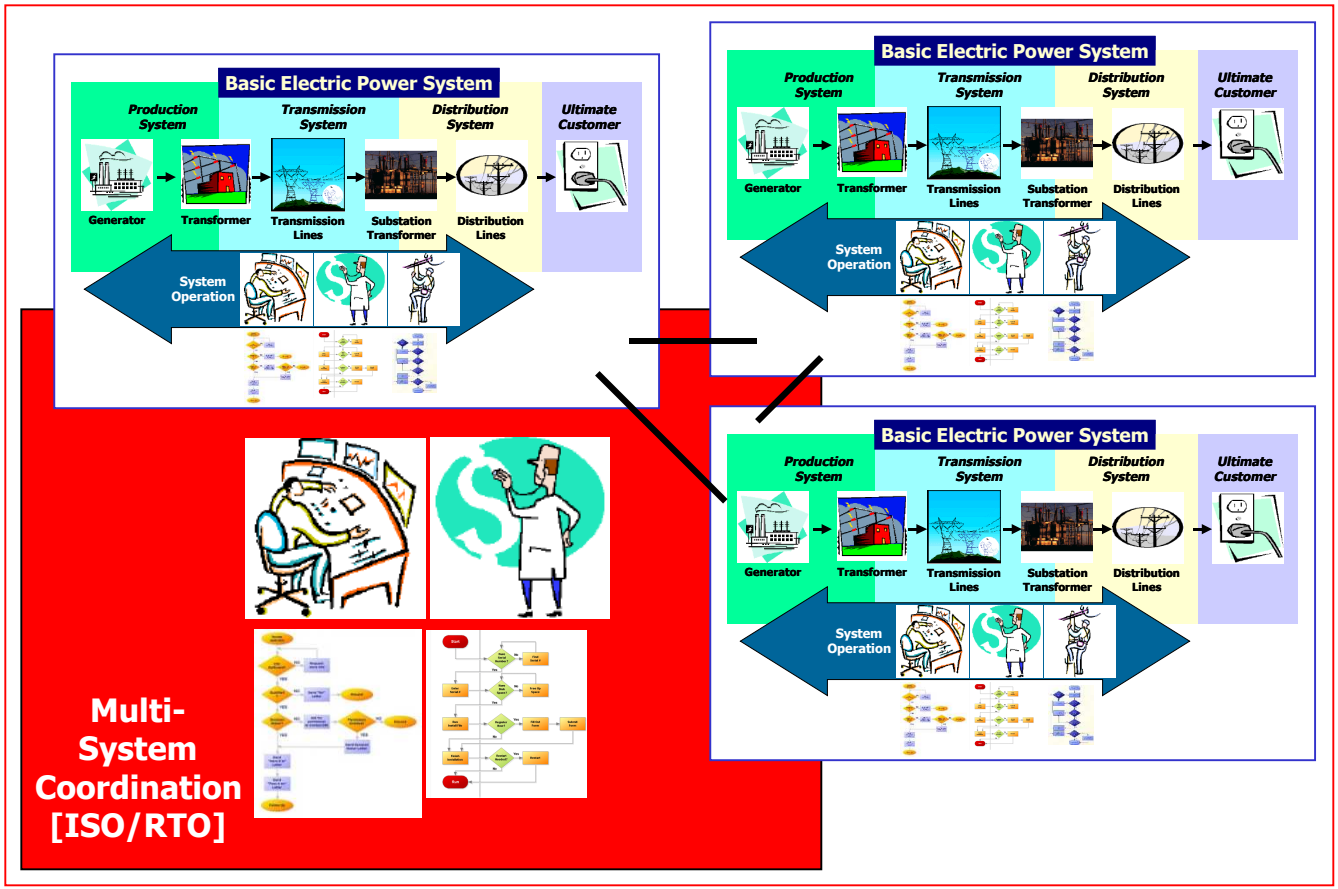
Non-Binary Heuristic Control of Infrastructure Systems is Local



Sandia National Laboratories

Axioms of Interdependencies

Non-Binary Heuristic Control of Infrastructure Systems is Local

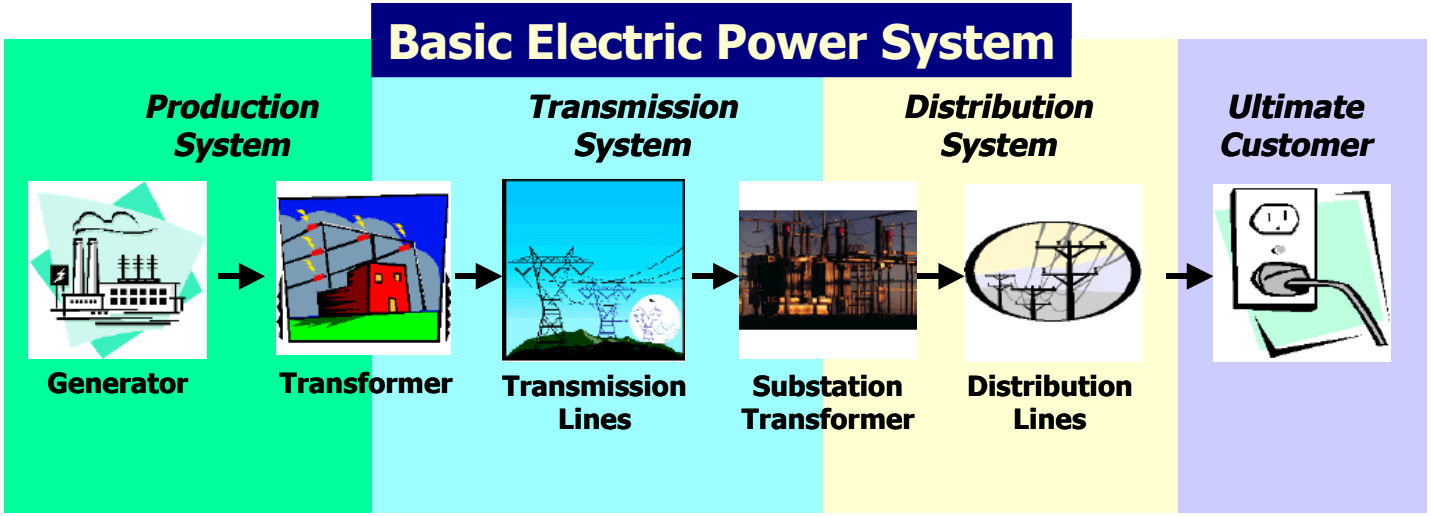


- Rules will vary by system
- Groups of systems will have joint rules
- Goals of some rules will conflict
- Goals of some rules will work together

Sandia National Laboratories

Axioms of Interdependencies

Binary Heuristic Control of Infrastructure Systems is Component-Specific and Myopically Local



- Each element composed of physical components
- Physical components include limitations on the physical performance of the component
- These rules exist for the physical protection of the components (primarily) and the system as a whole (hopefully)

Sandia National Laboratories

The Importance of Timing

- Timing of events is important
  - When the event occurs
  - What preceded/follows
- Delays in consequences vary widely
  - Storage a key factor

