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Operating Transformation
Knowledge Base Article

Nuclear Energy in the Build Economy

Prerequisites, Gaps, and the AI/Automation Imperative

A Strategic Analysis of the U.S. Nuclear Energy Supply Chain

Executive Summary

The United States is experiencing a nuclear energy renaissance, driven by Small Modular Reactor (SMR) development and the need for clean, reliable baseload power. However, the nuclear restart depends on **critical prerequisites** that either don't exist or are severely limited in the U.S. supply chain.

> **The core challenge:** The U.S. nuclear industry faces three fundamental bottlenecks:
>
> 1. **No commercial HALEU production** — High-Assay Low-Enriched Uranium (5-20% enriched) is essential for SMRs, but no commercial production exists in the U.S.
> 2. **Atrophied component supply chain** — Reactor vessels, steam generators, and nuclear-qualified components are in short supply, with limited manufacturing capacity
> 3. **Construction capacity constraints** — Limited EPC firms and qualified workforce for nuclear construction

The competitive disadvantage: Global leaders (South Korea, China, Russia, France) have cost advantages through:

- Lower labor costs (South Korea: $10-15/hour, China: $6-8/hour vs. U.S.: $25-35/hour)

- Established supply chains and manufacturing capacity
- Skilled workforce availability

The solution: AI and automation are not optional — they are strategic necessities to offset labor cost disadvantages, accelerate development, and ensure competitive costs despite higher U.S. labor rates. Combined with robust OT security, AI-enabled automation represents the only path to competitive advantage in the nuclear build economy.

The opportunity: Every stage of the nuclear value chain — from fuel production to reactor operations — requires operational technology (OT) systems, creating significant opportunities for OT security services, AI/OT integration, and supply chain security.

The Nuclear Value Chain

The nuclear energy value chain spans five critical stages:

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FUEL CYCLE                COMPONENTS
REACTOR CONSTRUCTION   REACTOR OPERATIONS
DECOMMISSIONING
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Uranium mining,           Reactor vessels,          Build
containment,     I&C systems,           Decontamination,
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enrichment, fuel          steam generators,
install systems,       safety systems,        waste
management
```

```
fabrication (HALEU        pumps, valves,
commission             operations
```

