Nuclear Command in the Age of Cyber and AI

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Introduction

Nuclear command, control, and communications—NC3—was designed for a world of analog sensors, fixed lines, and human-centered judgment. That world is changing. Cyber operations now routinely probe the perimeters and interiors of critical infrastructure. Machine learning and automation are accelerating detection, shrinking decision windows, and creating new seams where error, spoofing, or malicious manipulation can take root. This book examines how emerging technologies alter both the risks and the controls that govern nuclear systems, and what must be done to ensure that strategic stability is preserved rather than undermined.

The central thesis is straightforward: cyber and AI are double-edged. They can improve reliability, resilience, and situational awareness; they can also amplify uncertainty, compress timelines, and create new failure modes that interact in unexpected ways with legacy hardware and procedures. In nuclear affairs, where the tolerance for error is effectively zero, this duality demands a posture of layered skepticism: design systems to work when they must, fail safely when they should, and be provably hard to subvert. Throughout these chapters, we disentangle hype from hazard and map concrete pathways to reduce systemic risk.

We anchor the analysis in the real constraints of NC3: heterogeneous components spanning decades of technology; stringent security and safety requirements; adversaries that are capable, adaptive, and incentivized to operate below the threshold of open conflict; and decision processes that must reconcile technical telemetry with human judgment under intense pressure. The book explores how AI-enabled sensors might improve early warning yet be vulnerable to adversarial inputs; how automation can accelerate command workflows yet exacerbate automation bias; and how cyber intrusions can blur attribution, inviting misperception at precisely the moments when clarity matters most.

Because technology alone neither guarantees safety nor causes catastrophe, we combine technical proposals with policy and organizational reforms. Recommended safeguards include adopting zero-trust principles tailored to NC3; expanding the use of formal methods and memory-safe languages in safety-critical software; deploying hardware roots of trust; and building resilient, diversified communications paths that assume partial compromise. On the policy side, we outline verifiable guardrails—such as commitments to maintain meaningful human control over launch decisions, mechanisms for out-of-band crisis communication, and transparency measures that reduce the incentives for risky automation races.

This is a forward-looking assessment, but it does not start from a blank slate. Historical

near-misses and exercises reveal recurring patterns: noisy sensors, ambiguous data, and human factors that can either correct or compound technical faults. Emerging technologies change the texture of those patterns by making systems faster, more opaque, and more tightly coupled. Our aim is to stress-test today’s assumptions against tomorrow’s realities, using scenarios that illuminate where the greatest leverage lies for risk reduction.

Ultimately, the question is not whether cyber and AI will permeate nuclear command and control—they already have—but whether their integration will be governed by principles that privilege safety, accountability, and stability. This book offers a roadmap to that end: practical steps for engineers and operators, policy options for governments and alliances, and confidence-building measures for rivals who must coexist under conditions of mutual vulnerability. The stakes could not be higher; the goal is simple to state and hard to achieve—a nuclear enterprise that is smarter without being brittle, faster without being reckless, and more connected without being less secure.

CHAPTER ONE: The New Attack Surface of Nuclear Command, Control, and Communications (NC3)

Nuclear command, control, and communications—NC3—has never been static. From the earliest alert systems to today's networked early-warning architectures, the enterprise has evolved to manage complexity, reduce latency, and increase reliability. In recent decades, digital systems replaced analog interfaces, satellite links supplemented terrestrial cables, and software became the nervous system binding sensors, decision nodes, and effectors. Each step improved capability, but each step also expanded the attack surface. That expansion is not an indictment of progress; it is a description of modernization. With every added sensor, every new protocol, and every connected console, there are more places where failure or malice can enter.