The Importance of Timing

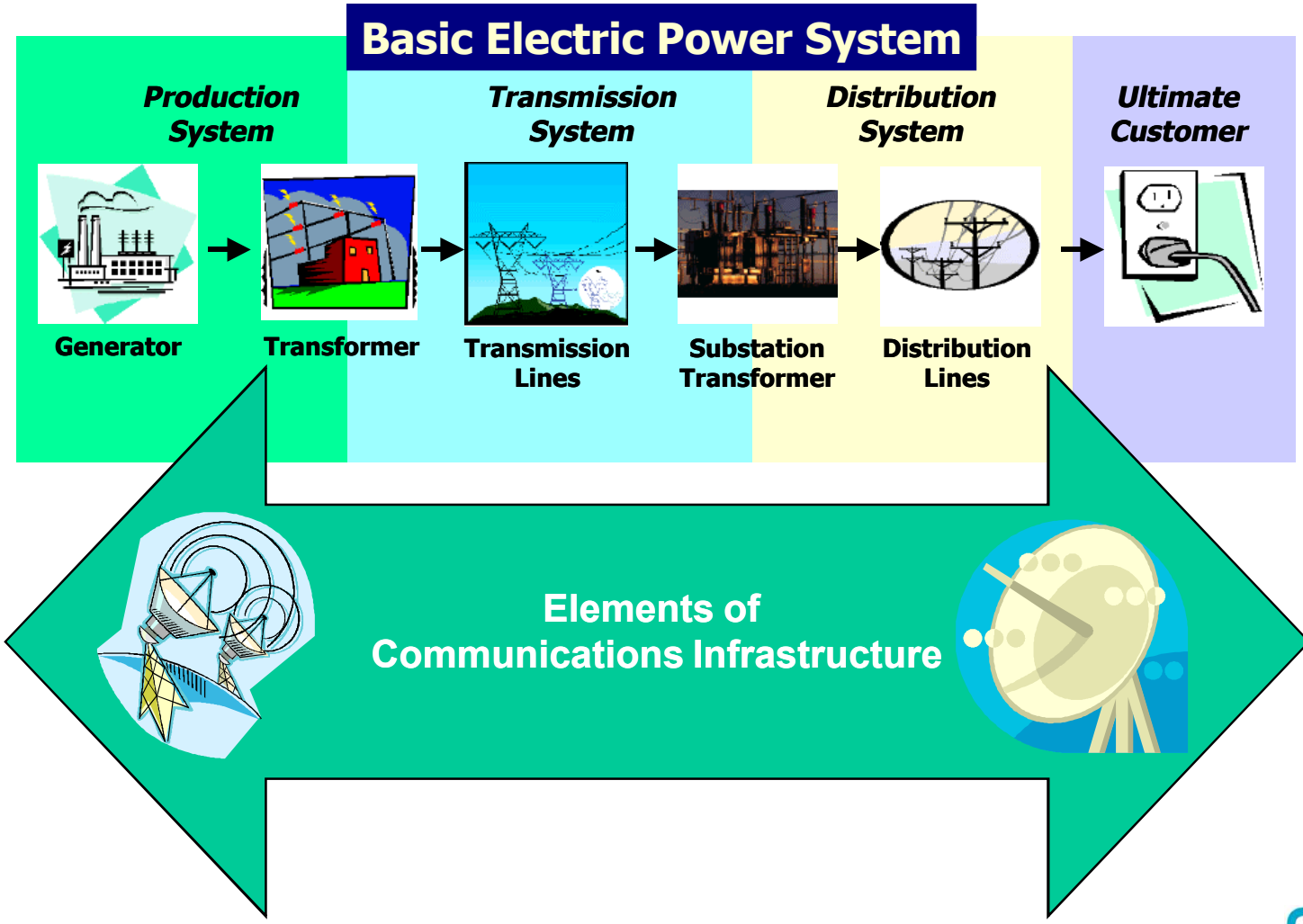
- Timing and Information
  - The "Just In Time" (JIT) Nature of the Infrastructure
    - Traditionally, Electric Power (along with telecommunications) has been the most JIT of the infrastructures (production to consumption)
    - Layering of a market structure has increased the number of JIT layers involved in day-to-day operations
      - This increases the potential for disruption
  - Information from other infrastructures
    - Is critical to reducing the potential for disruption
    - Is a dual-edged sword
      - Information can help you mitigate
      - Information could be used to litigate against you

Dependencies *of* the Energy Infrastructure

- On other segments of the same sector of the energy infrastructure
- On other sectors of the energy infrastructure
- On other infrastructures
  - Water
  - Telecommunications
  - Transportation

