Micron® 9200 MAX NVMe™ SSDs + Red Hat® Ceph Storage 3.0

Reference Architecture

Contents

Executive Summary

This document describes an example configuration of a performance-optimized Red Hat® Ceph Storage cluster using Micron® SSDs with NVMe™, standard x86 architecture rack-mount servers and 100 GbE networking.

It details the hardware and software building blocks used to construct this reference architecture (including the Red Hat Enterprise Linux OS configuration, network switch configurations and Ceph tuning parameters) and shows the performance test results and measurement techniques for a scalable 4-node Ceph architecture.

This all-NVMe solution is optimized for block performance while also providing very high object performance in a compact, rack-efficient design to enable:

Faster deployment: The configuration has been pre-validated and is thoroughly documented to enable faster deployment.

Balanced design: The right combination of NVMe SSDs, DRAM, processors and networking ensures subsystems are balanced and performance-matched.

Broad use: Complete tuning and performance characterization across multiple IO profiles for broad deployment across multiple uses.

Exceptional performance results were recorded for 4KB random block workloads and 4MB object workloads.

4KB Random Block Performance		
IO Profile	IOPS	Ave. Latency
100% Read	1,955,599	0.8 ms
70%/30% R/W	781,002	3.6 ms
100% Writes	367,011	6.1 ms

4MB Object Performance		
IO Profile	GB/s	Ave. Latency
100% Read	30	44 ms
70%/30% R/W	—	—
100% Writes	10.3	50 ms

Tables 1a and 1b: Performance Summary

Note: The entry "—" in Table 1 indicates this performance metric is not commonly used with this performance profile; therefore, it was not measured.

Why Micron for this Solution

Storage (SSDs and DRAM) represent a large portion of the value of today's advanced server/storage solutions. Micron's storage expertise starts at memory technology research, innovation and design and extends through collaborating with customers on total data solutions. Micron develops and manufactures the storage and memory products that go into the enterprise solutions we architect.

Micron's Reference Architectures

Micron Reference Architectures are optimized, pre-engineered, enterprise-leading solution templates for platforms co-developed between Micron and industry leading hardware and software companies.

Designed and tested at Micron's Storage Solutions Center, they provide end users, system builders, independent software vendors (ISVs) and OEMs with a proven template to build next-generation solutions with reduced time investment and risk.

Ceph Distributed Architecture Overview

A Ceph storage cluster is frequently built from large numbers of Ceph nodes for scalability, fault-tolerance, and performance. Each node is based on industry standard hardware and uses intelligent Ceph daemons that communicate with each other to:

- Store, retrieve and replicate data
- Monitor and report on cluster health
- Redistribute data dynamically (remap and backfill)
- Ensure data integrity (scrubbing)
- Detect and recover from faults and failures

To the Ceph client interface that reads and writes data, a Ceph storage cluster looks like a simple pool where data is stored. However, the storage cluster performs many complex operations in a manner that is completely transparent to the client interface. Ceph clients and Ceph Object Storage Daemons (Ceph OSD daemons, or OSDs) both use the Controlled Replication Under Scalable Hashing (CRUSH) algorithm for storage and retrieval of objects.

For a Ceph client, the storage cluster is very simple. When a Ceph client reads or writes data (referred to as an I/O context), it connects to a logical storage pool in the Ceph cluster. The figure below illustrates the overall Ceph architecture, with concepts that are described in the sections that follow.

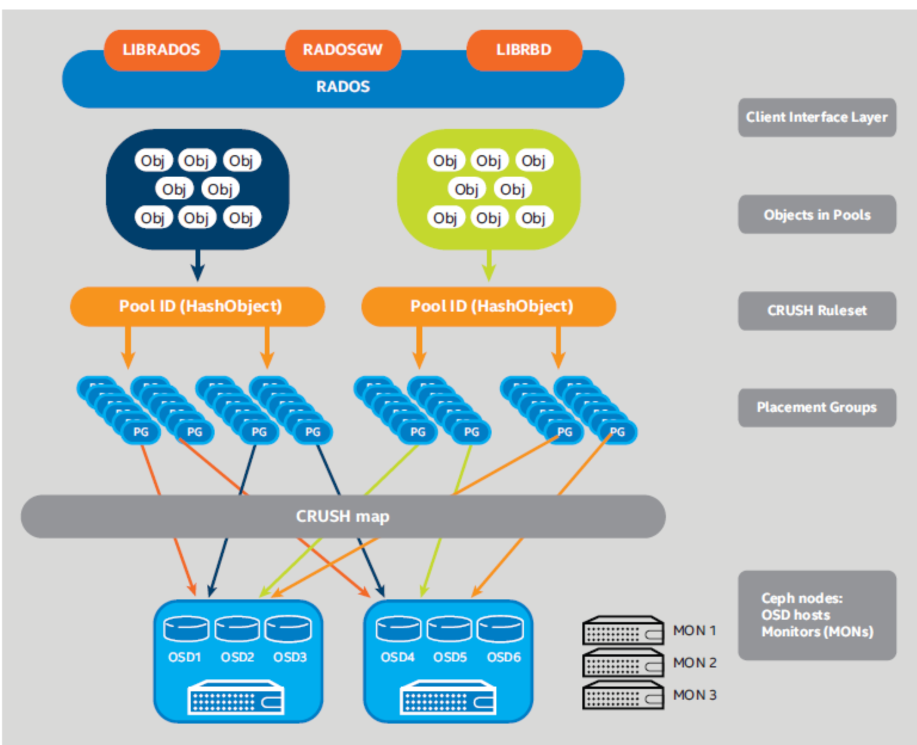


Figure 1: Ceph Architecture

Clients write to Ceph storage pools while the CRUSH ruleset determines how placement groups are distributed across object storage daemons (OSDs).

- **Pools:** A Ceph storage cluster stores data objects in logical dynamic partitions called pools. Pools can be created for particular data types, such as for block devices, object gateways, or simply to separate user groups. The Ceph pool configuration dictates the number of object replicas and the number of placement groups (PGs) in the pool. Ceph storage pools can be either replicated or erasure coded, as appropriate for the application and cost model. Additionally, pools can "take root" at any position in the CRUSH hierarchy, allowing placement on groups of servers with differing performance characteristics—allowing storage to be optimized for different workloads.

- **Placement groups:** Ceph maps objects to placement groups (PGs). PGs are shards or fragments of a logical object pool that are composed of a group of Ceph OSD daemons that are in a peering relationship. Placement groups provide a means of creating replication or erasure coding groups of coarser granularity than on a per object basis. A larger number of placement groups (e.g., 200 per OSD or more) leads to better balancing.

- **CRUSH ruleset:** The CRUSH algorithm provides controlled, scalable, and declustered placement of replicated or erasure-coded data within Ceph and determines how to store and retrieve data by computing data storage locations. CRUSH empowers Ceph clients to communicate with OSDs directly, rather than through a centralized server or broker. By determining a method of storing and retrieving data by an algorithm, Ceph avoids a single point of failure, a performance bottleneck, and a physical limit to scalability.

- **Ceph monitors (MONs):** Before Ceph clients can read or write data, they must contact a Ceph MON to obtain the current cluster map. A Ceph storage cluster can operate with a single monitor, but this introduces a single point of failure. For added reliability and fault tolerance, Ceph supports an odd number of monitors in a quorum (typically three or five for small to mid-sized clusters). Consensus among various monitor instances ensures consistent knowledge about the state of the cluster.

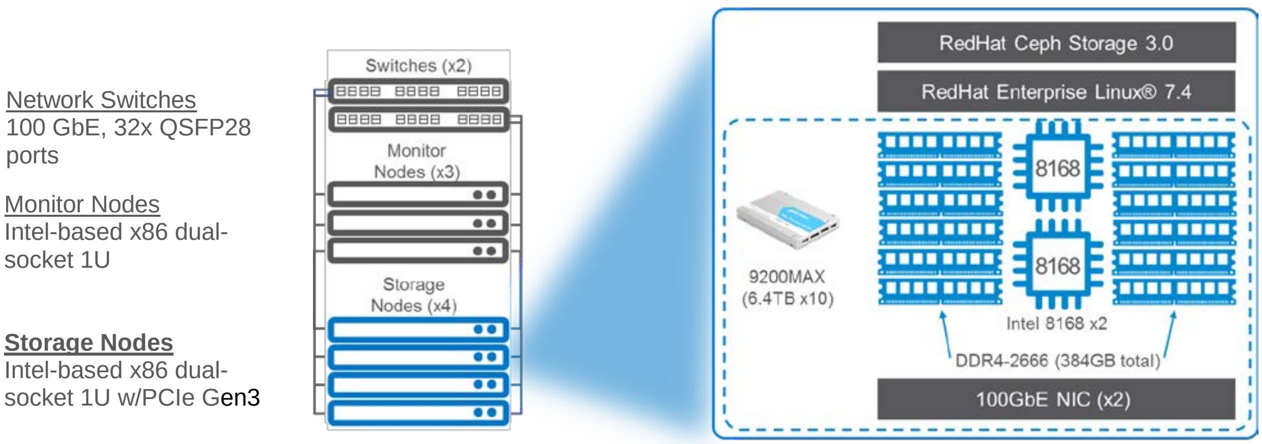
- **Ceph OSD daemons:** In a Ceph cluster, Ceph OSD daemons store data and handle data replication, recovery, backfilling, and rebalancing. They also provide some cluster state information to Ceph monitors by checking other Ceph OSD daemons with a heartbeat mechanism. A Ceph storage cluster configured to keep three replicas of every object requires a minimum of three Ceph OSD daemons, two of which need to be operational to successfully process write requests. Ceph OSD daemons roughly correspond to a file system on a physical hard disk drive.