The new attack surface is not just larger; it is qualitatively different. The classic NC3 model presumed a relatively clear boundary: a limited set of hardened facilities, dedicated communication paths, and trusted operators. Modern NC3 is a hybrid enterprise: commercial satellites, commercial cloud services, fiber routes shared with civilian traffic, and software stacks maintained by contractors across multiple jurisdictions. The result is a system that is more resilient in some ways—diverse paths, redundant nodes—yet also more entangled with the everyday digital world. In the language of risk, dependencies multiply faster than protections, and the interactions among them can be nonlinear.

A helpful way to think about this new attack surface is as a set of concentric rings. At the core is the launch and readiness function, which must be secure, safe, and reliable under duress. Surrounding it are communications and data links, both encrypted and public. Beyond those are sensors—ground radars, space-based infrared systems, undersea acoustic arrays—feeding early warning. Further out still are supply chains for hardware and software, maintenance and updates, training systems, and logistics. An adversary does not need to breach the hardened command center to cause harm; disruption of timing, integrity, or availability at any ring can cascade inward, especially under time pressure.

Cyber operations have demonstrated the reach of this layered exposure. In other critical sectors, intrusions have moved from email phishing to operational disruption, from data theft to control-system manipulation. Industrial control systems are often not designed for hostile environments; they prioritize uptime over defensibility. The NC3 ecosystem, while more rigorously protected, still relies on components with the same roots: commercial operating systems, off-the-shelf processors, widely used protocols, and common programming languages with known memory-safety pitfalls.

An attacker who cannot directly command a launch might still degrade confidence in early warning, degrade communications, or introduce ambiguity that accelerates dangerous decision-making.

Artificial intelligence adds new dimensions to the attack surface by changing how data is processed and decisions are made. Machine learning models can sift through vast streams of sensor data, classify patterns, and suggest timelines; they can also make mistakes at scale and be tricked by adversarial inputs. When AI is inserted into early-warning pipelines or command workflows, it introduces new dependencies on data quality, model integrity, and computational environments. Those dependencies can be targeted indirectly: corrupt training data, inject noise into sensor feeds, or exploit hardware vulnerabilities that cause silent errors. The result is a system where the mere presence of AI alters the ways adversaries can interfere.

Consider an early-warning scenario: a constellation of satellites reports thermal signatures consistent with missile launches, and ground radars corroborate tracks. Algorithms fuse these inputs and raise an alert. Under normal conditions, analysts validate the alert, and human commanders assess. But if an adversary has subtly manipulated infrared calibration or injected spoofed telemetry, the algorithm may still produce a high-confidence alert. The attack surface here spans hardware (sensors), software (fusion algorithms), communications (data links), and human factors (analyst workload and bias). The failure is not necessarily a crash; it is a mischaracterization under time pressure, a degrading of the trust model at the heart of early warning.

The communications layer has its own complexities. NC3 traditionally relied on dedicated lines and specialized radio systems. Today, strategic communications often traverse satellite constellations that include commercial payloads, terrestrial fiber that overlaps with global internet infrastructure, and microwave links that are easier to intercept or jam than underground cables. Encryption is robust, but it is not magic: metadata can reveal patterns, encryption endpoints are vulnerable, and key management is nontrivial at scale. Moreover, communication outages—whether from solar weather, accidental damage, or deliberate interference—can force operators onto secondary paths that may be less familiar or less secure, increasing cognitive load at the worst possible moment.

Space assets introduce a distinctive mix of exposure and necessity. Satellites are essential for global situational awareness and command relay, but they are also inherently hard to patch, difficult to secure physically, and increasingly contested. As commercial space services proliferate, NC3 systems can lease capacity to diversify risk, yet they also inherit the security practices and threat models of providers not purpose-built for nuclear command. Ground stations, uplinks, and terminals become chokepoints. Cyber intrusions at a provider’s network operations center may not compromise a satellite directly, but they can degrade navigation data, disrupt scheduling, or inject subtle timing errors into signals used for synchronization.