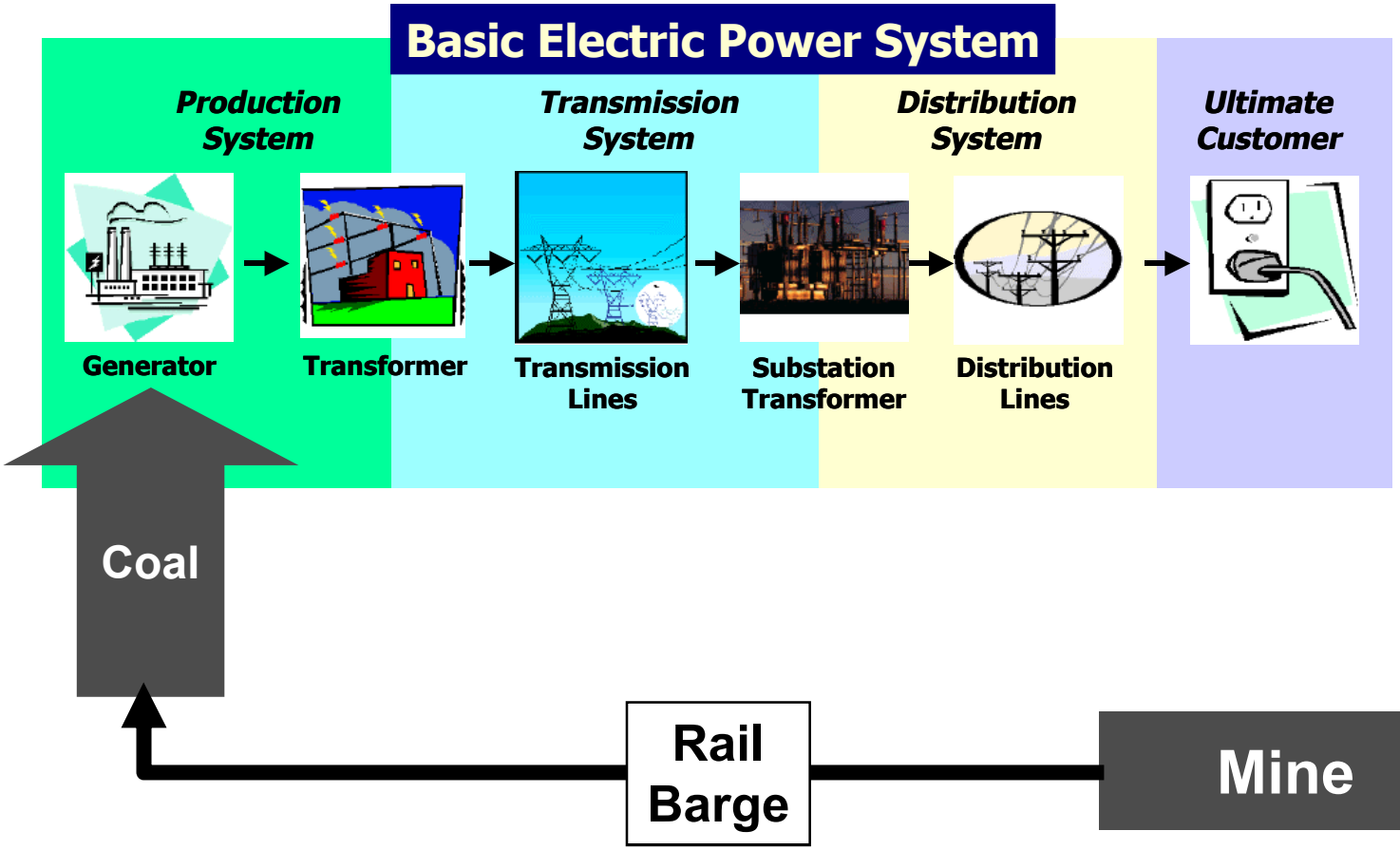
Sandia National Laboratories

Dependencies *of* the Energy Infrastructure



Sandia National Laboratories

Dependencies *of* the Energy Infrastructure



Sandia National Laboratories

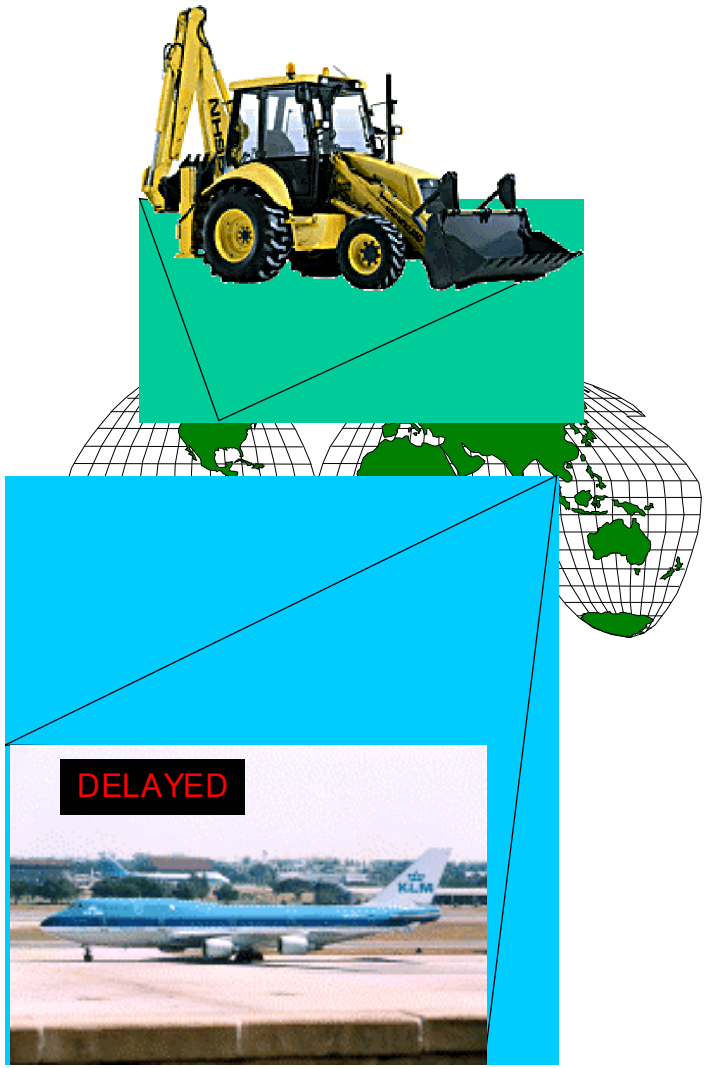
Co-location

- The location of infrastructure elements along a common corridor
  - Examples include pipelines, electric power transmission lines, rail lines, highways, telecommunications trunks
- Often chosen to utilize existing rights-of-way
  - Rail rights of way most common
- Within an infrastructure sector, occasionally used as a marketplace (or market reference point)
  - Henry Hub

Co-location

YAHOO! FINANCE

Associated Press



NW Airlines Loses Communication

EAGAN, Minn. (AP) -- Northwest Airlines lost most of its communications lines systemwide for about 2 1/2 hours Tuesday when an independent contractor hit a fiber-optic cable, leading to cancellations and delays around the country.

Passengers aboard planes were not in danger, but Northwest temporarily suspended boarding additional flights until the problem was fixed, said spokeswoman Mary Beth Schubert.

About **130 of the airline's 1,700 daily flights were canceled** systemwide, and an undetermined number were delayed. Schubert said communications lines went down just after 2 p.m. CST, affecting reservations and baggage information and the airline's electronic ticketing system.

Major delays were reported in Detroit, where about 30 flights were canceled, according to Northwest spokesman Doug Killian.

Another 19 were canceled in Minneapolis, with the remainder scattered around the system. **Some delays also were experienced in Singapore and Bangkok**, he said.

Northwest's Web site also was out of service because of the severed cable.

Kim Bothun, a spokesman for U S West, the telecom that owns the fiber-optic cable, said the **line was cut by a competitor McLeod USA, a local and long-distance telecommunications company based in Cedar Rapids, Iowa**. She said it is not uncommon for telecommunications companies' cables to be very close to each other.

Calls to McLeod USA were met with a busy signal Tuesday night.