Reference Architecture Overview

This reference architecture (RA) is based on the Intel® Purley platform with Xeon® 8168 processors. This combination provides the high CPU performance required for a performance-optimized Ceph cluster and yields an open, cost-effective software-defined storage (SDS) platform. This platform can be utilized as an effective building block for implementing a multi-petabyte OpenStack® cloud infrastructure.

The Micron 9200 MAX NVMe SSDs used in this RA offer tremendous performance with low latencies. Capacity per rack unit is maximized with 10 6.4TB NVMe SSDs per 1U storage node. This entire RA takes up seven rack units (including three monitor nodes) and can be easily scaled up 1U and 64TB at a time.

Network throughput is handled by two separate Mellanox® ConnectX®-5 100 GbE network cards per storage node—one for the client network and another for the internal Ceph replication network. Clients and monitor nodes are connected to the client network via Mellanox ConnectX-4 50 GbE networking.



RA Layout *Storage Node Details*

Figure 2: Micron NVMe RA Design

Software

Red Hat Ceph Storage 3.0

Red Hat collaborates with the global open source Ceph community to develop new Ceph features, then packages changes into predictable, stable, enterprise-quality releases. Red Hat Ceph Storage 3.0 is based on the Ceph community 'Luminous' version 12.2.1, to which Red Hat was a leading code contributor.

As a self-healing, self-managing, unified storage platform with no single point of failure, Red Hat Ceph Storage decouples software from hardware to support block, object, and file storage on standard servers, HDDs and SSDs, significantly lowering the cost of storing enterprise data. Red Hat Ceph Storage is tightly integrated with OpenStack services, including Nova, Cinder, Manila, Glance, Keystone, and Swift, and it offers user-driven storage lifecycle management. Voted the number 1 storage option in a 2015 OpenStack user survey, the product's highly tunable, extensible, and configurable architecture offers mature interfaces for enterprise block and object storage, making it well suited for archival, rich media, and cloud infrastructure environments.

Among many of its features, Red Hat Ceph Storage 3 provides the following advantages to this RA:

- Block storage integrated with OpenStack, Linux and KVM hypervisor
- Data durability via erasure coding or replication
- Red Hat Ansible® automation-based deployment
- Advanced Ceph monitoring and diagnostic information with an on-premise monitoring dashboard
- Graphical visualization of the entire cluster or single components
  - with cluster and per-node usage
  - and performance statistics
- Availability of service level agreement (SLA)-backed technical support
- Red Hat Enterprise Linux (included with subscription) and the backing of a global open source community

Red Hat Enterprise Linux 7.4

Red Hat® Enterprise Linux® (RHEL) is a high-performing operating system that has been deployed in IT environments for more than a decade.

Red Hat Enterprise Linux 7.4 is noted for its enterprise-level performance, reliability, and security as well as its broad use (it is certified by leading hardware and software vendors), broad scalability (from workstations, to servers, to mainframes) and consistent application environment across physical, virtual, and cloud deployments.

Software by Node Type

Table 2 shows the software and version numbers used in the Ceph Monitor and Storage Nodes.

Operating System	Red Hat Enterprise Linux 7.4
Storage	Red Hat Ceph Storage 3.0: Luminous 12.2.1
NIC Driver	Mellanox OFED Driver 4.1.1

Table 2: Ceph Storage and Monitor Nodes: Software

Table 3 shows the software and version numbers for the Ceph Load Generation Servers. Note that the Load Generation server software stack is very similar to the Storage Node software stack.

Operating System	Red Hat Enterprise Linux 7.4
Storage	Red Hat Ceph Storage 3.0 Client: Luminous 12.2.1
NIC Driver	FIO 3.0 w/ librbd enabled
	Mellanox OFED Driver 4.1.1

Table 3: Ceph Load Generation Nodes: Software

Hardware

This RA uses standard 1U, x86 architecture platforms each housing up to 10 NVMe SSDs (U.2 form factor) with additional storage for local operating systems.

Ceph Storage Node

We chose Supermicro's latest SuperServer product line SYS-1029U-TN10RT servers because they are built with compelling NVMe capacity in a compact form factor. Designed to deliver performance, flexibility, scalability, and serviceability, the servers are well suited for demanding enterprise workloads.

Performance: The SYS-1029U-TN10RT server platform features powerful dual Intel Xeon Platinum 81xx CPUs (165W/ 28 cores) and up to 3TB of memory in 24 DIMMs, NVMe support for increased storage bandwidth, and energy efficient titanium-level (96%+) power supplies.

Flexibility: SYS-1029U-TN10RT enables enterprise IT professionals to easily use a single server platform that can be configured for a wide variety of workloads, reducing qualification time and the need for excessive spare inventories to manage.

Scalability: SYS-1029U-TN10RT is highly scalable and provides extreme expansion density for a 1U/2U system. Supporting up to four add-on cards in 1U, SYS-1029 offers the flexibility to support an ever-changing set of business needs.

Serviceability: Supermicro's remote management software packages make monitoring infrastructure simple and effective.

Figure 3: Supermicro Ultra Server SYS-1029U-TNRT

Server Type	x86 (dual-socket) 1U with PCIe Gen 3 (“Purley”)
Model	Supermicro SuperServer 1029U-TN10RT
CPU (x2)	Intel Xeon 8168: 24 cores, 48 threads, 2.7 GHz base (3.7 GHz turbo)
DRAM (x12)	Micron 32GB DDR4-2666 MT/s, 384GB total per node
NVMe (x10)	Micron 9200 MAX NVMe SSDs, 6.4TB each
SATA (OS)	Micron 5100 SATA SSD
Network	2x Mellanox ConnectX-5 100 GbE dual-port (MCX516A-CCAT)

Table 4: Storage Nodes Hardware Details

Ceph Monitor Node

Server Type	x86 (dual-socket) 1U with PCIe Gen 3 ("Broadwell")
Model	Supermicro SuperServer 1028U
CPU (x2)	2x Intel Xeon 2690v4: 14 cores, 28 threads, 2.6 GHz base (3.5 GHz turbo)
DRAM (x8)	Micron 16GB DDR4-2400 MT/s, 128GB total per node
SATA (OS)	Micron 5100 SATA SSD
Network	1x Mellanox ConnectX-4 50GbE single-port (MC4X413A-GCAT)

Table 5: Monitor Nodes Hardware Details

Micron 9200 MAX NVMe SSDs

The Micron 9200 series of NVMe SSDs is our flagship performance family and our second generation of NVMe SSDs. The 9200 family has the right capacity for demanding workloads, with capacities from 1.6TB to 11TB in write-intensive, mixed-use and read-intensive designs.

Model	9200 MAX	Interface	PCIe Gen 3 x4
Form Factor	1.6TB	Capacity	6.4TB
NAND	Micron® 3D TLC	MTTF	2M device hours
Sequential Read	3.35 GB/s	Random Read	800,000 IOPS
Sequential Write	2.4 GB/s	Random Write	260,000 IOPS
Endurance	35.1PB	Status	Production

Table 6: 9200 MAX 6.4TB Specifications Summary

Note: GB/s measured using 128K transfers, IOPS measured using 4K transfers. All data is steady state. Complete MTTF details are available in the product data sheet.

Network Switches

We used two 100 GbE switches (32x QSFP28 ports each) — one for the client network and one for the Ceph Storage network (these switches are based on the Broadcom "Tomahawk" switch chip).

Model	Supermicro SSE-C3632SR
Software	Cumulus Linux 3.4.2

Table 7: Network Switches (Hardware and Software)

The SSE-C3632S Layer 2/3 Ethernet Switch is the latest entry from Supermicro in the Open Networking arena. Open Networking provides customers with the ability to maximize the efficient and flexible use of valuable data center resources, while providing an ideal platform for managing and maintaining those resources in a manner in tune with the needs of the organization.

Offering 32 Ethernet ports at 40 Gbps/100 Gbps, the SSE-C3632S switch enables robust layer-3 IP fabric for flexible layer-2 overlay in Ethernet fabric architecture. For modern scale-out, leaf-and-spine data center network deployments, the SSE-C3632S is positioned as the high-speed spine layer to provide scalable bisectional fabric bandwidth for leaf layer such as the SSE-X3648S switch.

Depending on deployment connectivity, physical Ethernet QSFP28 ports in the SSE-C3632S can be configured for either 40 Gbps or 100 Gbps per port, thus enabling a flexible physical connectivity option between the spine layer and leaf layer in the datacenter Ethernet fabric.

The compact 1U form factor gives users the ability to optimize deployment in standalone or top-of-rack environments. A rail kit facilitates rack-mounting installations. These switches are ideal for deployment in datacenter, cloud and enterprise environments with the capability of handling access for the most demanding applications.

Mellanox ConnectX®-5 EN Dual Port NICs

The ConnectX-5 EN Network Controller with two ports of 100 Gb/s Ethernet connectivity and advanced offload capabilities delivers high bandwidth, low latency and high computation efficiency for high-performance, data-intensive and scalable HPC, cloud, data analytics, database and storage platforms.