Even physical security is entangled with the digital. Modern security systems—access control, sensors, alarms—are networked and software-driven. The line between physical and cyber defense is porous. An attacker who compromises the administrative network of a secure facility might not reach the command bunkers, but they can still cause nuisance alarms, blind cameras, or lock doors at inopportune times, sowing confusion. Meanwhile, the analog safety valves that once provided fallback assurance—manual levers, mechanical interlocks—are increasingly rare or replaced by software equivalents that can be subverted if the underlying system is compromised.

Supply chains are a critical and often underappreciated component of the new attack surface. Semiconductor fabrication, board assembly, firmware development, and software updates pass through multiple vendors and jurisdictions. The complexity makes it hard to verify provenance at every step. A compromised component need not be maliciously designed; it may be vulnerable in ways that an adversary can exploit after deployment. The SolarWinds incident, though not nuclear in nature, illustrated how a routine software update from a trusted vendor can become a vector for deep and persistent access. In NC3, similar mechanisms exist for maintenance and monitoring tools, logging systems, and performance analytics.

The software stack itself is a vast surface. Nuclear systems have long lifespans, and software updates occur on schedules that must avoid disrupting readiness. Legacy code, often written in languages like C and C++, is still common in safety-critical environments. While these languages offer performance and control, they are also prone to memory errors, buffer overflows, and undefined behaviors that can be exploited. Modern software practices—containerization, continuous integration, dependency management—are not inherently hostile to security, but they can introduce new risks if dependencies are unvetted or if the build pipeline itself is compromised. A single vulnerable library can propagate across multiple systems, creating a broad attack surface with a narrow cause.

Operational technology (OT) and industrial control systems form a bridge between IT and the physical world. Many NC3 facilities use OT for power management, environmental controls, and communications equipment. Historically, these systems were air-gapped, but connectivity has grown for maintenance, monitoring, and efficiency. The Purdue model, which segments industrial networks into levels, is widely used, but real-world implementations often have exceptions and backdoors. A misconfigured bridge between IT and OT can provide an entry point from which an attacker can pivot to more sensitive systems, leveraging privilege escalation paths that were not originally intended to exist.

Data integrity is a subtle aspect of the attack surface. Encryption protects confidentiality, and authentication ensures identity, but ensuring that data accurately

represents the real world is a separate challenge. GPS spoofing can shift timing and location; radar clutter can hide targets or create ghosts; telemetry can be altered to show false readings. AI systems that learn from data are especially sensitive to integrity issues because they may encode biases or vulnerabilities in ways that are difficult to detect. A model trained on clean data may behave unpredictably when exposed to manipulated inputs, especially if the adversary has access to the training pipeline or the online learning loop.

The human interface is the final, and perhaps most critical, part of the attack surface. Operators interact with displays, alerts, and checklists that translate complex data into decisions. These interfaces are software, and like any software, they can be tricked. A subtle change in the color palette of a map, a timestamp error, or an ambiguous alert banner can introduce doubt or misdirection. Phishing and social engineering remain effective because they target trust and habit. Even rigorous training cannot eliminate the possibility that an operator will misinterpret a manipulated signal under stress, particularly when the system itself appears to be functioning normally.

The concept of cross-domain operations—actions that combine cyber, information, space, and kinetic effects—creates new seams. An adversary may simultaneously degrade satellite communications and flood hotlines with spam, while pushing misinformation through social media to confuse decision-makers. The NC3 enterprise must defend against each vector and, more challenging, against their interactions. Defenders must assume that attacks will not occur in isolation; they will be timed and coordinated to maximize confusion. This is not a theoretical concern: modern conflicts have already demonstrated the use of multi-domain harassment to disrupt command and erode confidence.

Risk in this environment is not simply additive; it is multiplicative. Two vulnerabilities that are minor in isolation can become critical when combined with time pressure and human factors. A sensor glitch may be acceptable if communications are robust; a communications delay may be tolerable if sensors are reliable. But when sensor errors coincide with degraded links, operators face ambiguity and must make decisions with incomplete information. Adversaries understand this and aim for synergistic effects that push systems into regime where errors cascade. The new attack surface is full of such synergies, and understanding them requires looking beyond individual components to the interactions between them.