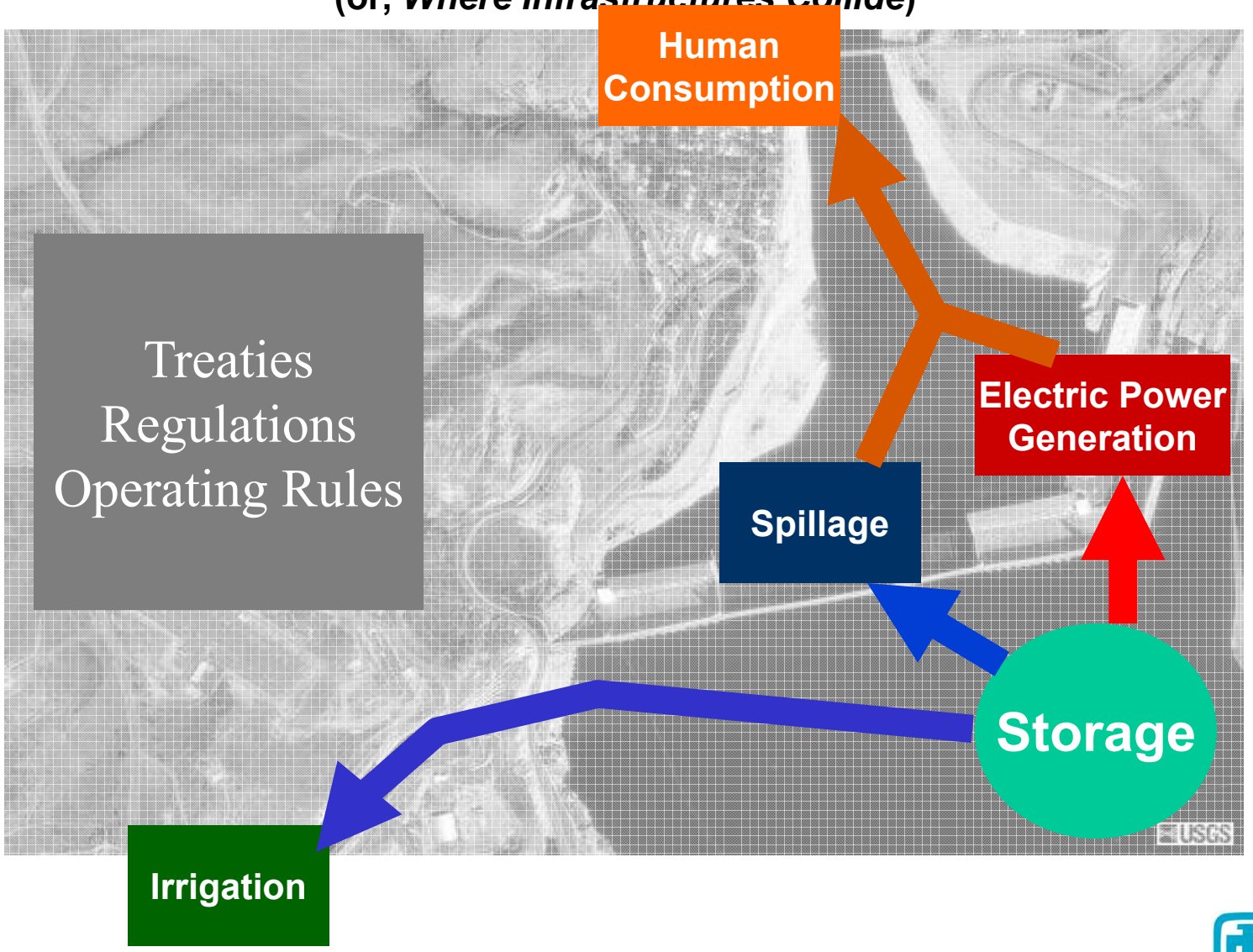
Northwest officials said the airline expected to be back to normal operations by Wednesday morning.

Passengers scheduled to fly on Northwest Tuesday evening were given the option of rescheduling their flights.

Sandia National Laboratories

Co-dependence

(or, *Where Infrastructures Collide*)

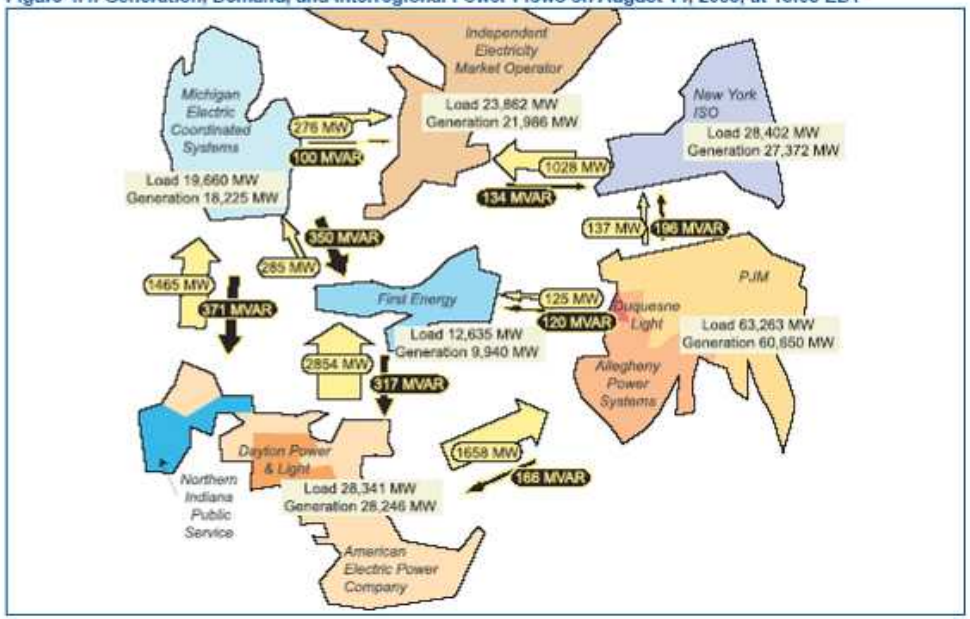


Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 4.4. Generation, Demand, and Interregional Power Flows on August 14, 2003, at 15:05 EDT



Initial Conditions

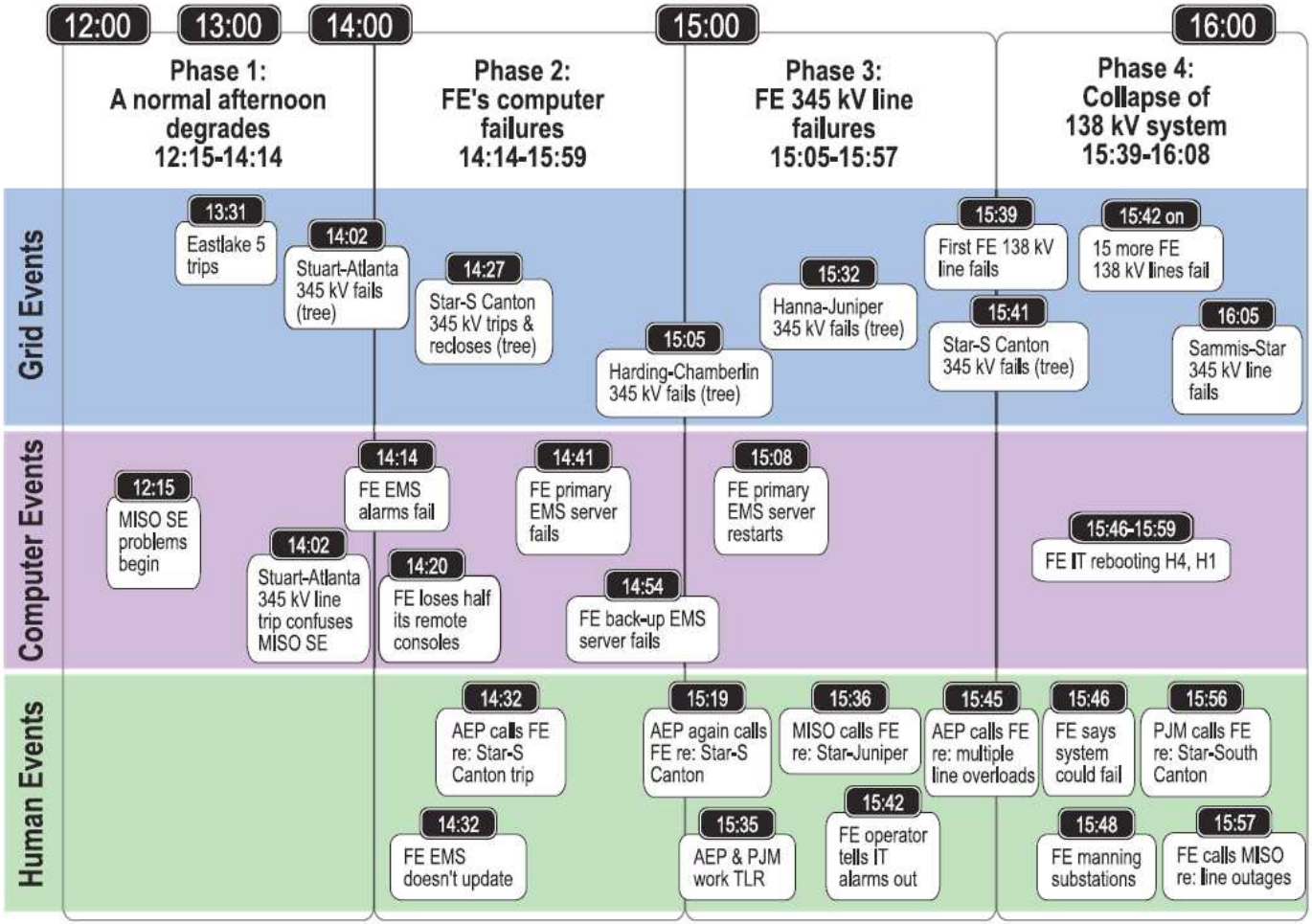
- Some benign unplanned outages
- Analysis indicated that the loss of the Perry nuclear plant or Eastlake plant would have a severe impact on the grid margin in northeastern Ohio
  - Reduced reactive power margin
  - Less options for operators
  - Challenging voltage control
    - Danger of voltage collapse – did not happen
    - Danger of voltage depression – did happen, with disastrous results

