Security Review Report
NM-0452 King cross-chain

NETHERMIND
SECURITY

(Feb 14, 2025)

Contents

1 Executive Summary

This document presents the security review performed by Nethermind Security of the King Protocol. The review focused on the new cross-chain integration leveraging LayerZero to facilitate the efficient transfer of liquid restaking rewards across multiple chains.

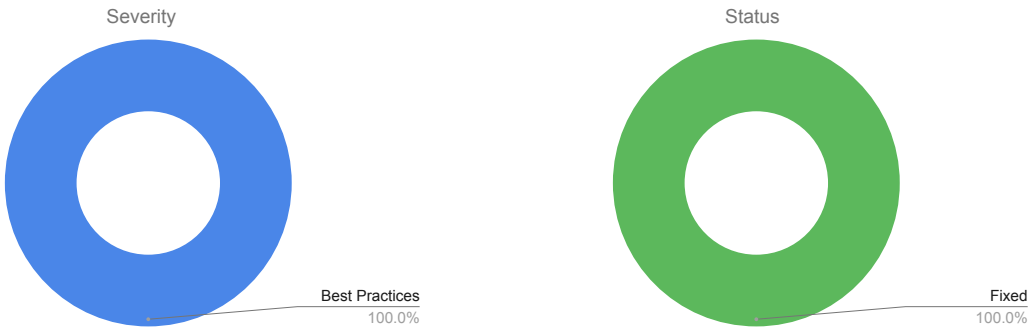
King Protocol introduces a standardized mechanism for consolidating and distributing rewards from Actively Validated Services (AVSs). In traditional liquid restaking token (LRT) systems, these rewards are fragmented across multiple protocols, making them costly and inefficient to claim. The protocol addresses this by aggregating AVS rewards into a unified vault, allowing LRTs to mint `KING` tokens as a representation of deposited assets. Users receive `KING` instead of multiple reward tokens, significantly simplifying distribution.

The new integration enables seamless bridging of `KING` between Ethereum mainnet and Swell Chain, a staking-focused Layer 2 built on the OP Stack. This approach reduces gas costs and streamlines the user experience by ensuring that rewards remain within the LRT ecosystem. Claims and redemptions are processed directly through each LRT protocol, maintaining efficiency and asset integrity.

The audited code comprises 224 lines of code written in the Solidity language. The audit focused on the new cross-chain integration of the King protocol.

The audit was performed using (a) manual analysis of the codebase, (b) automated analysis tools, and (c) creation of test cases. **Along this document, we report** three points of attention, all of which are classified as `Best Practice` severity. The issues are summarized in Fig. 1.

This document is organized as follows. Section 2 presents the files in the scope. Section 3 summarizes the issues. Section 4 presents the system overview. Section 5 discusses the risk rating methodology. Section 6 details the issues. Section 7 discusses the documentation provided by the client for this audit. Section 8 presents the test suite evaluation. Section 9 concludes the document.



(a) (b)

Fig. 1: Distribution of issues: Critical (0), **High** (0), **Medium** (0), **Low** (0), **Undetermined** (0), **Informational** (0), **Best Practices** (3). **Distribution of status: Fixed** (3), **Acknowledged** (0), **Mitigated** (0), **Unresolved** (0)

Summary of the Audit

Audit Type	Security Review
Initial Report	February 13, 2025
Final Report	February 14, 2025
Repository	king-cross-chain
Start Commit	c444200eed5dbe2548d9c6d6954a314ed5efa8b2
Final Commit	0afc4c01797848fd5bb9172dc659b42b97edd020
Documentation	Docs
Documentation Assessment	Medium
Test Suite Assessment	Low

2 Audited Files

The following table presents the files at the start of the audit, corresponding to commit c444200. During the audit, these files were renamed in commit 664b05d, but their content remained unchanged. For consistency, this security review report references the file names as they appeared in the initial commit.

Specifically, the following renames were made:

- `KingOFTAdapterUpgradeable.sol` → `KingOFTL1.sol`
- `KingOFTUpgradeable.sol` → `KingOFTL2.sol`
- `PairwiseRateLimiter.sol` remained unchanged.

