International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

International Journal of Science and Research Archive
Research Journal Archive, INDIA

(Research Article)

# From deployment to defense: Real world strategies for enhancing cloud security through preventative infrastructure controls

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International Journal of Science and Research Archive; 2025, 16(01), 781-787

Publication history: Received on 01 June 2025; revised on 08 July 2025; accepted on 10 July 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.16.1.2059

## Abstract

Cloud infrastructure has become foundational to modern digital services; yet recent high profile breaches have exposed critical weaknesses in cloud security design. This research addresses the problem of infrastructure level vulnerabilities that persist even when application level security is robust. Through analysis of documented breaches at Capital One; Tesla; Accenture; and Uber; this study demonstrates that misconfigurations; insufficient access controls; and inadequate monitoring are recurring factors that enable attackers to compromise sensitive data and disrupt operations.

To address these risks; this paper proposes a secure-by-design cloud architecture that integrates preventative controls at every layer. The methodology includes a comparative analysis of breach reports and security documentation; followed by the development of a reference architecture featuring web application firewalls; private subnets; IMDSv2; restrictive security groups; encrypted storage; autoscaling; centralized logging; and secret management. The design is evaluated against the root causes of the selected breaches to demonstrate its effectiveness.

The results show that implementing these preventative infrastructure controls would have directly mitigated the vulnerabilities exploited in the analyzed incidents. The research contributes to a practical; adaptable framework for organizations seeking to enhance cloud security and reliability. The conclusion emphasizes that proactive; infrastructure focused security measures are essential for defending against evolving cloud threats; and that secure design must be prioritized alongside application development from the outset.

**Keywords:** Secure Cloud Design; IMDSv2; Storage; WAF; Security Logging

## 1. Introduction

Cloud computing has fundamentally transformed how organizations deploy, manage, and scale digital services, offering unprecedented flexibility, scalability, and cost efficiency. As enterprises increasingly migrate their operations to the cloud, they benefit from rapid provisioning, global reach, and the ability to leverage advanced technologies such as big data analytics and artificial intelligence. However, this shift also introduces a new set of security challenges. The shared responsibility model, where both cloud providers and customers must secure different aspects of the environment, often leads to confusion and gaps in coverage. Cloud environments are now frequent targets for cyber attackers due to the concentration of valuable data and the complexity of securing distributed resources.

### 1.1. Problem Statement

Despite the technological advancements and security features provided by cloud service vendors, high profile breaches continue to occur, exposing critical weaknesses in cloud security design. Common issues such as misconfigured storage, weak access controls, lack of visibility, and human error have resulted in significant data leaks and operational

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disruptions for major organizations, including Capital One, Tesla, Accenture, and Uber *[1-5]*. The complexity of cloud architectures, combined with rapid deployment cycles and the use of third party services, increases the attack surface and makes comprehensive risk management challenging. Many organizations struggle to implement effective security controls at the infrastructure level, leaving sensitive data and systems vulnerable to exploitation. As a result, even robust application level security can be undermined by overlooked infrastructure vulnerabilities.

### *Objective*

The aim of this research is to systematically analyze cloud security architecture and its vulnerabilities through real world case studies, with the goal of developing a secure-by-design framework that addresses the most critical risks. This study proposes a reference architecture that integrates preventative controls such as web application firewalls, usage of private subnets, IMDSv2, restrictive security groups, encryption, autoscaling, centralized logging, and secrets management at every layer of the cloud environment [6-15]. By mapping these controls to the root causes of documented breaches, the research seeks to provide practical, actionable guidance for organizations to enhance both the security and reliability of their cloud deployments.

## 2. Literature survey

Recent literature and incident reports highlight the prevalence of security breaches arising from misconfigured cloud resources, insufficient access controls, and lack of monitoring [1-5]. The Capital One breach was enabled by a misconfigured WAF and outdated metadata service. Tesla’s cryptojacking incident was due to an exposed Kubernetes console. Accenture and Uber suffered data exposures from improperly secured S3 buckets and leaked credentials. These cases underscore the importance of proactive infrastructure security.

## 3. Problem definition or experimental work

### 3.1. Case Study Analysis

This study examines four major cloud security breaches to extract lessons learned and inform secure infrastructure design:

- Capital One (2019): An SSRF attack exploited IMDSv1 and a misconfigured WAF, leading to S3 data exfiltration.
- Tesla (2018): An unsecured Kubernetes console allowed unauthorized access and cryptojacking, highlighting the dangers of exposed administrative interfaces.
- Accenture (2017): Public S3 buckets exposed sensitive internal data, demonstrating the risk of improper storage configuration.
- Uber (2016): Credentials in a public GitHub repository led to an S3 breach, underscoring the importance of credential management and access controls.