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.1. Timeline: Start of the Blackout in Ohio



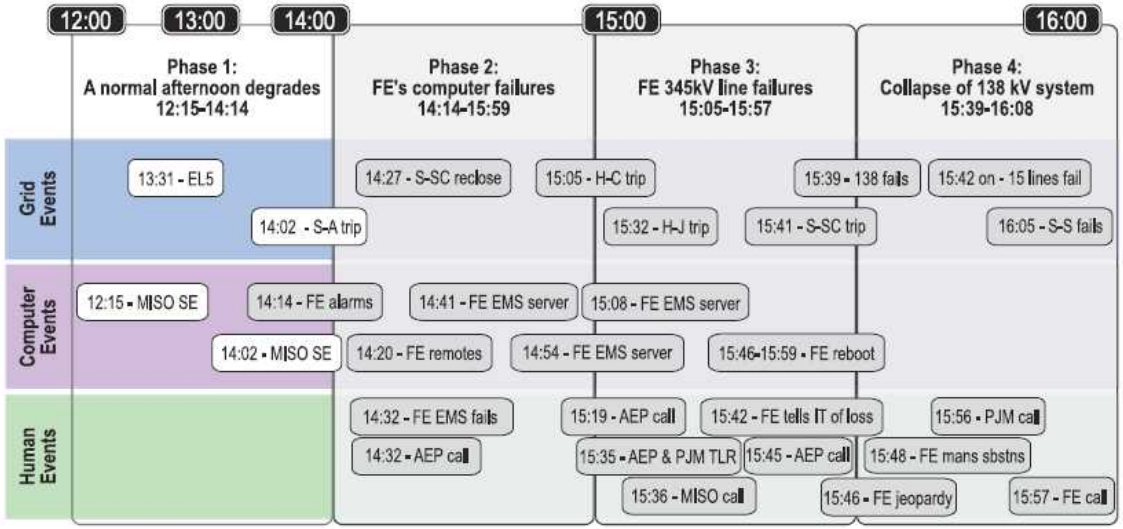
Reference: ***Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations.*** **U.S.–Canada Power System Task Force. April 2004.**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.2. Timeline Phase 1



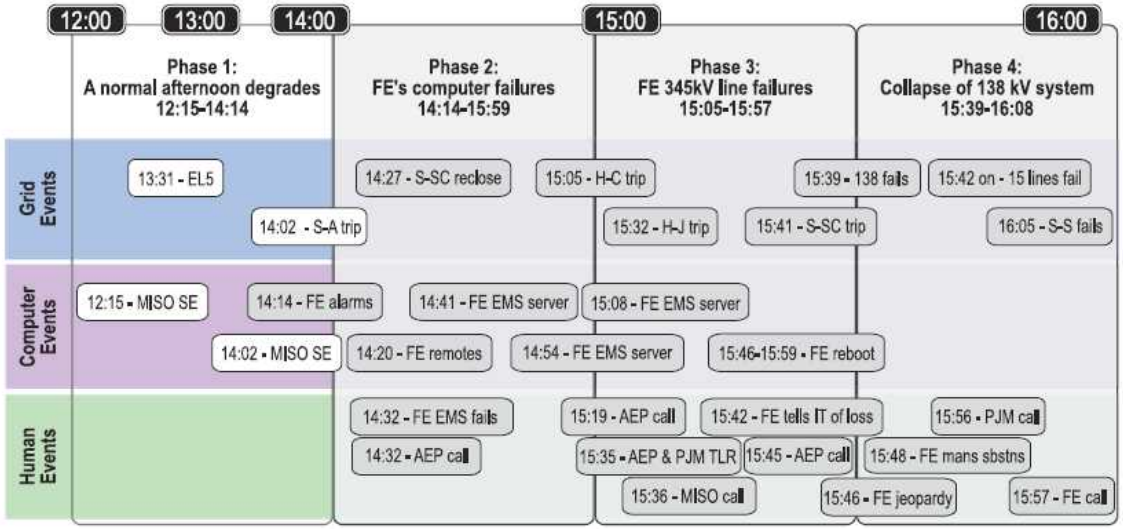
- **Phase 1 Events**
  - **1215: MISO State Estimator compromised**
    - **program used to calculate state of the system based on measurements and a model**
    - **230kV Bloomington-Denois line trips**
      - **In Cinergy's territory**
      - **No electrical effect with the blackout**
      - **Trip data was not effectively communicated to MISO**
      - **As a result, MISO's SE showed high mismatch (unacceptable error)**
  - **about 1300: Line inaccuracy in the model discovered and fixed**
    - **Automatic trigger disabled**
    - **SE solves once at 1307**
  - **about 1440: Trigger error discovered**
    - **Trigger was re-enabled**
  - **Meanwhile…**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.2. Timeline Phase 1