```
for SMRs)                 instrumentation
monitoring
```

Stage 1: Fuel Cycle

- **Uranium mining:** Extraction of uranium ore

- **Enrichment:** Increasing U-235 concentration (3-5% for traditional reactors, 5-20% HALEU for SMRs)
- **Fuel fabrication:** Manufacturing fuel assemblies

Stage 2: Components

- **Reactor vessels:** Containment vessels, pressure vessels
- **Steam generators:** Heat exchangers for power generation
- **Pumps and valves:** Nuclear-qualified mechanical components
- **Instrumentation:** Control systems, sensors, monitoring equipment

Stage 3: Reactor Construction

- **Containment construction:** Building reactor containment structures
- **System installation:** Installing I&C, safety systems, mechanical systems
- **Commissioning:** Testing, validation, regulatory approval

Stage 4: Reactor Operations

- **I&C systems:** Instrumentation and control for reactor operations
- **Safety systems:** Safety-instrumented systems (SIS), emergency systems
- **Operations monitoring:** Real-time monitoring, maintenance, optimization

Stage 5: Decommissioning

- **Decontamination:** Removing radioactive materials
- **Waste management:** Handling spent fuel, radioactive waste
- **Site remediation:** Restoring sites to regulatory standards

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Current State and Capacity Gaps

Capacity Assessment by Stage

Stage	U.S. Capacity	Global Leader	Gap	Labor Intensity
Fuel Cycle	Limited (mining, some enrichment), **no HALEU production**	Russia (enrichment), France (fuel fabrication)	**Critical gap in HALEU**	**High (precision processes)**
Components	Limited (reactor vessels, pumps, valves)	South Korea, Japan, France	**Critical gap**	**High (precision manufacturing)**
Reactor Construction	Limited (Westinghouse, but supply chain atrophied)	South Korea, China, Russia	**Critical gap**	**Very high (thousands of workers)**
Reactor Operations	Strong (existing fleet)	U.S., France, South Korea	No gap	Moderate (highly automated)
Decommissioning	Limited	U.S., France	Moderate gap	**High (specialized processes)**

The HALEU Crisis

HALEU (High-Assay Low-Enriched Uranium) is enriched to 5-20% U-235, compared to 3-5% for traditional reactors. This higher enrichment enables:

- Smaller reactor cores (essential for SMR designs)
- Longer fuel cycles
- Advanced reactor designs (molten salt, high-temperature gas)

The problem:

- **No commercial HALEU production in the U.S.**
- All major SMR developers (TerraPower, X-energy, NuScale) require HALEU
- Current HALEU availability is limited to small quantities from DOE inventory
- Commercial production is years away despite DOE funding

The impact: HALEU is the **gating function for SMR deployment**. Without commercial HALEU production, SMRs cannot be deployed at scale.

Component Supply Chain Challenges

Nuclear-qualified components must meet stringent requirements:

- **ASME N-stamp certification:** Nuclear quality assurance requirements
- **10 CFR Part 50/52 compliance:** NRC regulatory requirements
- **Extensive documentation:** Quality records, material traceability

The problem:

- Supply chain has **atrophied** since the last new reactor construction in the 1970s
- Limited foundry capacity for reactor vessels (only a few facilities worldwide)
- Long lead times for critical components (steam generators, reactor vessels)
- Limited manufacturing capacity for pumps, valves, instrumentation

The impact: Component availability is a bottleneck for new reactor construction and SMR deployment.

Construction Capacity Constraints

Nuclear construction requires:

- **EPCs with nuclear experience:** Fluor, Bechtel, Westinghouse

- **Qualified workforce:** Welders with nuclear certifications, inspectors, engineers
- **Regulatory expertise:** NRC licensing, quality assurance programs

The problem:

- Limited EPC capacity for multiple simultaneous projects
- Workforce shortages (welders, inspectors, nuclear engineers)
- High costs and schedule risks (Vogtle 3 & 4 cost overruns)

The impact: Construction capacity limits the pace of nuclear deployment.

The Prerequisite Problem: What Must Be Built

Priority 1: HALEU Production

Current status:

- **Centrus Energy** building HALEU facility (Piketon, OH)
- **DOE funding** multiple HALEU production projects
- Commercial production expected in mid-to-late 2020s

What's needed:

- Commercial-scale HALEU enrichment capacity
- Fuel fabrication facilities for HALEU fuel assemblies
- Supply chain infrastructure for HALEU transport and handling

The urgency: HALEU availability is the **gating function** for SMR deployment. Without it, SMRs cannot proceed.

Priority 2: Component Manufacturing

What's needed:

- **Reactor vessel foundries:** Expand capacity for large pressure vessels
- **Steam generator manufacturing:** Increase capacity for heat exchangers
- **Pump and valve manufacturing:** Nuclear-qualified mechanical components
- **Instrumentation manufacturing:** Control systems, sensors, monitoring equipment

The challenge: Rebuilding the component supply chain requires:

- Capital investment in manufacturing facilities
- Workforce development (skilled machinists, welders, inspectors)
- N-stamp certification and quality assurance programs
- Long lead times for facility construction and certification

Priority 3: Construction Capacity

What's needed:

- **EPC capacity:** Multiple firms capable of nuclear construction
- **Workforce development:** Qualified welders, inspectors, engineers
- **Regulatory expertise:** NRC licensing, quality assurance programs
- **Project management:** Experience managing complex nuclear projects

The challenge: Building construction capacity requires:

- Workforce training and certification programs
- EPC investment in nuclear capabilities
- Learning from past projects (Vogtle, Summer) to improve efficiency
- Adoption of modular construction techniques (SMRs)

Labor Challenges and the AI/Automation Imperative

The Labor Cost Disadvantage

Region	Manufacturing Labor Cost	Skilled Technician Availability
U.S.	$25-35/hour	Limited (skills gap)

South Korea	$10-15/hour	Abundant
China	$6-8/hour	Abundant (vocational training)
Japan	$20-25/hour	Abundant

Reactor Construction: The Labor Challenge

Global leaders (South Korea, China):

- Can deploy **thousands of workers** for construction (welding, inspection, assembly)
- Lower labor costs enable competitive construction costs
- Established workforce with nuclear construction experience

U.S. constraints:

- **3-5x higher labor costs** compared to China
- **1.5-2x higher labor costs** compared to South Korea
- Limited skilled workforce availability
- Immigration constraints limit workforce scaling

> **The math:** If China can build reactors with $6/hour labor and the U.S. needs $30/hour labor, the U.S. needs **5x productivity** to break even — achievable only through automation and AI.

Component Manufacturing: The Precision Challenge

Global leaders (South Korea, Japan):

- Precision manufacturing of reactor vessels, steam generators
- Established supply chains and manufacturing expertise
- Lower labor costs (offset by automation in some cases)

U.S. challenge:

- Need to match precision while automating more
- Higher labor costs require greater automation
- Supply chain rebuilding requires significant capital investment

Why AI/Automation Is Necessary

AI and automation are not optional — they are strategic necessities for competitive advantage in the U.S. nuclear build economy.

1. Construction Automation

AI for welding:

- Automated welding systems reduce labor content
- Improve quality and consistency
- Reduce human error and rework
- Enable 24/7 operations

AI for inspection:

- Automated inspection systems (ultrasonic, radiographic, visual)
- Reduce labor content for quality assurance
- Improve detection rates and consistency
- Enable real-time quality feedback

Result: Faster construction, lower costs, competitive despite higher labor rates

2. Predictive Maintenance

AI for operations:

- Predict equipment failures before they happen (pumps, valves, I&C systems)
- Optimize maintenance schedules
- Reduce unplanned downtime
- Extend equipment lifetime

Result: Less downtime, higher uptime, lower maintenance costs

3. Fuel Optimization

AI for fuel management:

- Optimize fuel loading patterns
- Maximize burnup and efficiency
- Optimize refueling schedules
- Reduce fuel costs

Result: Higher efficiency, lower fuel costs, extended fuel cycles

4. Safety Systems

AI for safety:

- Predict safety system needs

- Optimize safety system performance
- Enhance emergency response
- Improve regulatory compliance

Result: Higher safety, regulatory compliance, reduced risk

AI/Automation Adoption Examples

SMR developers leading in automation:

- **TerraPower:** Automation focus in Natrium SMR design
- **X-energy:** Automation investments in Xe-100 design
- **NuScale:** Factory-built modules reduce construction labor

Industry trend: SMR designs are incorporating more automation and AI from the start, recognizing that labor cost competitiveness requires automation.

OT Security Requirements

OT Systems Across the Value Chain

Every stage of the nuclear value chain requires operational technology (OT) systems:

Stage	OT Requirements
Fuel Cycle	Process control, safety systems, security (nuclear materials), enrichment controls
Components	Manufacturing control, quality systems, N-stamp compliance, testing systems

Reactor Construction	Construction automation, inspection systems, quality assurance
Reactor Operations	I&C systems, safety-instrumented systems (SIS), cybersecurity (NRC requirements), AI/ML integration
Decommissioning	Process control, waste management, security, monitoring systems

The Unique Nuclear OT Security Challenge

Nuclear facilities are highest-consequence OT environments:

The stakes: A compromised nuclear facility could cause:

- **Safety incidents:** Radiation release, core damage
- **Environmental damage:** Contamination, long-term impacts
- **Grid instability:** Loss of baseload power capacity
- **National security implications:** Critical infrastructure, nuclear materials

Regulatory requirements:

- **10 CFR 73.54:** NRC cybersecurity requirements for nuclear facilities
- **NRC Regulatory Guide 5.71:** Cybersecurity programs for nuclear facilities
- **NEI 08-09:** Cybersecurity plan for nuclear power reactors

> **The requirement:** OT security is not optional. It is a **gating function** for:
>
> - Regulatory approval (NRC licensing)
> - Insurance coverage
> - Operational license
> - Public trust

OT Security Gaps

1. Legacy systems:

- Many nuclear facilities use legacy I&C systems
- Hard to secure (can't patch, limited security features)

- Replacement is expensive and requires regulatory approval

2. AI/ML systems:

- AI introduces new attack vectors:
  - **Model poisoning:** Corrupt training data → AI makes wrong decisions
  - **Adversarial inputs:** Fool AI vision systems → wrong classifications
  - **Data exfiltration:** Steal AI models, process IP, algorithms
- AI/OT integration creates new attack surfaces

3. Supply chain security:

- Components and vendors introduce security risks
- Foreign components (especially from Russia, China) are security concerns
- Vendor remote access creates security vulnerabilities

4. Digital I&C migration:

- Transition from analog to digital I&C systems