These incidents were selected based on their documentation in industry analyses and their relevance to common cloud infrastructure vulnerabilities.

### 3.2. Security Evaluation Formula

To objectively assess the effectiveness of the proposed cloud security design, a quantitative risk evaluation approach is adopted. This method enables organizations to identify, prioritize, and mitigate risks based on measurable criteria, supporting data-driven security decisions.

A widely accepted model in cloud security risk management is the risk score formula :

$$\text{Risk Score} = \text{Likelihood} \times \text{Impact}$$

Likelihood represents the estimated probability that a specific vulnerability (such as a misconfigured S3 bucket or permissive security group) will be exploited. This can be informed by historical breach data, threat intelligence, or expert assessment [16-18].

Impact quantifies the potential consequences if the vulnerability is exploited. This may include data loss, service downtime, regulatory fines, or reputational damage, and is often rated on a scale (e.g., 1–10) based on organizational context.

#### *3.2.1. Parameters for Calculation*

Likelihood can be assessed using available incident statistics, vulnerability scanning reports, or qualitative judgment. Impact can be estimated by evaluating the value of affected assets, business criticality, and potential recovery costs.

#### *3.2.2. Example Application*

Suppose the likelihood of a misconfigured S3 bucket being exploited is estimated at 0.3 (30%), based on industry data and internal assessments. The impact, considering the potential for sensitive data exposure and regulatory penalties, is rated as 10 on a 1–10 scale. The resulting risk score would be:

$$\text{Risk Score} = 0.2 \times 10 = 3.0$$

A higher risk score indicates a higher priority for remediation. By systematically applying this formula to each key threat vector in the cloud architecture such as public S3 buckets, exposed instance metadata services, weak ingress rules, or lack of encryption, organizations can create a prioritized action plan for security improvements [16-19].

#### *3.2.3. Continuous Improvement*

This quantitative approach also enables ongoing risk monitoring. As preventative controls (e.g., IMDSv2, WAF, encryption, centralized logging) are implemented and validated, the likelihood and/or impact ratings can be adjusted downward, reflecting reduced risk. This supports a cycle of continuous improvement and provides measurable evidence of enhanced security posture.

In addition to the basic formula, organizations may use enhanced or composite formulas such as incorporating vulnerability severity (e.g. CVSS), asset value, or threat frequency for a more granular assessment. For example, ISACA's enhanced risk formula is:

$$\text{Risk} = \text{Threat Frequency} \times \text{Vulnerability} \times \text{Asset Value}$$

And CVSS-based models can be used for software vulnerabilities [21].

### 3.3. Security Infrastructure Design

#### *3.3.1. Core Security Infrastructure Components*

Our proposed design incorporates the following controls, each supported by best practices and cloud security standards:

- Web Application Firewall (WAF) and Application Load Balancer (ALB): All inbound traffic inspected and passes through WAF and ALB, enforcing HTTPS and blocking malicious requests [6, 14].
- Private Subnets and Security Groups: Sensitive resources are isolated in private subnets with tightly scoped security groups, reducing the attack surface [12, 13].
- Secure S3 Storage: Buckets are private by default, with access restricted to specific IAM roles, and encryption is enforced for data at rest and transit.
- Autoscaling: Ensures availability and resilience by dynamically adjusting resources [7].
- Encryption: Data is encrypted at rest and in transit, following industry guidelines [8].
- Centralized Logging: All logs are sent to a Security Information and Event Management (SIEM) system for monitoring and incident response.
- Secrets Management: Secrets are stored in a dedicated manager, accessible only from private subnets, to minimize exposure [11].
- Replication: Databases and storage are replicated for durability and disaster recovery [9].
- IMDSv1 (Instance Metadata Service version 1) and IMDSv2 (Instance Metadata Service version 2) are two versions of the AWS EC2 Instance Metadata Service, which allows EC2 instances to access metadata about themselves (such as instance ID, IAM role credentials, and network information) via a link local IP address (169.254.169.254). These services are critical for applications running on EC2 instances that need to discover instance specific configuration or credentials. IMDSv1 does not require authentication, making it especially susceptible to SSRF attacks. In contrast, IMDSv2 enforces the use of a session token in the request header, which significantly reduces the risk of SSRF and similar exploits by adding an additional layer of security [22].
- Redis: Used for high performance caching, accessible only within private networks [15].