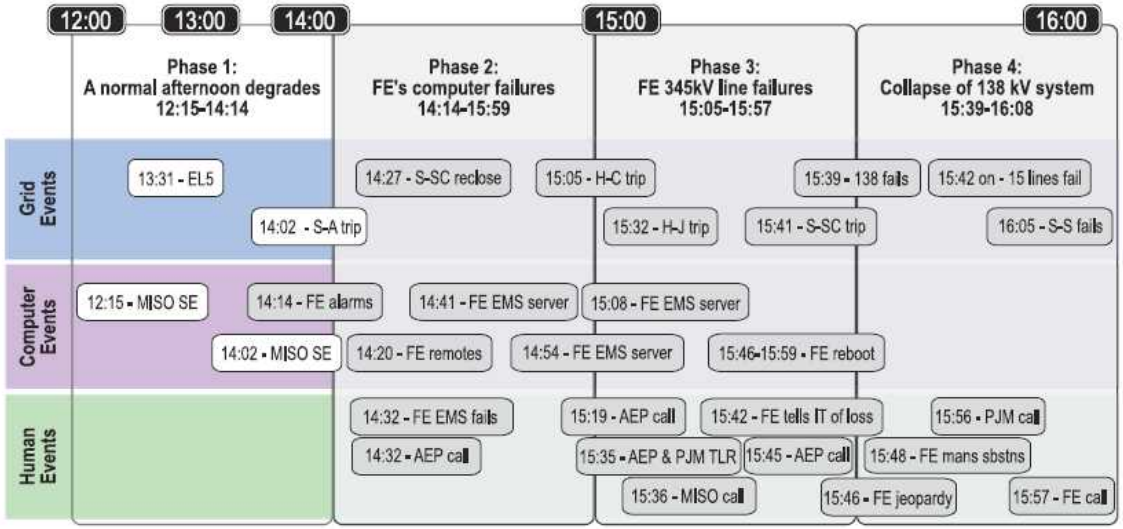
- **Phase 1 Events**
  - **1331: Eastlake 5 unit trips**
    - **Excitation system failure**
    - **Loss of 597 MW**
    - **A main contributor for northeastern Ohio load**
    - **Reactive power support for northeast Ohio weakened**
    - **Afterward, some contingencies would cause line overloads above emergency ratings**
    - **FirstEnergy (FE) operators concerned about voltage support**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.2. Timeline Phase 1



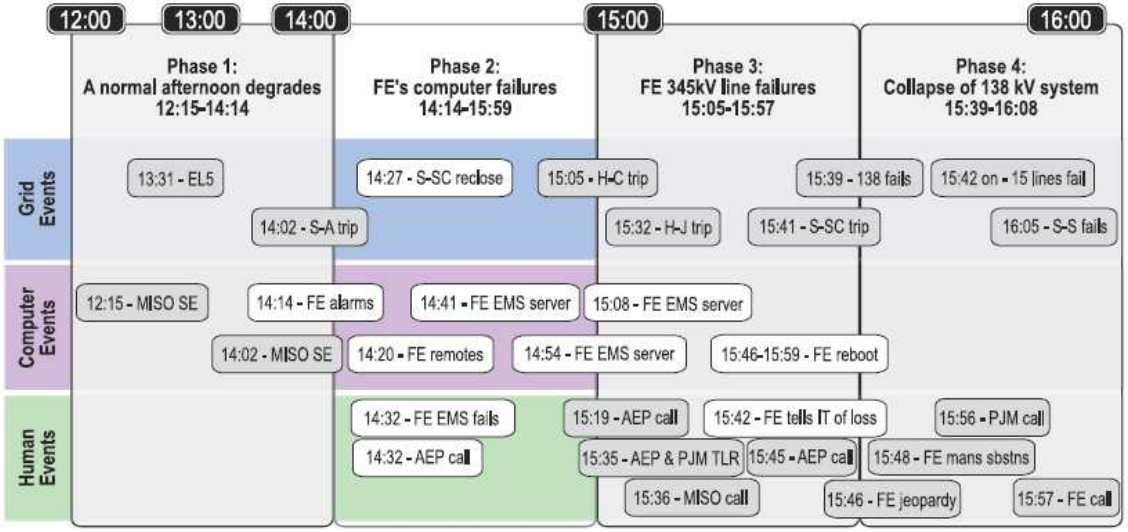
- **Phase 1 Events**
  - **1402: Stuart – Atlanta 345 kV line trips**
    - **Dayton P&L**
    - **Contact w/ tree**
    - **No electrical effect**
    - **Data not effectively communicated to MISO**
    - **Won't be discovered for over an hour (1509)**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.4. Timeline Phase 2



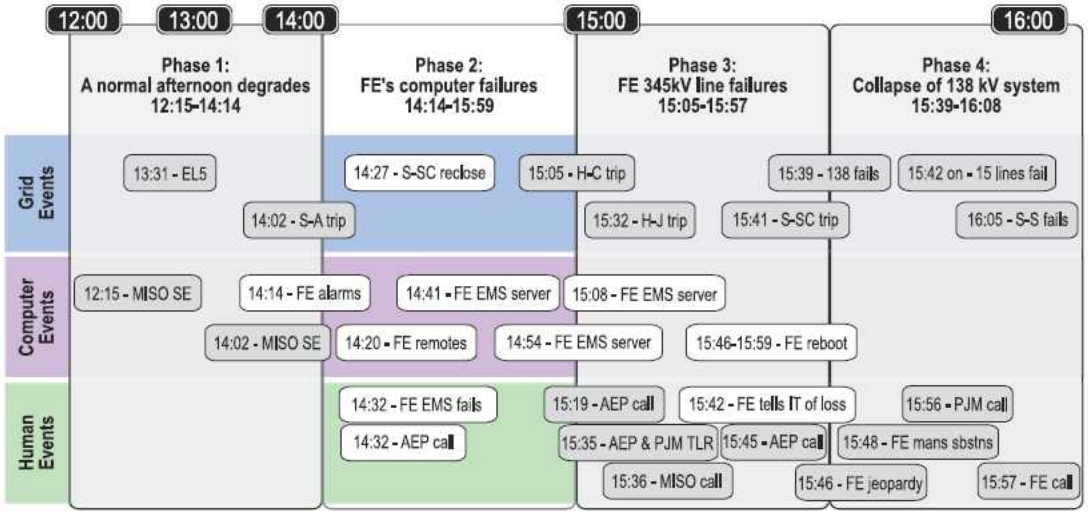
- **Phase 2 Events**
  - **1414: FE Alarm/Logging system Failure**
  - **1420: FE Remote EMS console failure (overload)**
    - **Last time a valid alarm recorded**
    - **System lack alarms on Human-Machine Interfaces (HMIs), recorded/printed record, map board for quick diagnosis**
    - **FirstEnergy (FE) relies on alarms for updates about changing grid conditions**
    - **Operators were unaware that alarms had failed**
    - **Processing of an alarms stalled**
    - **New data fills and overfills input buffers**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.4. Timeline Phase 2



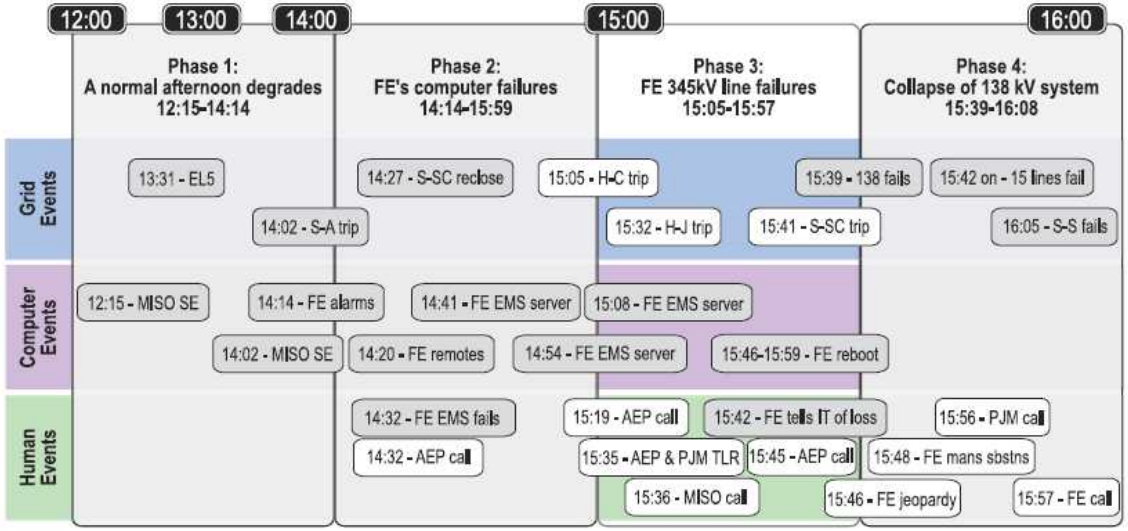
- **Phase 2 Events**
  - **1427: Star – S. Canton 345 kV line trips and closes**
    - **Tree contact**
  - **1432: AEP calls FE re: Star – S. Canton**
    - **Not seen in FE because of alarm failure**
  - **1441: Primary FE Control Server Fails**
    - **Alarm stall also transfers**
  - **1454: Back-up FE Control Server Fails**
    - **HMI refresh rate, normally 1-3 seconds, now 59 seconds**
    - **Warm reboot of primary alarm server at 1508 resolves refresh rate issue *but not* alarm stall**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.7. Timeline Phase 3