The non-upgradeable `KingOFTAdapter.sol` has been removed entirely from the codebase.

	Contract	LoC	Comments	Ratio	Blank	Total
1	contracts/KingOFTAdapterUpgradeable.sol	51	17	33.3%	14	82
2	contracts/KingOFTAdapter.sol	11	1	9.1%	3	15
3	contracts/PairwiseRateLimiter.sol	94	91	96.8%	21	206
4	contracts/KingOFTUpgradeable.sol	68	27	39.7%	18	113
	Total	**224**	**136**	**60.7%**	**56**	**416**

3 Summary of Issues

	Finding	Severity	Update
1	Incorrect use of the `reinitializer` modifier in `initialize(...)`	Best Practices	Fixed
2	The `PairwiseRateLimiter` contract should reserve space for future state variable upgrades	Best Practices	Fixed
3	Unused imports	Best Practices	Fixed

4 System Overview

King Protocol introduces a standardized mechanism for handling liquid restaking rewards across multiple chains, leveraging LayerZero for seamless interoperability. The primary goal of the new cross-chain integration is to efficiently aggregate and distribute restaking rewards while minimizing transaction costs and user overhead.

4.1 Motivation and Problem Statement

Liquid Restaking Tokens (LRTs) allow users to stake assets while maintaining liquidity. However, rewards from Actively Validated Services (AVSs) accrue in small, fragmented amounts across various protocols, making them difficult and costly to claim. The King Protocol addresses this by consolidating these rewards into a unified vault, enabling users to claim proportional shares efficiently.

4.2 Architecture and Workflow

The protocol's key mechanism involves:

- LRT protocols consolidating AVS rewards and depositing them into the King vault.
- Minting King tokens (`KING`) as a representation of the deposited assets.
- Users receiving `KING` instead of multiple reward tokens, simplifying distribution.
- Bridging `KING` across chains, currently integrating with Swell, a staking-focused Layer 2 on the OP Stack.
- `KING` tokens can be burned on mainnet to receive the original AVS rewards.

4.3 Cross-Chain Functionality

The integration leverages LayerZero to enable:

- Bridging of `KING` between Ethereum mainnet and Swell Chain.
- Ensuring that claims and reward calculations remain within the LRT ecosystem.
- Redemption of `KING` solely on Ethereum mainnet to maintain protocol efficiency and asset integrity.

By centralizing reward aggregation and distribution while allowing selective cross-chain transfers, King Protocol enhances user experience and reduces fragmentation within the liquid restaking ecosystem.

5 Risk Rating Methodology

The risk rating methodology used by Nethermind Security follows the principles established by the OWASP Foundation. The severity of each finding is determined by two factors: **Likelihood** and **Impact**.

Likelihood measures how likely the finding is to be uncovered and exploited by an attacker. This factor will be one of the following values:

a) **High**: The issue is trivial to exploit and has no specific conditions that need to be met;

b) **Medium**: The issue is moderately complex and may have some conditions that need to be met;

c) **Low**: The issue is very complex and requires very specific conditions to be met.

When defining the likelihood of a finding, other factors are also considered. These can include but are not limited to motive, opportunity, exploit accessibility, ease of discovery, and ease of exploit.

Impact is a measure of the damage that may be caused if an attacker exploits the finding. This factor will be one of the following values:

a) **High**: The issue can cause significant damage, such as loss of funds or the protocol entering an unrecoverable state;

b) **Medium**: The issue can cause moderate damage, such as impacts that only affect a small group of users or only a particular part of the protocol;

c) **Low**: The issue can cause little to no damage, such as bugs that are easily recoverable or cause unexpected interactions that cause minor inconveniences.

When defining the impact of a finding, other factors are also considered. These can include but are not limited to Data/state integrity, loss of availability, financial loss, and reputation damage. After defining the likelihood and impact of an issue, the severity can be determined according to the table below.