Planning Considerations

Number of Ceph Storage Nodes

At least three storage nodes must be present in a Ceph cluster to become eligible for Red Hat technical support. Ten storage nodes are the recommended scale for an enterprise Ceph cluster. Four storage nodes represent a valid building block to use for scaling up to larger deployments. This RA uses four storage nodes.

Number of Ceph Monitor Nodes

At least three monitor nodes should be configured on separate hardware. These nodes do not require high-performance CPUs. They do benefit from having SSDs to store the monitor map data. One monitor node is the minimum, but three or more monitor nodes are typically used in production deployments.

Replication Factor

NVMe SSDs have high reliability with high MTBR and low bit error rate. 2x replication is recommended in production when deploying OSDs on NVMe versus the 3x replication common with legacy storage.

CPU Sizing

Ceph OSD processes can consume large amounts of CPU while doing small block operations. Consequently, a higher CPU core count generally results in higher performance for I/O-intensive workloads. For throughput-intensive workloads characterized by large sequential I/O, Ceph performance is more likely to be bound by the maximum network bandwidth of the cluster.

Ceph Configuration Tuning

Tuning Ceph for NVMe devices can be complex. The ceph.conf settings used in this RA are optimized for small block random performance and are included in Appendix A.

Networking

A 25 GbE network is required to leverage the maximum block performance benefits of a NVMe-based Ceph cluster. For throughput-intensive workloads, 50 GbE to 100 GbE is recommended

Two OSDs per 9200 MAX SSD greatly reduce tail latency for 4KB random writes. It also improves 4KB random write IOPS at higher queue depths.

Number of OSDs per Drive

To reduce tail latency in 4KB write transfers, it is recommended to run more than one OSD per drive for NVMe SSDs. Testing with one OSD per drive yields good performance that is roughly equivalent to the performance seen when using two OSDs per drive, from an IOPS and average latency standpoint. However, running two OSDs per NVMe SSD provides **greatly** reduced tail latency for 4KB random writes, as seen in Figure 4.

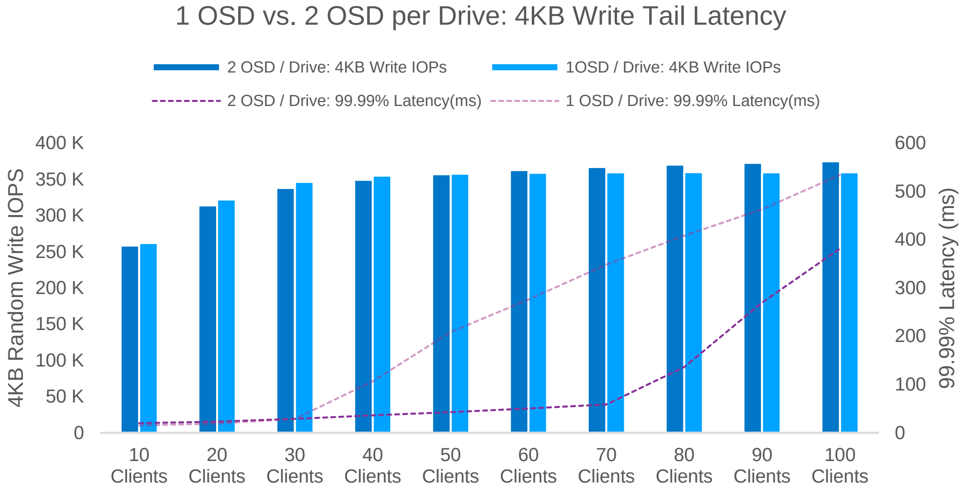


Figure 4: Number of OSDs and Write Tail Latency

Figure 5 shows using two OSDs per drive also increased 4KB random read IOPS at higher queue depths.

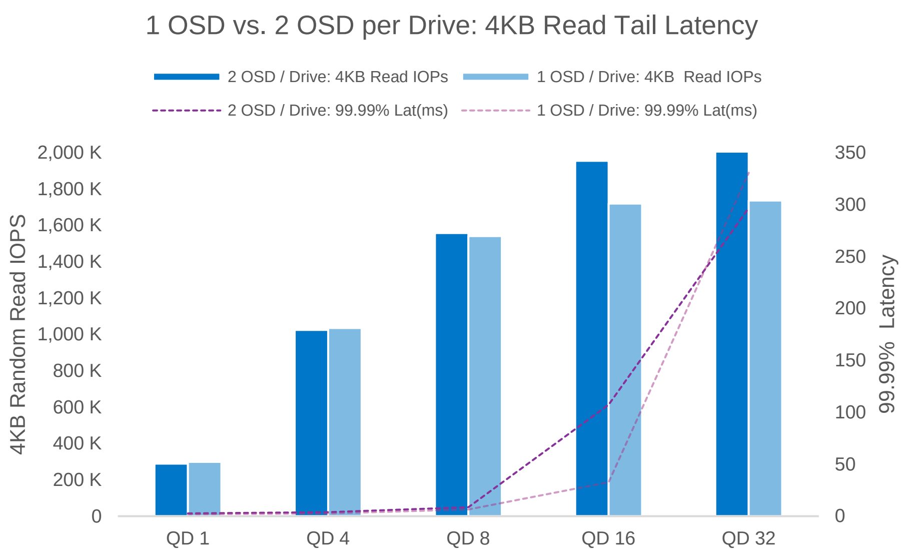


Figure 5: OSDs and Read Tail Latency

For this RA, two OSDs per NVMe device is recommended. The method used for deploying two OSDs per drive is included in Appendix A.

OS Tuning/NUMA

OS tuning parameters are deployed by Ceph-Ansible. The following OS settings were used:

```
disable_transparent_hugepage: true
kernel.pid_max, value: 4,194,303
fs.file-max, value: 26,234,859
vm.zone_reclaim_mode, value: 0
vm.swappiness, value: 1
vm.min_free_kbytes, value: 1,000,000
net.core.rmem_max, value: 268,435,456
net.core.wmem_max, value: 268,435,456
net.ipv4.tcp_rmem, value: 4096 87,380 134,217,728
net.ipv4.tcp_wmem, value: 4096 65,536 134,217,728
ceph_tcmalloc_max_total_thread_cache: 134,217,728
```

NUMA tuning was not used during testing due to the unbalanced nature of the servers used—four NVMe devices and both NICs go to CPU 1 and the other six NVMe devices are on CPU 2. Irqbalance was active for all tests and did a reasonable job balancing across CPUs.

Measuring Performance

4KB Random Workloads: FIO + RBD

4KB random workloads were tested using the FIO synthetic IO generation tool and the Ceph RADOS Block Device (RBD) driver.

100 RBD images were created at the start of testing. When testing on a 2x replicated pool, the RBD images were 75GB each (7.5TB of data); on a 2x replicated pool, that equals 15TB of total data stored. When testing on a 3x replicated pool, the RBD images were 50GB each (5TB of data); on a 3x pool, that also equals 15TB of total data stored. The four storage nodes have a combined total of 1.5TB of DRAM, which is 10% of the dataset size.

4KB random writes were measured by scaling up the number of FIO clients running load against Ceph at a fixed queue depth of 32. A client in this case is a single instance of FIO running on a load generation server. Using a queue depth of 32 simulates a reasonably active RDB image consumer and allows our tests to scale up to a high client count. The number of clients was scaled from 10 clients up to 100 clients. 10 load generation servers were used in testing with an equal number of FIO instances on each.

4KB random reads and 70/30 read/write tests were measured by using all 100 RBD images, scaling up the queue depth per FIO client from 1 to 32. It is important to use all 100 clients for reads so that the entire 15TB dataset is being accessed; otherwise, Linux filesystem caching can skew results higher.

Each test was run three times for 10 minutes with a two-minute ramp up time. Linux filesystem caches were cleared between each test. The results reported are the averages across all test runs.

4MB Object Workloads: RADOS Bench

RADOS Bench is a built-in tool for measuring object performance. It represents the best-case object performance scenario of data coming directly to Ceph from a RADOS Gateway node.

4MB object writes were measured by running RADOS Bench with a “threads” value of 16 on a load generation server writing directly to a Ceph storage pool. The number of load generation servers scaled up from 2 to 10.

4MB object reads were measured by first writing 15TB of data into a 2x or 3x replicated pool using 20 RADOS Bench instances. Once the data load was complete, all 20 RADOS Bench instances were used to run 4MB object reads against the storage pool. The thread count of RADOS Bench scaled up from 4 threads to 32 threads.

Object workload tests were run for 10 minutes, three times each. Linux filesystem caches were cleared between each test. The results reported are the averages across all test runs.

Baseline Test Methodology

Storage and network performance were baseline tested (tested without Ceph software to determine the theoretical hardware performance maximums) with FIO and iPerf.

- Storage testing was done with one locally run FIO command test across all 10 NVMe drives simultaneously.
- Network testing used two concurrent iperf3 tests (details provided below).

Storage Baseline Results

Each storage node was tested using FIO across all 10 9200 MAX 6.4TB NVMe SSDs. 4KB random writes were measured with 20 jobs at a queue depth of 4. 4KB random reads were measured with 50 jobs at a queue depth of 32.