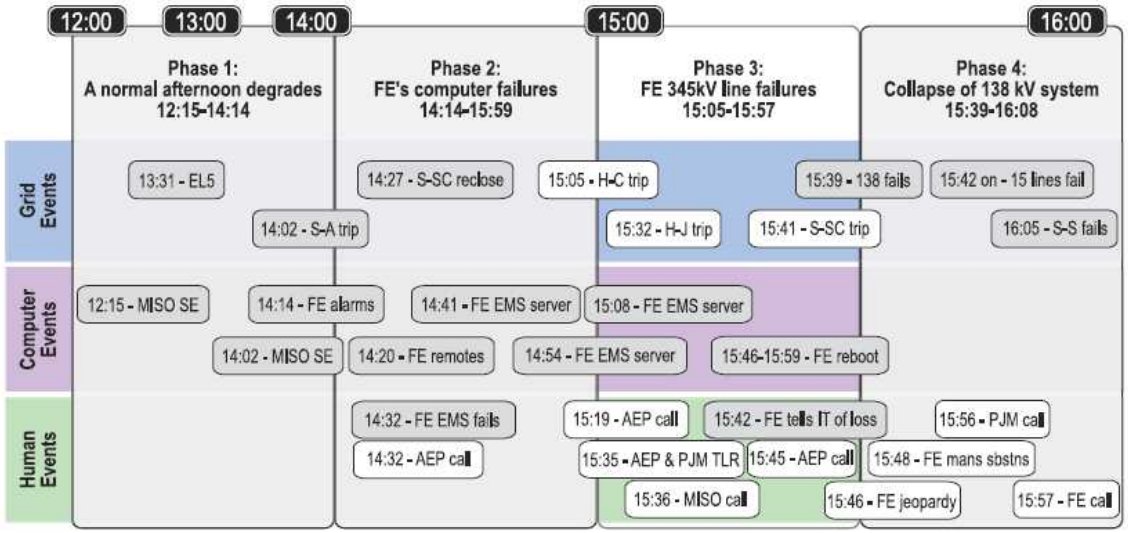
- **Phase 3 Events**
  - **1505: Harding-Chamberlain 345 kV line trips**
    - Tree contact
    - Tripped at 44% of load
  - **1519: AEP calls FE *again* on Star-So. Canton trip**
    - FE operator reiterates that they observe no problem
    - AEP decides to analyze the signal as a potential fluke
  - **1532: Hanna-Juniper 345 kV line trips**
    - Load shifted from Harding-Chamberlain
    - Tripped at 88% load
    - Extra current led to it sagging into a tree

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.7. Timeline Phase 3



- **Phase 3 Events**
  - **1535: AEP and PJM Begin Arranging for TLR for Star – S. Canton**
  - **1536: MISO calls PJM to confirm Stuart-Atlanta trip**
  - **1541: Star – S. Canton 345 kV line trips again, locks out**
    - **Load shift from other outages pushed it to 93%**
    - **Again, outage was tree-related**

Loss of the three 345 kV paths (Star – S. Canton, Hanna – Juniper, Harding – Chamberlain) shift the grid load to the 138kV network, which *cannot carry it.*

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.10. Cause of the Hanna-Juniper Line Loss

This August 14 photo shows the tree that caused the loss of the Hanna-Juniper line (tallest tree in photo). Other 345-kV conductors and shield wires can be seen in the background. Photo by Nelson Tree.

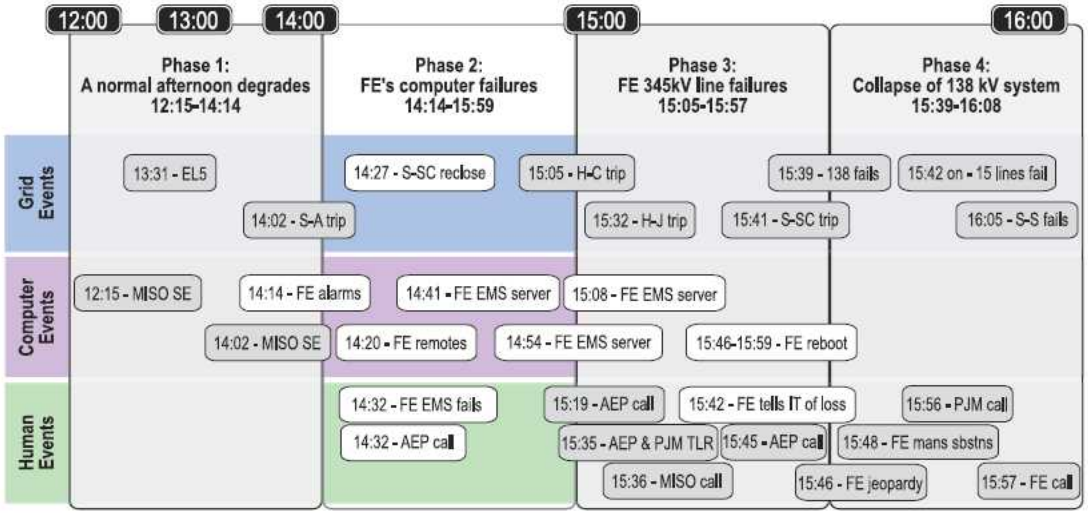
- **More Phase 2 Events**
  - **1542: FE's western transmission operator calls to describe their compromised EMS**
    - **Control center operators mention their EMS problems to the IT staff**
    - **More calls to FE control center**
  - **1545: A tree-trimming crew reported a tree fault on the Eastlake – Juniper (345kV) line**
    - **The actual fault was to the nearby Hanna – Juniper line**
    - **This confused FE more, since the balky EMS accurately showed flow on Eastlake – Juniper**
  - **1545: AEP called about the third and last trip of the Star – S. Canton line**
    - **FE believes them**
  - **1546: Perry operator calls back to report imminent trip**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.4. Timeline Phase 2