		Severity Risk		
Impact	**High**	Medium	High	Critical
	Medium	Low	Medium	High
	Low	Info/Best Practices	Low	Medium
	Undetermined	Undetermined	Undetermined	Undetermined
		Low	**Medium**	**High**
		Likelihood		

To address issues that do not fit a High/Medium/Low severity, Nethermind Security also uses three more finding severities: **Informational**, **Best Practices**, and **Undetermined**.

a) **Informational** findings do not pose any risk to the application, but they carry some information that the audit team intends to pass to the client formally;

b) **Best Practice** findings are used when some piece of code does not conform with smart contract development best practices;

c) **Undetermined** findings are used when we cannot predict the impact or likelihood of the issue.

6 Issues

6.1 [Best Practices] Incorrect use of the `reinitializer` modifier in `initialize(...)`

File(s): `contracts/KingOFTAdapterUpgradeable.sol`

Description: The `initialize(...)` function in the `KingOFTAdapterUpgradeable` contract is responsible for initializing the state of an upgradeable contract. However, it incorrectly applies the `reinitializer(2)` modifier from OpenZeppelin's `Initializable` module. In an upgradeable contract's initial deployment, the `initializer` modifier should be used to ensure proper initialization. The `reinitializer` modifier is intended for use in subsequent upgrades where new storage variables are introduced. By setting `reinitializer(2)`, the contract mistakenly suggests that this is the second version, even though it is the first deployment. This could lead to issues in upgradeability and contract lifecycle management.

Recommendation(s): Consider replacing the `reinitializer(2)` with `initializer` to correctly handle the contract's first deployment.

Status: Fixed.

6.2 [Best Practices] The `PairwiseRateLimiter` contract should reserve space for future state variable upgrades

File(s): `contracts/PairwiseRateLimiter.sol`

Description: King Protocol's cross-chain contracts are upgradeable to support future code changes. However, the `PairwiseRateLimiter` contract, despite being used alongside other upgradeable contracts, does not account for potential state variable upgrades.

If new storage variables are added to `PairwiseRateLimiter` or other contracts, the storage layout could shift, leading to corruption. While this is not currently an issue due to other contracts using the EIP-7201 namespaced storage layout, best practices recommend adding a storage gap to any upgradeable contract to safeguard against future changes.

Recommendation(s): Consider introducing a `uint256[50] private __gap` variable in `PairwiseRateLimiter` to reserve space for future upgrades and maintain storage integrity.

Status: Fixed.

6.3 [Best Practices] Unused imports

File(s): `contracts/*`

Description: The codebase contains imports that are not utilized by the contracts:

- OpenZeppelin's `Ownable` in `KingOFTAdapter.sol`;
- OpenZeppelin's `Ownable` in `KingOFTUpgradeable.sol`;

Recommendation(s): Consider removing unused imports to make the codebase clean and maintainable.

Status: Fixed.

7 Documentation Evaluation

Software documentation refers to the written or visual information that describes the functionality, architecture, design, and implementation of software. It provides a comprehensive overview of the software system and helps users, developers, and stakeholders understand how the software works, how to use it, and how to maintain it. Software documentation can take different forms, such as user manuals, system manuals, technical specifications, requirements documents, design documents, and code comments. Software documentation is critical in software development, enabling effective communication between developers, testers, users, and other stakeholders. It helps to ensure that everyone involved in the development process has a shared understanding of the software system and its functionality. Moreover, software documentation can improve software maintenance by providing a clear and complete understanding of the software system, making it easier for developers to maintain, modify, and update the software over time. Smart contracts can use various types of software documentation. Some of the most common types include:

- Technical whitepaper: A technical whitepaper is a comprehensive document describing the smart contract's design and technical details. It includes information about the purpose of the contract, its architecture, its components, and how they interact with each other;
- User manual: A user manual is a document that provides information about how to use the smart contract. It includes step-by-step instructions on how to perform various tasks and explains the different features and functionalities of the contract;
- Code documentation: Code documentation is a document that provides details about the code of the smart contract. It includes information about the functions, variables, and classes used in the code, as well as explanations of how they work;
- API documentation: API documentation is a document that provides information about the API (Application Programming Interface) of the smart contract. It includes details about the methods, parameters, and responses that can be used to interact with the contract;
- Testing documentation: Testing documentation is a document that provides information about how the smart contract was tested. It includes details about the test cases that were used, the results of the tests, and any issues that were identified during testing;
- Audit documentation: Audit documentation includes reports, notes, and other materials related to the security audit of the smart contract. This type of documentation is critical in ensuring that the smart contract is secure and free from vulnerabilities.