It is tempting to view these developments as a reason to abandon new technology or to seek an idealized return to earlier, simpler architectures. But simplicity is not a guarantee of safety, and nostalgia can be misleading. The older NC3 systems had their own vulnerabilities: limited redundancy, single points of failure, and reliance on human vigilance without algorithmic assistance. The path forward is to accept the complexity of modern systems and to engineer them for security, resilience, and controlled failure. That means building architectures that assume compromise, designing

interfaces that degrade gracefully, and establishing policies that ensure human judgment remains central, even as automation accelerates.

To illustrate the breadth of the new attack surface, it helps to map the core elements and their interdependencies. The following table summarizes major components, how they connect, and where they are vulnerable:

Component	Connections	Primary Vulnerabilities	Impact on NC3
Sensors (radar, IR, undersea)	Data links to fusion nodes; calibration pipelines	Spoofing, jamming, calibration drift, integrity corruption	False early warning or missed detection
Space assets (satellites, ground stations)	Uplinks, downlinks, timing services	Orbital interference, link jamming, provider network intrusion	Loss of global awareness and command relay
Communications (terrestrial and RF)	Fiber, microwave, satellite, dedicated lines	Interception, degradation, routing manipulation	Reduced reliability, increased latency
Command centers (fixed and mobile)	Internal networks, OT for power and environment	IT/OT bridging, supply chain, insider misuse	Disrupted operations or loss of situational awareness
Software and algorithms (fusion, decision aids)	Patched over networks, dependent on libraries	Supply chain, memory safety, adversarial ML	Misleading recommendations or degraded function
Supply chains (hardware and software)	Vendor updates, maintenance portals, logistics	Counterfeit components, compromised updates	Persistent, hard-to-detect vulnerabilities
Human operators (interfaces and training)	Displays, checklists, alerts, hotlines	Phishing, social engineering, interface deception	Procedural errors and misinterpretation

This mapping is not exhaustive, but it highlights a pattern: the most consequential risks often lie at the intersections—between networks and control systems, between data and algorithms, between automation and human judgment. NC3 has always had to manage intersections, but the number and complexity of them have grown. The challenge is not to eliminate intersections; that would mean dismantling the modern enterprise. The challenge is to control the interactions so that failures are detectable, contained, and recoverable, even under attack.

Where do we start? Begin with the observation that attacks on NC3 will rarely be obvious. They will manifest as small errors, timing slips, or ambiguous signals that compound under pressure. Defenders must design for detectability: instruments that report their own health, algorithms that expose confidence levels and uncertainty, communications that carry checksums and proofs of origin, and interfaces that make anomalies visible without overwhelming operators. The goal is to create a system that is honest about its limits—friction in the right places that slows down bad decisions

without paralyzing good ones.

The new attack surface also requires a shift in mindset from perimeter defense to resilience. Perimeter thinking assumes a clear boundary between trusted and untrusted; resilience assumes that parts of the system will be compromised and must continue to function. This means compartmentalization, redundancy, diversity, and graceful degradation. It means validating data across independent sources, maintaining out-of-band channels that are physically separated from primary networks, and designing critical functions with minimal dependencies on nonessential components. It means practicing failure as seriously as we practice success.

Finally, acknowledging the new attack surface is not an invitation to despair or to abandon innovation. It is an invitation to build systems that are secure by design, resilient by construction, and accountable in operation. In subsequent chapters, we will explore the history of NC3, the anatomy of modern architectures, and the specific threats posed by cyber actors and AI-driven techniques. We will discuss safeguards from formal methods and zero trust to hardware roots of trust and cross-domain norms. But the foundation is clear: we are operating in a world where nuclear command sits at the center of a sprawling, interconnected digital ecosystem. Understanding the shape and scope of that ecosystem is the first step toward governing it responsibly.

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