4KB Workloads: FIO on 10x 9200MAX NVME SSDs				
Storage Node	Write IOPS	Write Avg. Latency (µsec)	Read IOPS	Read Avg. Latency (µsec)
Node 1	2.92M	26.8	7.08M	225.2
Node 2	2.94M	26.7	7.10M	224.6
Node 3	2.96M	26.5	7.09M	224.9
Node 4	2.91M	26.9	7.09M	225.0

Table 8: Baseline FIO 4KB Random Workloads

10 Micron 9200 MAX SSDs deliver **7 million** 4KB random read IOPS and **2.9 million** 4KB random write IOPS in baseline testing on a single storage server.

4MB writes were measured with 20 jobs at a queue depth of 1. 4MB reads were measured with 20 jobs at a queue depth of 2.

4MB Workloads: FIO on 10x 9200MAX NVME SSDs				
Storage Node	Write Throughput	Write Avg. Latency (ms)	Read Throughput	Read Avg. Latency (ms)
Node 1	26.3 GB/s	3.2	32.2 GB/s	5.2
Node 2	25.8 GB/s	3.3	32.1 GB/s	5.2
Node 3	25.6 GB/s	3.3	32.1 GB/s	5.2
Node 4	25.4 GB/s	3.3	32.0 GB/s	5.2

Table 9: Baseline FIO 4MB Workloads

Network Baseline Results

Each server's network connectivity was tested using two concurrent iPerf3 runs for one minute. Each server was tested against each other.

All storage nodes with 100 GbE NICs averaged 99+ Gb/s during testing. Monitor nodes and clients with 50 GbE NICs averaged 49+ Gb/s during testing.

Test Results and Analysis

The results detailed below were collected on a 2x replicated storage pool in Red Hat Ceph 3.0 (Luminous 12.2.1) with 8192 placement groups.

4KB Random Workload Testing

Red Hat Ceph 3.0 was tested with 100 RBD images at 75GB each, providing 7.5TB of data on a 2x replicated pool (15TB of total data). Random writes were tested with a constant queue depth of 32, while the number of clients increased from 10 to 100. Using a queue depth of 32 simulated a reasonably active RDB image consumer and enabled our tests to scale to a high number of clients.

Random reads and 70/30 R/W workloads were measured by running load against all 100 RBD images, scaling up the queue depth per client from 1 to 32. We used all 100 clients for every read test to ensure Ceph used the Linux filesystem cache equally on all tests.

Each test was run three times at 10 minutes per run with a two-minute ramp-up time. The average results of those three runs are represented in the figures below.

4KB random writes reach 375,000 IOPS with 100 clients writing to RBD images concurrently. Tail latency spikes above 70 clients/ 367,000 IOPS.

4KB Random Write Workload Analysis

4KB random writes reached a maximum of 375K IOPS at 100 clients. Average latency ramped up linearly with the number of clients, reaching a maximum of 8.5ms at 100 clients.

Figures 6-8 show that IOPS increased rapidly, then flattened out at 50 – 60 clients. At this point, Ceph is CPU-limited. 99.99% tail latency increased linearly up to 70 clients, then spiked upward, going from 59ms at 70 clients to 136ms at 80 clients.

Average CPU utilization in Ceph was high, increasing from 68% with 10 clients to 90%+ at 70 clients. Above 70 clients, average CPU utilization was flat.

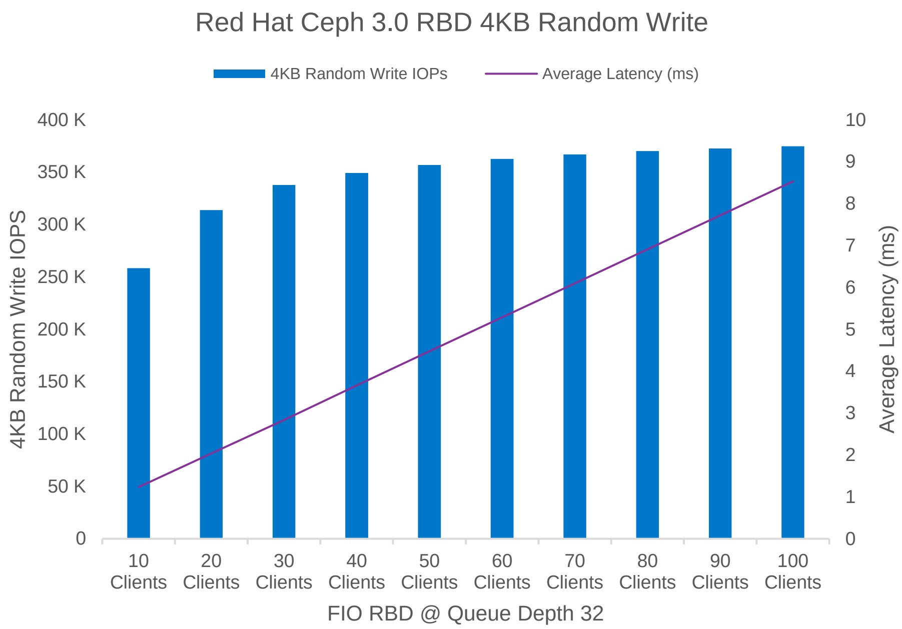


Figure 6: 4KB Random Write Performance

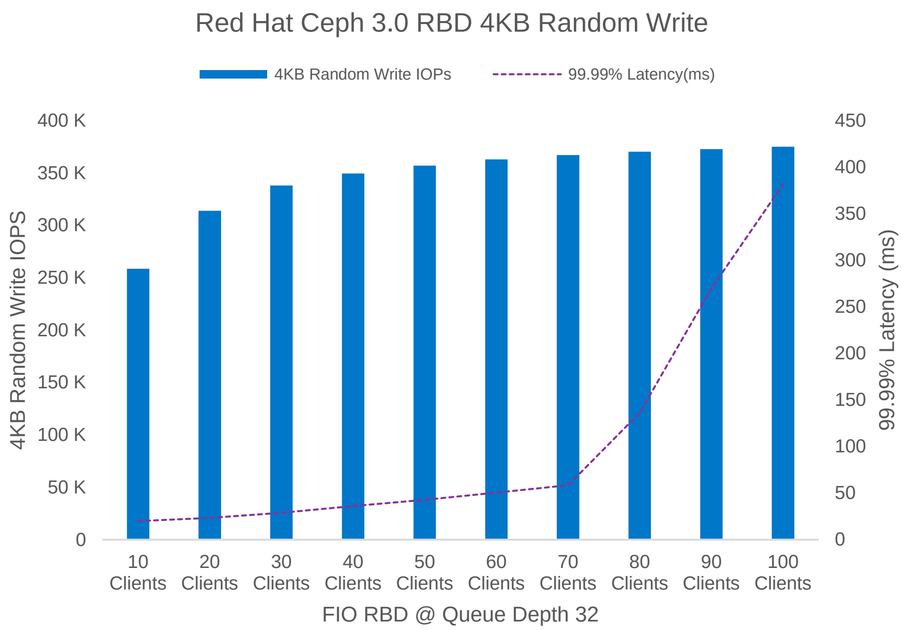


Figure 7: 4KB Random Write IOPS vs Tail Latency

CPU utilization was above 80% with just 20 clients and scaled up from there with its maximum at 76 clients (90%+ Maximum CPU utilization).

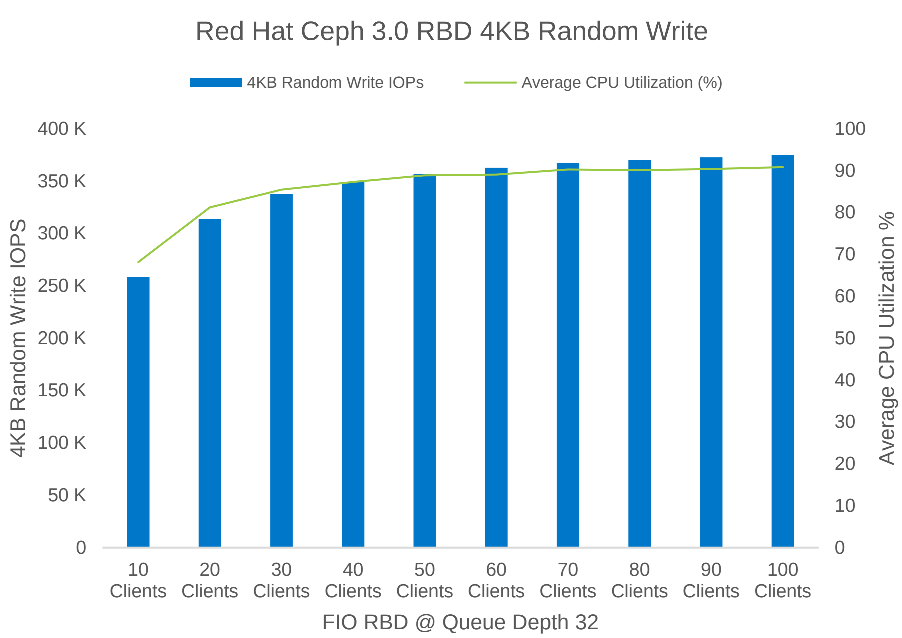


Figure 8: 4KB Random Write IOPS vs CPU Utilization

Table 10 includes 95% latency which scales linearly, like average latency.