- New systems require cybersecurity integration
- Legacy system integration challenges

Modern Nuclear OT Environments

A modern nuclear plant or SMR deployment requires:

- **Safety-instrumented systems (SIS)** — the last line of defense
- **Digital I&C systems** (replacing analog systems)
- **Remote monitoring** for operations and maintenance
- **AI/ML** for predictive maintenance, fuel optimization
- **Cloud integration** for data analytics, regulatory reporting

The attack surface has expanded: More connectivity, more vendors, more AI/ML systems, more integration points.

Strategic Opportunities

Opportunity 1: Nuclear Supply Chain Security

Service offering: OT security for nuclear supply chain facilities

Target facilities:

- **Fuel cycle facilities:** HALEU production, enrichment, fuel fabrication
- **Component manufacturers:** Reactor vessels, steam generators, pumps, valves
- **Construction sites:** Reactor construction, commissioning

Services:

- OT security assessments
- Supply chain security risk assessment
- Vendor security management
- N-stamp compliance support

Target clients:

- Centrus Energy (HALEU production)
- Component manufacturers (reactor vessels, etc.)
- EPC firms (Fluor, Bechtel, Westinghouse)

Opportunity 2: Reactor OT Security

Service offering: OT security for reactor operations

Target facilities:

- Existing nuclear plants (legacy systems, modernization)
- New reactor construction (security-by-design)
- SMR deployments (greenfield security)

Services:

- NRC compliance (10 CFR 73.54, Regulatory Guide 5.71)
- OT security assessments and remediation
- Legacy system security (hardening, monitoring)
- Digital I&C security integration
- Safety system security (SIS security)

Target clients:

- Constellation, Southern Company, Duke Energy (reactor operators)
- TerraPower, X-energy, NuScale (SMR developers)

Opportunity 3: AI/OT Integration Security

Service offering: Security for AI/ML systems in nuclear environments

The unique challenge:

- AI introduces new attack vectors (model poisoning, adversarial inputs)

- AI/OT integration creates new attack surfaces
- Nuclear facilities are highest-consequence environments
- Regulatory requirements for AI/ML systems in nuclear facilities

Services:

- AI model security assessment
- AI/OT integration security
- Adversarial testing for AI systems
- AI incident response planning
- AI governance framework for nuclear facilities

Target clients:

- All nuclear facilities using AI/ML (predictive maintenance, fuel optimization)
- SMR developers (automation and AI from the start)

Opportunity 4: Commissioning-to-Operate OT Security

Service offering: OT security from commissioning through operations

The nuclear build cycle creates unique opportunities:

- **Greenfield security:** Design security into new facilities
- **Commissioning security:** Secure systems during testing and validation
- **Operational security:** Maintain security through operations

Services:

- Security-by-design for new reactors
- Commissioning security (testing, validation)
- Operational security (monitoring, maintenance)
- Regulatory compliance support

Target clients:

- TerraPower, X-energy, NuScale (SMR developers)
- Utilities building new reactors
- EPC firms (security integration in construction)

Conclusion

The U.S. nuclear energy renaissance depends on building **critical prerequisites** that don't exist or are severely limited in the current supply chain:

1. **HALEU production** — the gating function for SMR deployment
2. **Component supply chain** — atrophied since the 1970s, needs rebuilding
3. **Construction capacity** — limited EPC capacity and qualified workforce

The competitive challenge: Global leaders (South Korea, China, Russia, France) have cost advantages through lower labor costs and established supply chains. The U.S. cannot compete on labor cost alone.

The solution: AI and automation are strategic necessities — not optional. To compete with countries that have 3-5x lower labor costs, the U.S. must achieve 5x productivity through:

- Construction automation (welding, inspection)
- Predictive maintenance (AI for operations)
- Fuel optimization (AI for fuel management)
- Safety systems (AI for safety)

The security imperative: Every stage of the nuclear value chain requires OT systems, and nuclear facilities are highest-consequence environments. OT security is a **gating function** for regulatory approval, insurance coverage, and operational license.

The opportunity: The nuclear build economy creates significant opportunities for:

- OT security services (supply chain, reactor operations)
- AI/OT integration security (new attack vectors, highest-consequence environments)
- Commissioning-to-operate security (greenfield security-by-design)
- NRC compliance support (10 CFR 73.54, Regulatory Guide 5.71)

> **The question:** Will the U.S. build the nuclear prerequisites with AI/automation and robust OT security, or accept dependency on foreign suppliers?
>
> **The answer:** AI/automation + OT security is not optional — it is the only path to competitive advantage and energy security in the nuclear build economy.

Sources

- TerraPower SMR plans (automation focus)
- X-energy SMR (automation investments)

- NuScale Power (factory-built modules)
- Centrus Energy (HALEU production)
- NRC regulations (10 CFR 73.54, Regulatory Guide 5.71)
- NEI 08-09 (Cybersecurity plan for nuclear power reactors)
- Industry analysis of nuclear construction costs
- Bureau of Labor Statistics (U.S. manufacturing wages)
- DOE HALEU production initiatives
- Vogtle 3 & 4 construction experience

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