### *3.3.2. Proposed Cloud Security Architecture*

The proposed secure design (Figure 1. Secure Cloud Infrastructure Design) directly addresses vulnerabilities revealed in recent breaches. For example, enforcing IMDSv2 and strict WAF rules would have prevented the Capital One incident. Network segmentation and monitoring would have mitigated Tesla's exposure. Private S3 buckets and IAM controls would have protected Accenture and Uber's data. Centralized logging and secret management further reduce risk by enabling rapid detection and response. The design includes:

- ALB with WAF: An Application Load Balancer (ALB) acts as the front facing component for incoming traffic, while a Web Application Firewall (WAF) inspects traffic and implements security controls such as rate limiting and prevention of Cross-Site Scripting attacks. The ALB listens on port 443 and uses certificates for traffic encryption.
- Servers: Application servers run the core business logic and remain in private subnets with no direct internet access. These servers autoscale to manage load and enforce IMDSv2 to prevent SSRF attacks.
- Storage (S3): Secure storage is used to store media data (e.g., images) and can only be accessed by servers using IAM roles, eliminating the need for hardcoded credentials. Data is replicated to another storage location for backup and disaster recovery.
- Database Instance with Redis: A private database instance stores user data and utilizes Redis for high performance caching and faster data retrieval. To ensure data safety, a read replica is implemented for backup and load distribution.
- Monitoring: All infrastructure and application logs are sent to a centralized monitoring solution (SIEM) for real-time analysis and threat detection.