FIO Clients	4KB Random Write Performance: FIO RBD @ Queue Depth 32 4KB Random Write IOPS	Average Latency	95% Latency	99.99% Latency	Average CPU Util.
10 Clients	258,469	1.2 ms	2.1 ms	20 ms	68.2%
20 Clients	313,844	2.0 ms	3.6 ms	23 ms	81.2%
30 Clients	337,893	2.8 ms	5.4 ms	28 ms	85.5%
40 Clients	349,354	3.7 ms	7.3 ms	36 ms	87.3%
50 Clients	356,939	4.5 ms	9.3 ms	42 ms	88.8%
60 Clients	362,798	5.3 ms	11 ms	50 ms	89.1%
70 Clients	367,011	6.1 ms	13 ms	58 ms	90.3%
80 Clients	370,199	6.9 ms	15 ms	136 ms	90.1%
90 Clients	372,691	7.7 ms	17 ms	269 ms	90.4%
100 Clients	374,866	8.5 ms	19 ms	382 ms	90.8%

Table 10: 4KB Random Write Results

4KB Random Read Workload Analysis

4KB random reads scaled from 289K IOPS up to 2 Million IOPS. Ceph reached maximum CPU utilization at a queue depth of 16; increasing to queue depth 32 doubled average latency and only marginally increased IOPS.

Tail latency spiked from 32.6ms at queue depth 16 to 330.7ms at queue depth 32, a result of CPU saturation above queue depth 16.

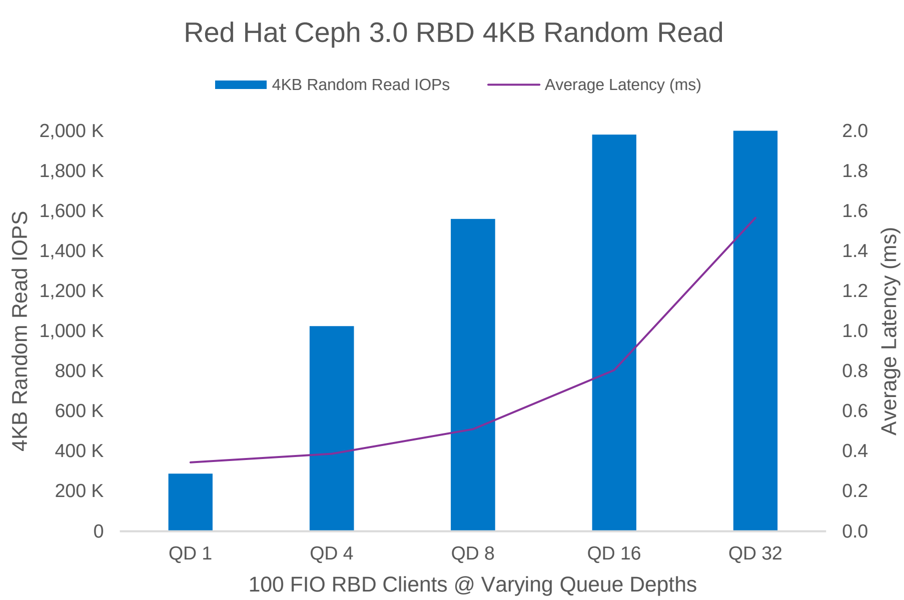


Figure 9: 4KB Random Read IOPS vs Average Latency

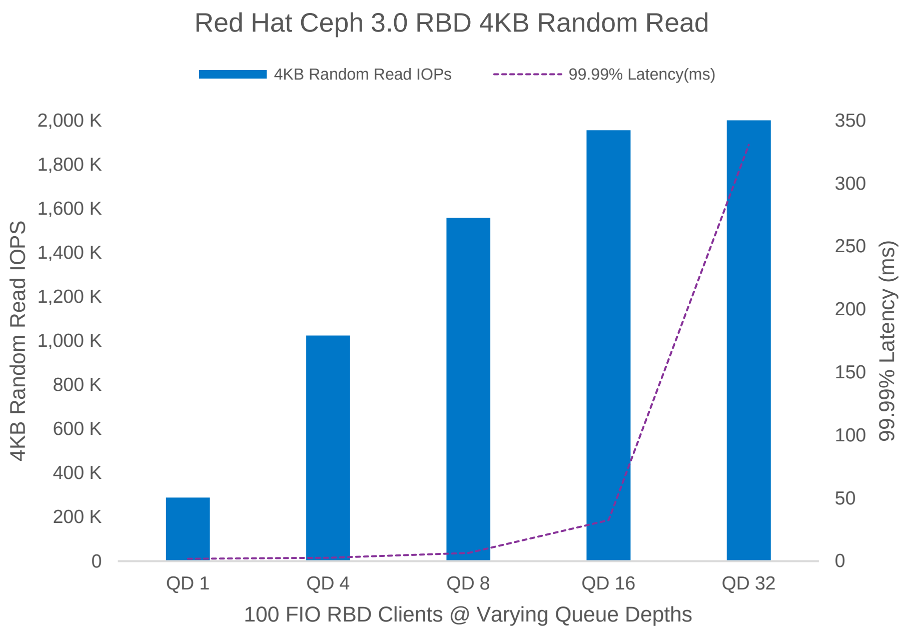


Figure 10: 4KB Random Read IOPS vs Tail Latency

Tail latency spikes above queue depth 16/1.95 million IOPS due to CPU saturation. CPU Utilization scales up with queue depth until a QD of 16. Above QD16, the storage node CPUs are saturated.

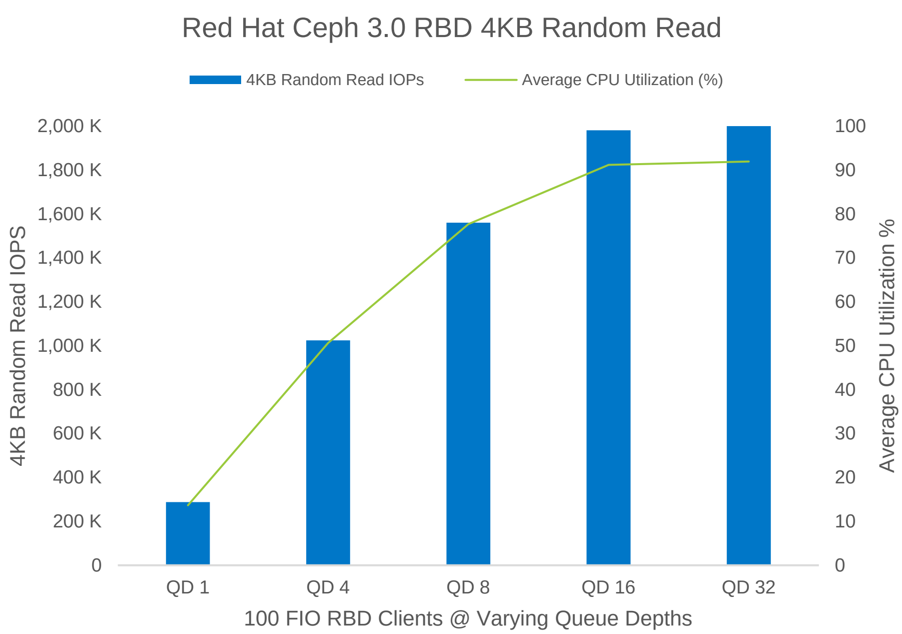


Figure 11: 4KB Random Read IOPS vs CPU Utilization

Table 11 summarizes these results, including 95% latency which scaled linearly, like average latency. Average and 95% latencies were close, indicating that 4KB read performance was consistent up to 95% of reads.

Random Read Results Summary

4KB Random Read Performance: 100 FIO RBD Clients at Varied QD					
Queue Depth	4KB Random Read IOPS	Average Latency	95% Latency	99.99% Latency	Average CPU Util
QD 1	288,956	0.34 ms	0.40 ms	1.9 ms	13.9%
QD 4	1,024,345	0.39 ms	0.51 ms	2.7 ms	50.6%
QD 8	1,558,105	0.51 ms	0.75 ms	6.5 ms	77.8%
QD 16	1,955,559	0.82 ms	1.4 ms	33 ms	91.4%
QD 32	2,012,677	1.6 ms	1.8 ms	330 ms	92.2%

Table 11: 4KB Random Read Results

4KB Random 70% Read / 30% Write Workload Analysis

70% read/30% write testing scaled from 211K IOPS at a queue depth of 1 to 837K IOPS at queue depth 32.

Read and write average latencies are graphed separately, with maximum average read latency at 2.71ms and max average write latency at 6.41ms.

Tail latency spiked dramatically above queue depth 16, as the 70/30 R/W test hit CPU saturation. Above queue depth 16, there was a small increase in IOPS and a large increase in latency.

70% Read/ 30% Write average read and write latencies are significantly different.