These types of documentation are essential for smart contract development and maintenance. They help ensure that the contract is properly designed, implemented, and tested, and they provide a reference for developers who need to modify or maintain the contract in the future.

Remarks about the King Protocol documentation

The documentation for the King Protocol contracts was well-structured and provided through their official documentation, along with clear explanations during the kickoff call. The documentation offers a high-level overview of the protocol and its core mechanisms.
Additionally, the King Protocol team was highly responsive in addressing all questions and clarifications raised by the Nethermind Security team, ensuring a thorough understanding of the system's functionality. One key recommendation for improvement would be to include all necessary contextual information directly in NatSpec comments within the code. This would allow developers and auditors to understand the purpose of the code without requiring external documentation or prior discussions.

8 Test Suite Evaluation

The King protocols's test suite contains very few test cases for the new cross-chain functionality. The in-scope contracts could benefit from higher test coverage to clearly outline the contract's specifications. To assess the test coverage for these files, the Nethermind Security team applied a technique called mutation testing to uncover the untested paths. This technique introduces slight modifications to the code called "mutations" or "mutants." An example of a mutation is, for example, changing the operator in an expression `(a + b)` to `(a - b)`, or removing a `require(a > b)` statement entirely from the code. With these changes, the code no longer follows the expected business logic of the application, and the test suite should reflect that by failing.

Evaluation of the test suite with mutation testing consists of two phases:

a. Generating the modified version of each contract, called "mutants."

b. Inserting the mutant into the original codebase and running the test suite.

Only one modification can be tested at a time. If the contract has ten mutations, the test suite must run ten times (once for every mutation). If any of the tests fail, it means that the test suite caught the change in the code. Whenever that happens, the particular mutant is considered "slain" or "killed" and is removed from the mutant's set. If that does not occur, a new test case can be added to cover the code branch to "kill" the mutant.

The following table outlines the results of the analysis performed on the King's cross-chain smart contracts. The first column lists the contracts that were tested using mutation testing. The second column indicates the number of mutants generated and how many were "slain" (i.e., caught by the test suite). The third column provides the percentage of mutants slain, reflecting the effectiveness of the test suite in covering the particular contract. The higher the score, the better the test suite is at finding bugs.

Contract	Mutants (slain / total generated)	Score
`KingOFTL1.sol`	5 / 12	41.67%
`PairwiseRateLimiter.sol`	36 / 93	38.71%
`KingOFTL2.sol`	0 / 15	0%
Total	41 / 120	34.17%

Remarks about the King Protocol's test suite

The test suite for the King Protocol covers basic functionalities but is notably shallow. A significant portion of the contract, such as the `KingOFTL2.sol` file is not tested at all, leaving parts of the codebase unverified. Additionally, the overall result of the mutation testing is below the average for similar projects, indicating a gap in test coverage and effectiveness.
This shallow testing increases the likelihood of undetected issues in edge cases, as the suite fails to thoroughly validate state transitions and specific conditions within the contract. The lack of coverage for important functionalities poses a risk of subtle, hard-to-manually detect bugs making their way into production.
To improve the reliability of the King Protocol, it is essential to enhance the depth and breadth of the test suite. This includes adding tests for undertested contracts, expanding coverage for edge cases, and ensuring that all significant code paths are properly exercised. Incorporating mutation testing would also help identify areas of weakness by introducing small code changes and checking whether the existing tests can detect them. This approach would provide valuable insights into the effectiveness of the current test suite and guide improvements in coverage.