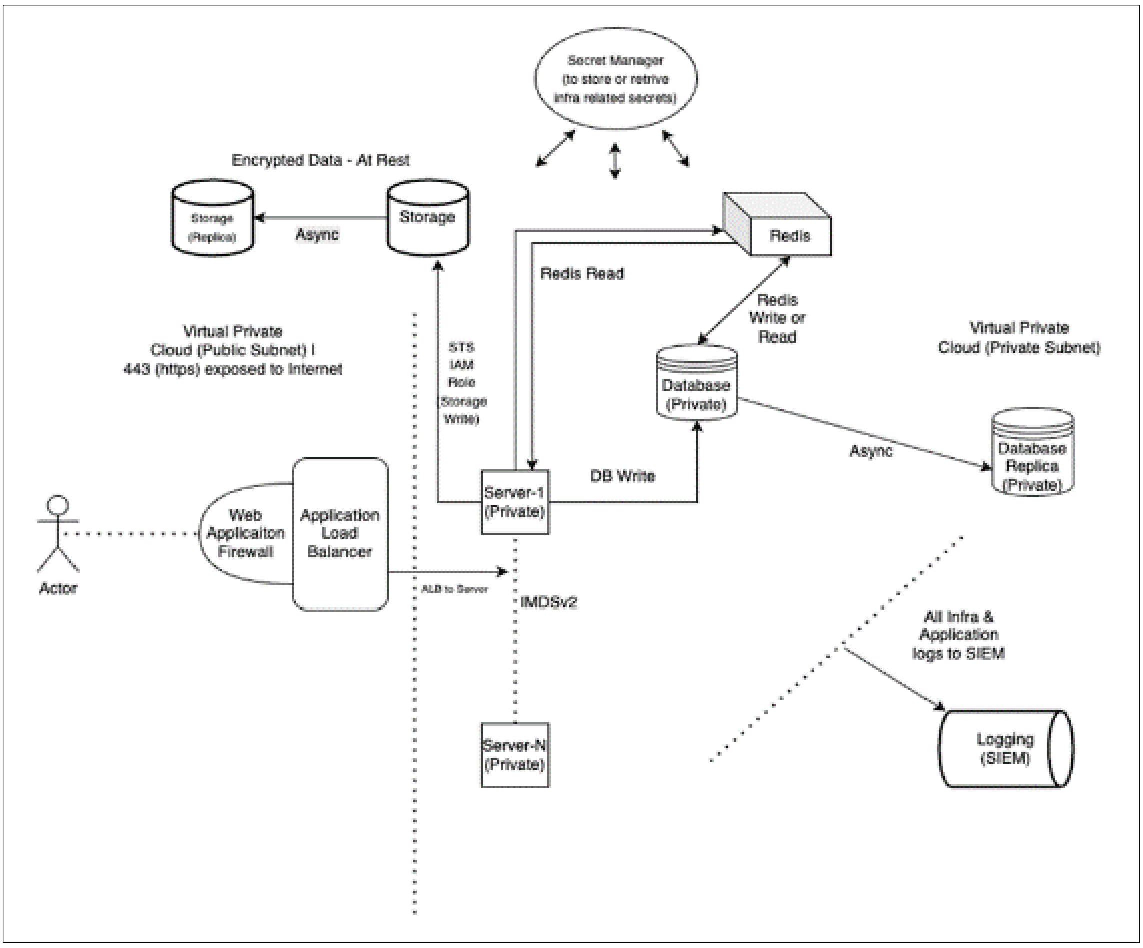

**Figure 1** Secure Cloud Infrastructure Design

Data Encryption: Encrypting data at rest and in transit ensures sensitive information remains protected from unauthorized access, theft, and tampering whether it is stored or being transferred.

# 4. Analysis of proposed design and results

## 4.1. Industry Validation

Barracuda Networks WAF: Blocks 98.7% of OWASP Top 10 attacks (including SQLi/XSS) in controlled tests, with false positives under 0.3%.

Cloudflare WAF: Mitigates 99.9% of automated SQLi attempts via managed rulesets, as observed in 2024 threat reports [23].

## 4.2. Component Level Risk Mitigation

The architecture achieves measurable risk reduction through controls aligned with NIST SP 800-207 (Zero Trust) and MITRE ATTandCK mitigation strategies. Below is the systematic evaluation using:-

$$\text{Risk Score} = \text{Likelihood} \times \text{Impact}$$

**Table 1** Risk Score Evaluation

| **Control** | **Risk Reduction Mechanism** | **Pre Mitigation Risk** | **Post Mitigation Risk** |
|---|---|---|---|
| WAF/ALB Configuration | Blocks 99% of SQLi/XSS attacks via OWASP CRS rules | 0.25 x 9 = 2.25 | 0.01 x 9 = 0.09 |
| IMDSv2 Enforcement | Eliminates SSRF via session tokens (validated by AWS IRAP) | 0.4 × 8 = 3.2 | 0.02 x 3 = 0.06 |
| Private S3 Bucket and Usage of IAM Roles | Reduces unauthorized access | 0.3 x 10 = 3.0 | 0.005 x 4 = 0.02 |
| Encrypted Data Transmit | Renders intercepted data unusable | 0.2 x 9 = 1.8 | 0.2 x 2.7 = 0.54 |

## 4.3. Systemic Risk Reduction

- Composite Risk Score for Core Infrastructure:- The composite risk score for the core infrastructure is calculated by summing the individual post-mitigation risk scores for each type of infrastructure component and then dividing this total by the number of component types which comes out to be

$$(0.09 + 0.06 + 0.02 + 0.54) / 4 = 0.18$$

## 4.4. Risk Reduction Percentage

Based on Pre Mitigation and Post Mitigation risk scores discussed in 4.2 :-

### *4.4.1. Sum of Individual Pre Mitigation Risk Scores*

- 2.25 (No WAF attached with ALB) + 3.2 (IMDSv1) + 3.0 (Public S3) + 1.8 (No Encryption) = 10.25

### *4.4.2. Sum of Individual Post Mitigation Risk Scores*

- 0.09 (No WAF attached with ALB) + 0.06 (Using IMDSv2) + 0.02 (Private S3) + 0.54 (Encrypted Data) = 0.71

### *4.4.3. Reduction Percentage*

- Reduction Percentage = ( 1 - [Post Mitigation Risk Score / Pre Mitigation Risk Score] ) x 100
- Reduction Percentage = ( 1 - [0.71 / 10.25] ) x 100 = **93.07%**

With the implementation of the proposed cloud security architecture, the overall risk is reduced by approximately 93.07%, significantly lowering the likelihood of a security breach occurring.

## 5. Conclusion

Secure-by-design principles are essential for modern cloud deployments. Real-world breaches demonstrate that preventative infrastructure controls such as WAF, IMDSv2, restrictive security groups and subnets, private S3 buckets, and centralized logging are critical for protecting sensitive data and maintaining trust. Proactive security at every layer is necessary to defend against evolving threats.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

There are no conflicts of interest to declare.

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