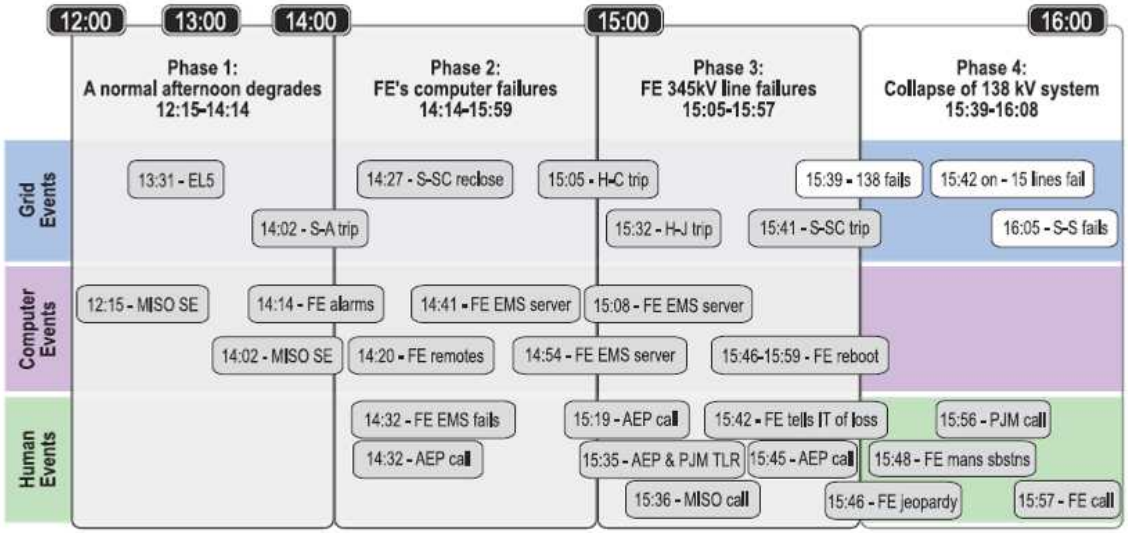
- **Still More Phase 2 Events**
  - **1546-1559: FE IT personnel try rebooting the primary and backup servers**
    - **A "cold" reboot was discussed and rejected because of the ongoing grid problems**
    - **A cold reboot probably the only thing that would have worked**
    - **EMS HMI refresh again crawls**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

Figure 5.13. Timeline Phase 4



- **Phase 4 Events**
  - **1539 – 1558: seven 138 kV lines trip**
  - **1559: W. Akron 138 kV bus trips, causing 5 more lines to trip**
  - **1605:55: Dale – W. Canton 138 kV line trips**
  - **1605:57: Sammis – Star 345 kV line trips, leading to**
    - **Additional 138 kV trips locally**
    - **Cascade**

Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

- **The Cascade Begins**
  - **1608:59:**
    - **Transmission lines into NW OH trip**
    - **Generation trips in MI and N OH**
  - **1609:06: E. Lima – Fostoria Central 345 kV line trips**
    - **Power swing from PA, NY to MI via ON**
  - **1609:08 to 1610:27: 8 units, capacity of 946 MW, trip in MI, OH**

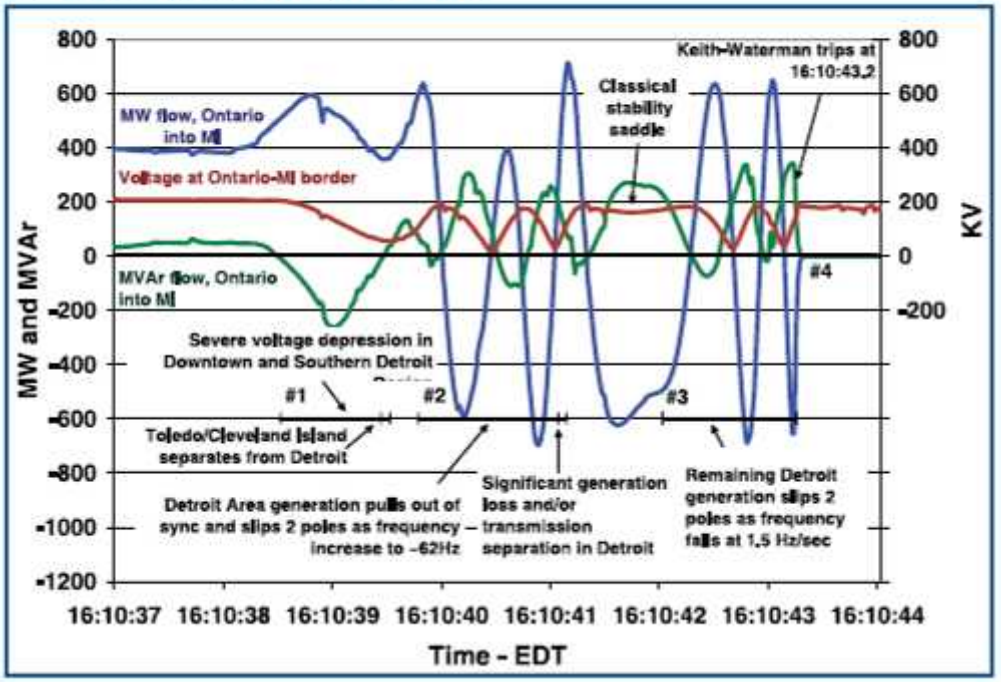
Sandia National Laboratories

Axiom Example

August 14, 2003 Northeast Blackout

- The Cascade Ends
  - 1610:36 to 1613:
    - Thousands of events (line trips, generator trips, load shed, under/overvoltage)
    - Northeast grid separates, islands
  - Shortly thereafter
    - Lots of interesting pictures on every network and news channel
    - All of it the equivalent of filming the result of the car wreck

Figure 6.19. Generators Under Stress in Detroit, as Seen from Keith PSDR



Sandia National Laboratories

Axiom Example

July 23, 1999 South-Central States Rolling Outages

At 1:59 p.m., Western Resources (WR) lost Jeffrey Unit 3 and entered a 700-MW derating contingency, creating a reserve deficiency for SPP. SPP's operating reserve-sharing software — SCCSWin — was unable to develop a feasible schedule. Therefore, SCCSWin output its most recent, infeasible solution and distributed this fictitious schedule to all reserve-sharing participants. Pool members then began to call SPP, asking it to check the validity of the schedule. The SPP found that the schedule was invalid and asked members seeking reserves to speak directly with WR. Although the reserve-sharing program malfunctioned at 1:59 p.m. and issued fictitious schedule notifications to participants, KCPL and Entergy continued to receive assistance, as scheduled. At this time, SPP had a reserve deficiency of 396 MW because five contingencies totaling 2,177 MW had been entered in the last hour.

During the 2 p.m. hour, Entergy continued to inquire about purchasing power from several parties. While none of these parties had power available, some agreed to assist Entergy in looking for power. SPP contingency events continued. At 2:09 p.m., Sunflower Electric Corporation lost its Garden City unit and entered a 50-MW derating contingency. At 2:18 p.m., WR lost Lawrence Energy Center Unit 5 and entered a 340-MW derating contingency. The SCCSWin software produced fictitious schedules for each of these contingencies.

Reference: ***Interim Report of the U.S. Department of Energy's Power Outage Study Team: Findings From the Summer of 1999.*** **January 2000, pp. 1-33, 1-34.**

Sandia National Laboratories