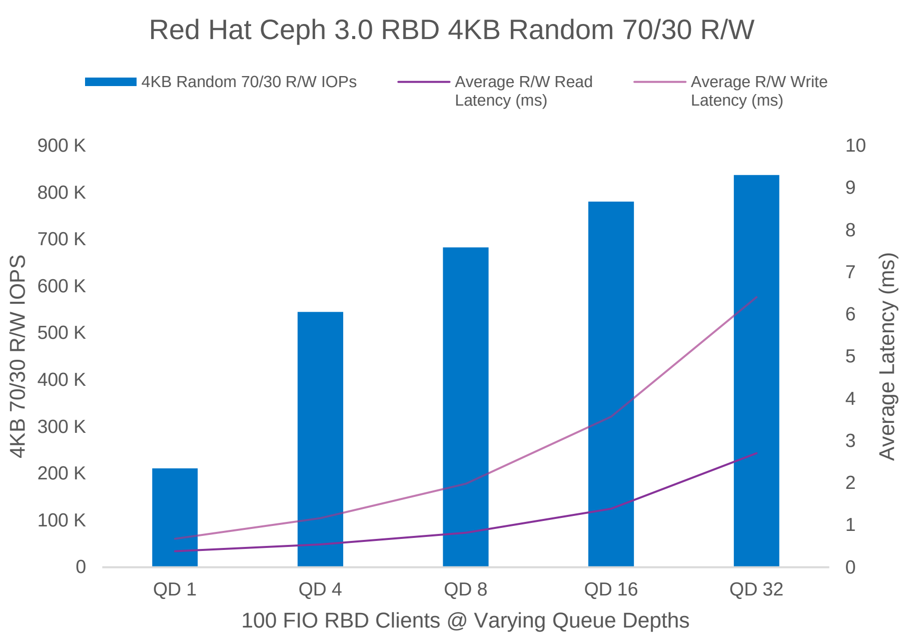


Figure 12: 4KB Random 70/30 R/W IOPS vs Average Latency

Figure 13 shows how 4KB random tail latencies converged for read and write operations as the CPUs became saturated above queue depth 16.

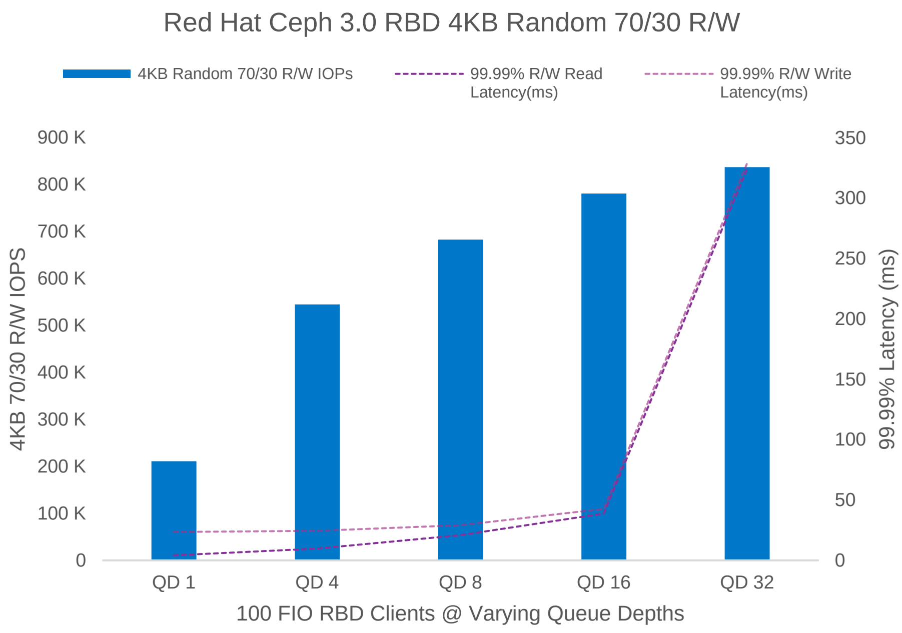


Figure 13: 4KB Random 70/30 R/W IOPS vs Tail Latency

Figure 14 below shows that CPUs became saturated at queue depth 16, where 4K random IOPS reached 781,000.

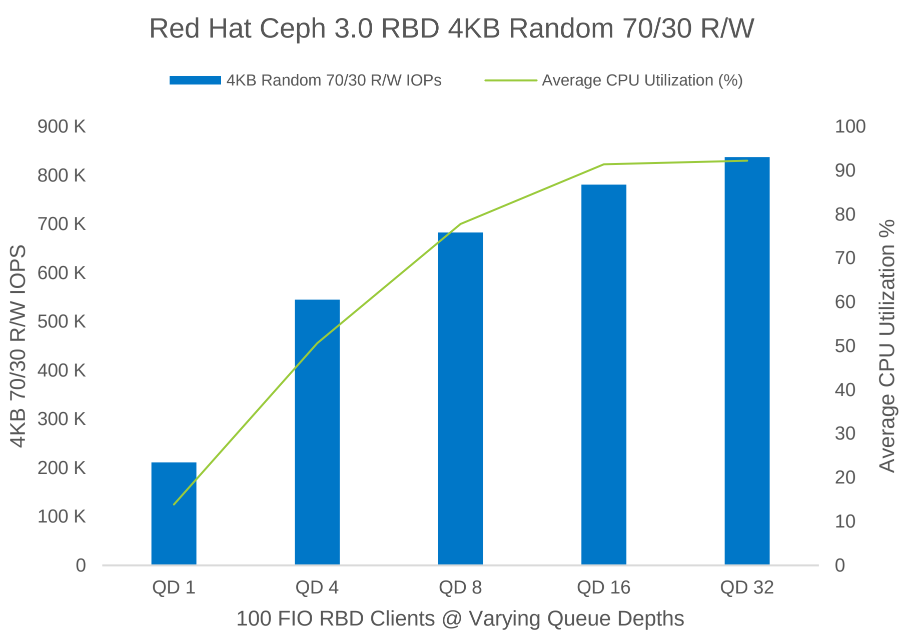


Figure 14: 4KB Random 70/30 R/W IOPS vs CPU Utilization

Random 70/30 R/W Results Summary

4KB Random 70/30 R/W Performance: 100 FIO RBD Clients at Varied QD						
Queue Depth	R/W IOPS	Avg. Read Latency	Avg. Write Latency	99.99% Read Latency	99.99% Write Latency	Avg. CPU Util
QD 1	211,322	0.38 ms	0.68 ms	4.2 ms	23 ms	13.9%
QD 4	545,172	0.54 ms	1.2 ms	9.8 ms	24 ms	50.6%
QD 8	682,920	0.82 ms	1.9 ms	20 ms	29 ms	77.8%
QD 16	781,002	1.4 ms	3.5 ms	38 ms	42 ms	91.4%
QD 32	837,459	2.7 ms	6.4 ms	324 ms	329 ms	92.2%

Table 12: 4KB 70/30 Random Read/Write Results

Increasing load from queue depth 16 to 32 increases IOPS by 7% but doubles average latency and increases tail latency by 100x.

4MB Object Workloads

Object workloads were tested using RADOS Bench, a built-in Ceph benchmarking tool. These results represent the best-case scenario of Ceph accepting data from RADOS Gateway nodes. The configuration of RADOS Gateway is out of scope for this RA.

Writes were measured by using a constant 16 threads in RADOS Bench and scaling up the number of clients writing to Ceph concurrently. Reads were measured by first writing out 7.5TB of object data with 10 clients, then reading back that data on all 10 clients while scaling up the number of threads used.

Figure 15 below shows that 4MB object writes reached 10 GB/s at 8 clients.

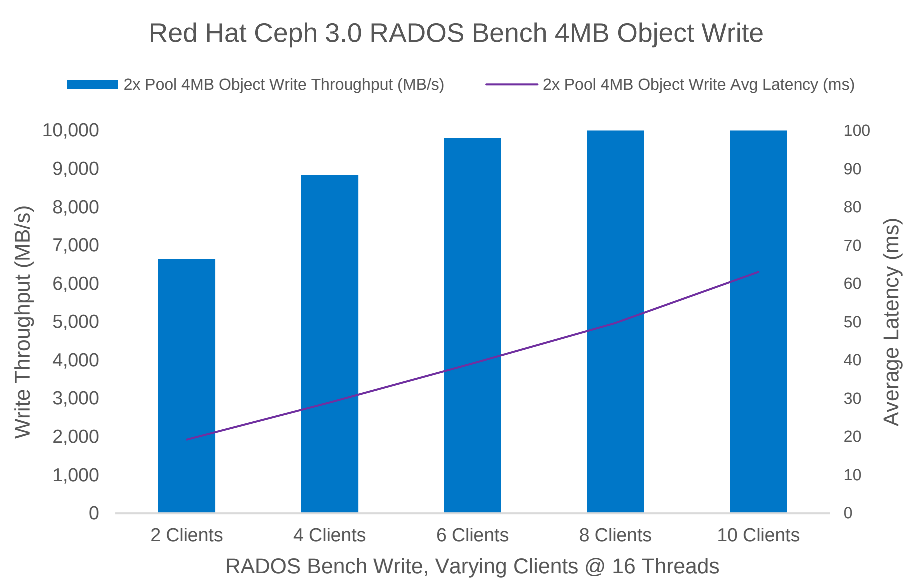


Figure 15: 4MB Object Write Throughput vs Average Latency

4MB Object writes reached their maximum value of 10.3 GB/s and 49.8ms average latency with 8 clients. CPU utilization was low for this test and never reached above 50% average CPU%.

4MB Object Write Results Summary

Clients @ 16 Threads	4MB Object Write Performance: RADOS Bench	
	Write Throughput	Average Latency (ms)
2 Clients	6.6 GB/s	19.3
4 Clients	8.8 GB/s	28.9
6 Clients	9.8 GB/s	39.2
8 Clients	10.3 GB/s	49.8
10 Clients	10.1 GB/s	63.1

Table 13: 4MB Object Write Results

Figure 16 shows that 4MB Object reads reached 30 GB/s at around 16 threads on 10 clients.