8.1 Automated Tools

8.1.1 AuditAgent

All the relevant issues raised by the AuditAgent have been incorporated into this report. The AuditAgent is an AI-powered smart contract auditing tool that analyses code, detects vulnerabilities, and provides actionable fixes. It accelerates the security analysis process, complementing human expertise with advanced AI models to deliver efficient and comprehensive smart contract audits. Available at https://app.auditagent.nethermind.io.

9 About Nethermind

Nethermind is a Blockchain Research and Software Engineering company. Our work touches every part of the web3 ecosystem - from layer 1 and layer 2 engineering, cryptography research, and security to application-layer protocol development. We offer strategic support to our institutional and enterprise partners across the blockchain, digital assets, and DeFi sectors, guiding them through all stages of the research and development process, from initial concepts to successful implementation.

We offer security audits of projects built on EVM-compatible chains and Starknet. We are active builders of the Starknet ecosystem, delivering a node implementation, a block explorer, a Solidity-to-Cairo transpiler, and formal verification tooling. Nethermind also provides strategic support to our institutional and enterprise partners in blockchain, digital assets, and decentralized finance (DeFi). In the next paragraphs, we introduce the company in more detail.

Blockchain Security: At Nethermind, we believe security is vital to the health and longevity of the entire Web3 ecosystem. We provide security services related to Smart Contract Audits, Formal Verification, and Real-Time Monitoring. Our Security Team comprises blockchain security experts in each field, often collaborating to produce comprehensive and robust security solutions. The team has a strong academic background, can apply state-of-the-art techniques, and is experienced in analyzing cutting-edge Solidity and Cairo smart contracts, such as ArgentX and StarkGate (the bridge connecting Ethereum and StarkNet). Most team members hold a Ph.D. degree and actively participate in the research community, accounting for 240+ articles published and 1,450+ citations in Google Scholar. The security team adopts customer-oriented and interactive processes where clients are involved in all stages of the work.

Blockchain Core Development: Our core engineering team, consisting of over 20 developers, maintains, improves, and upgrades our flagship product - the Nethermind Ethereum Execution Client. The client has been successfully operating for several years, supporting both the Ethereum Mainnet and its testnets, and now accounts for nearly a quarter of all synced Mainnet nodes. Our unwavering commitment to Ethereum's growth and stability extends to sidechains and layer 2 solutions. Notably, we were the sole execution layer client to facilitate Gnosis Chain's Merge, transitioning from Aura to Proof of Stake (PoS), and we are actively developing a full-node client to bolster Starknet's decentralization efforts. Our core team equips partners with tools for seamless node set-up, using generated docker-compose scripts tailored to their chosen execution client and preferred configurations for various network types.

DevOps and Infrastructure Management: Our infrastructure team ensures our partners' systems operate securely, reliably, and efficiently. We provide infrastructure design, deployment, monitoring, maintenance, and troubleshooting support, allowing you to focus on your core business operations. Boasting extensive expertise in Blockchain as a Service, private blockchain implementations, and node management, our infrastructure and DevOps engineers are proficient with major cloud solution providers and can host applications in-house or on clients' premises. Our global in-house SRE teams offer 24/7 monitoring and alerts for both infrastructure and application levels. We manage over 5,000 public and private validators and maintain nodes on major public blockchains such as Polygon, Gnosis, Solana, Cosmos, Near, Avalanche, Polkadot, Aptos, and StarkWare L2. Sedge is an open-source tool developed by our infrastructure experts, designed to simplify the complex process of setting up a proof-of-stake (PoS) network or chain validator. Sedge generates docker-compose scripts for the entire validator set-up based on the chosen client, making the process easier and quicker while following best practices to avoid downtime and being slashed.

Cryptography Research: At Nethermind, our Cryptography Research team is dedicated to continuous internal research while fostering close collaboration with external partners. The team has expertise across a wide range of domains, including cryptography protocols, consensus design, decentralized identity, verifiable credentials, Sybil resistance, oracles, and credentials, distributed validator technology (DVT), and Zero-knowledge proofs. This diverse skill set, combined with strong collaboration between our engineering teams, enables us to deliver cutting-edge solutions to our partners and clients.