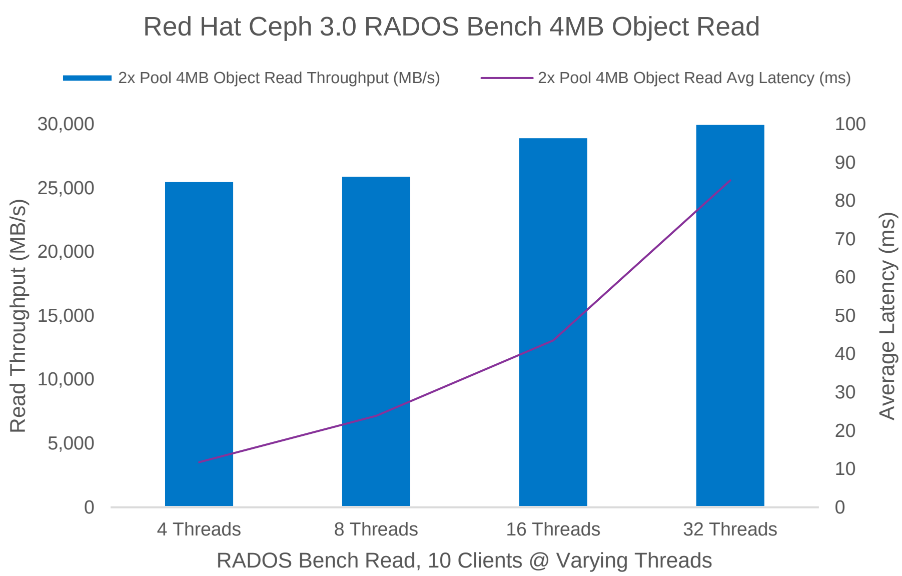


Figure 16: 4MB Object Read Throughput vs Average Latency

4MB Object reads reached their maximum of 30 GB/s and 85.4ms average latency at 32 clients. CPU utilization was low for this test and never reached above 50% average CPU%.

10 Clients @ Varied Threads	4MB Object Read Performance: RADOS Bench	
	Read Throughput	Average Latency (ms)
4 Threads	25.6 GB/s	11.8
8 Threads	26.0 GB/s	23.9
16 Threads	29.0 GB/s	43.6
32 Threads	30.0 GB/s	85.4

Table 14: 4MB Object Read Results

2x vs. 3x Replication Performance

Many Ceph users require the added data protection of a 3x replicated pool. The results detailed below compare data collected on a 2x and a 3x replicated storage pool in Red Hat Ceph 3.0 (Luminous 12.2.1) with 8192 placement groups.

2x vs. 3x Replication 4KB Random Workloads

The 2x replicated pool in Red Hat Ceph 3.0 was tested with 100 RBD images at 75GB each, providing 7.5TB of data on a 2x replicated pool (15TB of total data). The 3x replicated pool in Red Hat Ceph 3.0 was tested with 100 RBD images at 50GB each, providing 5TB of data on a 3x replicated pool (15TB of total data).

Random writes were tested with a constant queue depth of 32 while the number of clients increased from 10 to 100. Random reads and 70/30 R/W workloads were measured by running load against all 100 RBD images and scaling up the queue depth per client from 1 to 32.

Each test was run three times at 10 minutes per run; the average results of those runs are represented in the graphs that follow.

Increasing data protection by using a 3x replicated storage pool over a 2x replicated pool decreased 4KB random write performance by 35% but did not affect read performance.

2x vs. 3x Replication Random Write Workload Analysis

With 3x replication, IOPS performance reduced by ~35% over a 2x replicated pool. Average latency increased by a similar margin. Tail latency spiked more dramatically after 70 clients, and CPU utilization maxed out slightly higher at 91%.

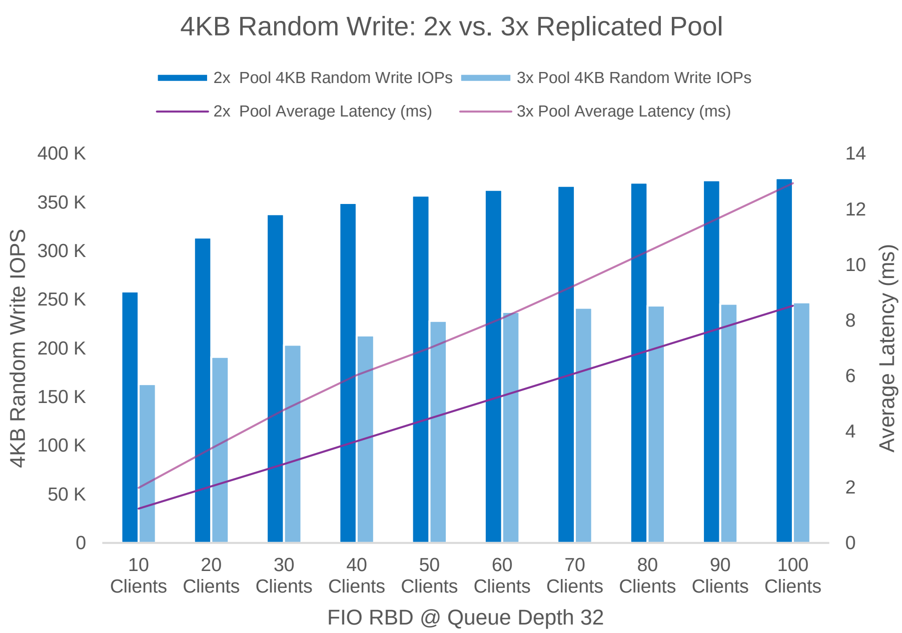


Figure 17: 2x vs 3x Replication Pool 4KB Write IOPS vs Average Latency

Figure 18 shows tail latency spiked more dramatically on a 3x replication pool above 70 clients, increasing from 133ms to 447ms.

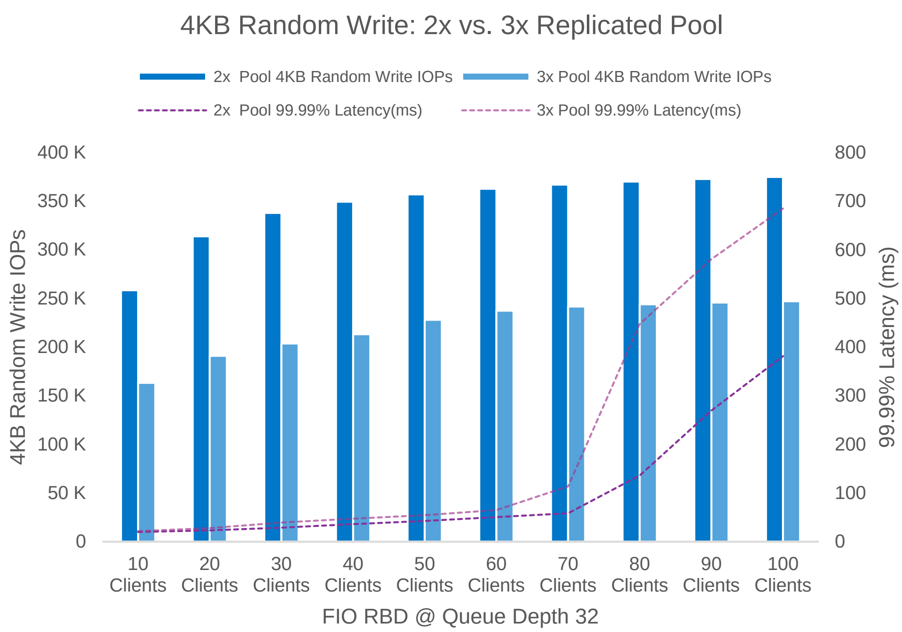


Figure 18: 2x vs 3x Replication Pool 4KB Write IOPS vs Tail Latency

Figure 19 shows CPU utilization started higher on a 3x replicated pool, hitting similar CPU utilization with 30+ clients. When the CPU saturated at 50+ clients, there was a ~35% decrease in IOPS and a similar increase in average latency.