Smart Contract Development & DeFi Research: Our smart contract development and DeFi research team comprises 40+ world-class engineers who collaborate closely with partners to identify needs and work on value-adding projects. The team specializes in Solidity and Cairo development, architecture design, and DeFi solutions, including DEXs, AMMs, structured products, derivatives, and money market protocols, as well as ERC20, 721, and 1155 token design. Our research and data analytics focuses on three key areas: technical due diligence, market research, and DeFi research. Utilizing a data-driven approach, we offer in-depth insights and outlooks on various industry themes.

Our suite of L2 tooling: Warp is Starknet's approach to EVM compatibility. It allows developers to take their Solidity smart contracts and transpile them to Cairo, Starknet's smart contract language. In the short time since its inception, the project has accomplished many achievements, including successfully transpiling Uniswap v3 onto Starknet using Warp.

- **Voyager** is a user-friendly Starknet block explorer that offers comprehensive insights into the Starknet network. With its intuitive interface and powerful features, Voyager allows users to easily search for and examine transactions, addresses, and contract details. As an essential tool for navigating the Starknet ecosystem, Voyager is the go-to solution for users seeking in-depth information and analysis;
- **Horus** is an open-source formal verification tool for StarkNet smart contracts. It simplifies the process of formally verifying Starknet smart contracts, allowing developers to express various assertions about the behavior of their code using a simple assertion language;
- **Juno** is a full-node client implementation for Starknet, drawing on the expertise gained from developing the Nethermind Client. Written in Golang and open-sourced from the outset, Juno verifies the validity of the data received from Starknet by comparing it to proofs retrieved from Ethereum, thus maintaining the integrity and security of the entire ecosystem.

Learn more about us at nethermind.io.

General Advisory to Clients

As auditors, we recommend that any changes or updates made to the audited codebase undergo a re-audit or security review to address potential vulnerabilities or risks introduced by the modifications. By conducting a re-audit or security review of the modified codebase, you can significantly enhance the overall security of your system and reduce the likelihood of exploitation. However, we do not possess the authority or right to impose obligations or restrictions on our clients regarding codebase updates, modifications, or subsequent audits. Accordingly, the decision to seek a re-audit or security review lies solely with you.

Disclaimer

This report is based on the scope of materials and documentation provided by you to Nethermind in order that Nethermind could conduct the security review outlined in **1. Executive Summary** and **2. Audited Files**. The results set out in this report may not be complete nor inclusive of all vulnerabilities. Nethermind has provided the review and this report on an as-is, where-is, and as-available basis. You agree that your access and/or use, including but not limited to any associated services, products, protocols, platforms, content, and materials, will be at your sole risk. Blockchain technology remains under development and is subject to unknown risks and flaws. The review does not extend to the compiler layer, or any other areas beyond the programming language, or other programming aspects that could present security risks. This report does not indicate the endorsement of any particular project or team, nor guarantee its security. No third party should rely on this report in any way, including for the purpose of making any decisions to buy or sell a product, service or any other asset. To the fullest extent permitted by law, Nethermind disclaims any liability in connection with this report, its content, and any related services and products and your use thereof, including, without limitation, the implied warranties of merchantability, fitness for a particular purpose, and non-infringement. Nethermind does not warrant, endorse, guarantee, or assume responsibility for any product or service advertised or offered by a third party through the product, any open source or third-party software, code, libraries, materials, or information linked to, called by, referenced by or accessible through the report, its content, and the related services and products, any hyperlinked websites, any websites or mobile applications appearing on any advertising, and Nethermind will not be a party to or in any way be responsible for monitoring any transaction between you and any third-party providers of products or services. As with the purchase or use of a product or service through any medium or in any environment, you should use your best judgment and exercise caution where appropriate. FOR AVOIDANCE OF DOUBT, THE REPORT, ITS CONTENT, ACCESS, AND/OR USAGE THEREOF, INCLUDING ANY ASSOCIATED SERVICES OR MATERIALS, SHALL NOT BE CONSIDERED OR RELIED UPON AS ANY FORM OF FINANCIAL, INVESTMENT, TAX, LEGAL, REGULATORY, OR OTHER ADVICE.