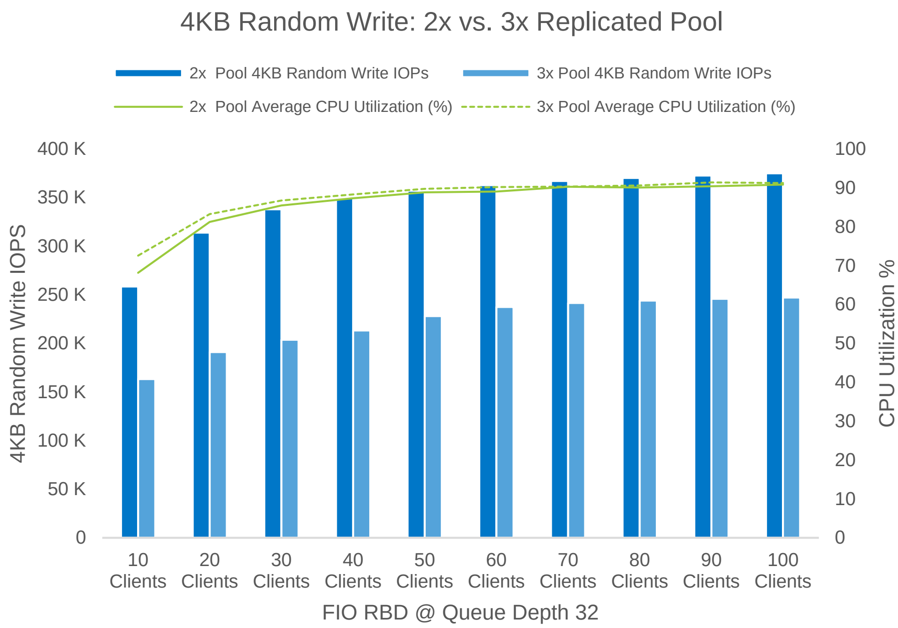


Figure 19: 2x vs 3x Replication Pool 4KB Write IOPS vs CPU Utilization

Table 15 summarizes 2x vs. 3x replicated pool 4KB random write results

	4KB Random Write Performance: 2x vs. 3x Replicated Pool				
FIO Clients	2x Pool Write IOPS	3x Pool Write IOPS	2x Pool Avg. Lat	3x Pool Avg. Lat	IOPS Decrease 2x to 3x
10 Clients	258,469	163,212	1.2 ms	2.0 ms	37%
20 Clients	313,844	191,116	2.0 ms	3.4 ms	39%
30 Clients	337,893	203,740	2.8 ms	4.8 ms	40%
40 Clients	349,354	213,286	3.7 ms	6.0 ms	39%
50 Clients	356,939	228,115	4.5 ms	7.0 ms	36%
60 Clients	362,798	237,373	5.3 ms	8.1 ms	35%
70 Clients	367,011	241,634	6.1 ms	9.3 ms	34%
80 Clients	370,199	244,009	6.9 ms	10.5 ms	34%
90 Clients	372,691	245,798	7.7 ms	11.7 ms	34%
100 Clients	374,866	247,201	8.5 ms	12.9 ms	34%

Table 15: 2x vs. 3x Replicated Pool Random Write Results

2x vs. 3x Replication Random Read Workload Analysis

4KB random read performance was essentially identical between a 2x and 3x replicated pool. As seen in Figure 20, 4KB random read performance was unaffected by replication level.

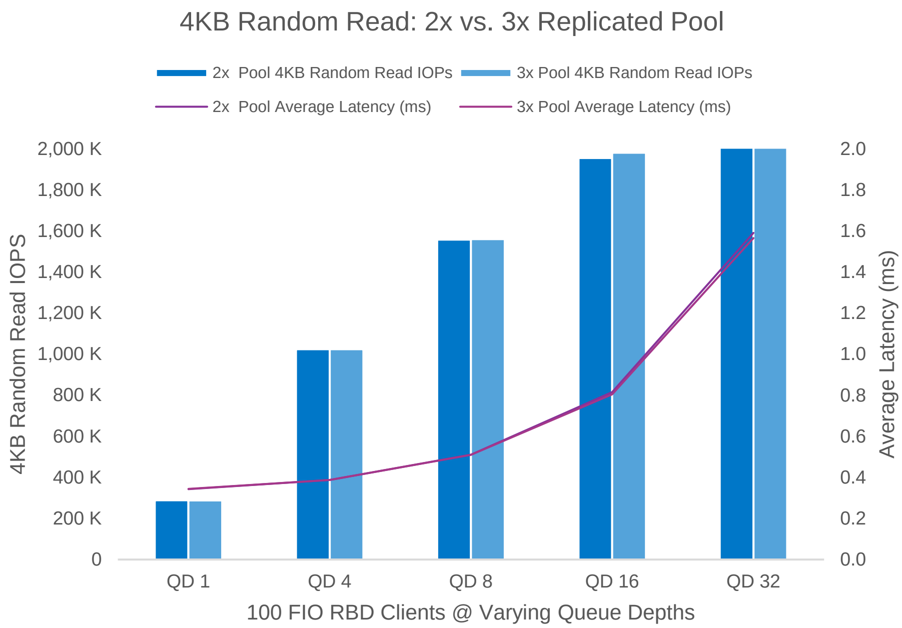


Figure 20: 2x vs 3x Replication Pool 4KB Read IOPS vs Average Latency

Figure 21 shows 4KB random read tail latency was the same with a 2x or 3x replicated pool.

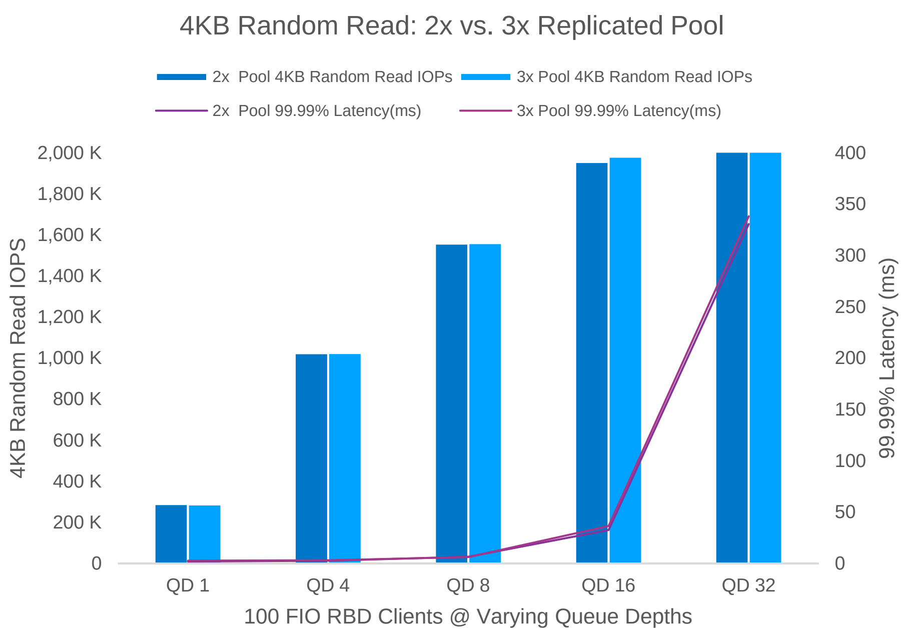


Figure 21: 2x vs 3x Replication Pool 4KB Read IOPS vs Tail Latency

Figure 22 shows a similar trend in CPU utilization with a 2x or 3x replicated pool.

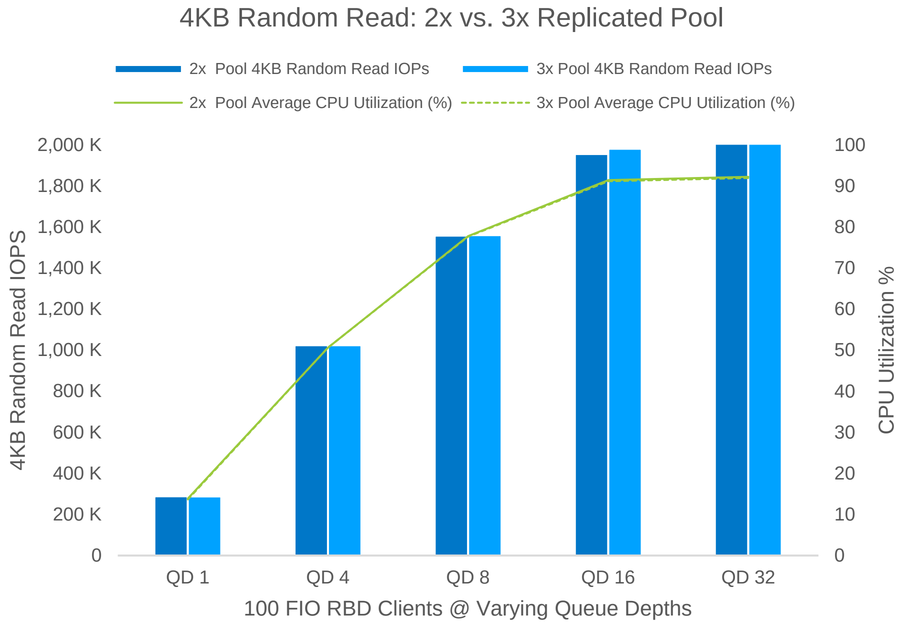


Figure 22: 2x vs 3x Replication Pool 4KB Read IOPS vs CPU Utilization

Table 16 summarizes these results, showing that storage pool replication does not affect 4K random read IOPS.

	4KB Random Read Performance: 2x vs. 3x Replicated Pool				
Queue Depth	2x Pool Read IOPS	3x Pool Read IOPS	2x Pool Avg. Lat.	3x Pool Avg. Lat.	IOPS Decrease 2x to 3x
QD 1	288,956	287,919	0.34 ms	0.34 ms	0%
QD 4	1,024,345	1,024,653	0.39 ms	0.39 ms	0%
QD 8	1,558,105	1,560,042	0.51 ms	0.51 ms	0%
QD 16	1,955,559	1,981,222	0.82 ms	0.80 ms	-1%
QD 32	2,012,677	2,057,021	1.59 ms	1.57 ms	-2%

Table 16: 2x vs. 3x Replicated Pool Random Read Results

2x vs. 3x Replication 70/30 R/W Workload Analysis

Figure 23 shows that 70/30 random R/W workload IOPS performance decreased by 25% when going from a 2x replicated pool to a 3x replicated pool. Read latencies were similar, slightly increasing for the 3x replicated pool. Write latencies were 50%+ higher for the 3x replicated pool.

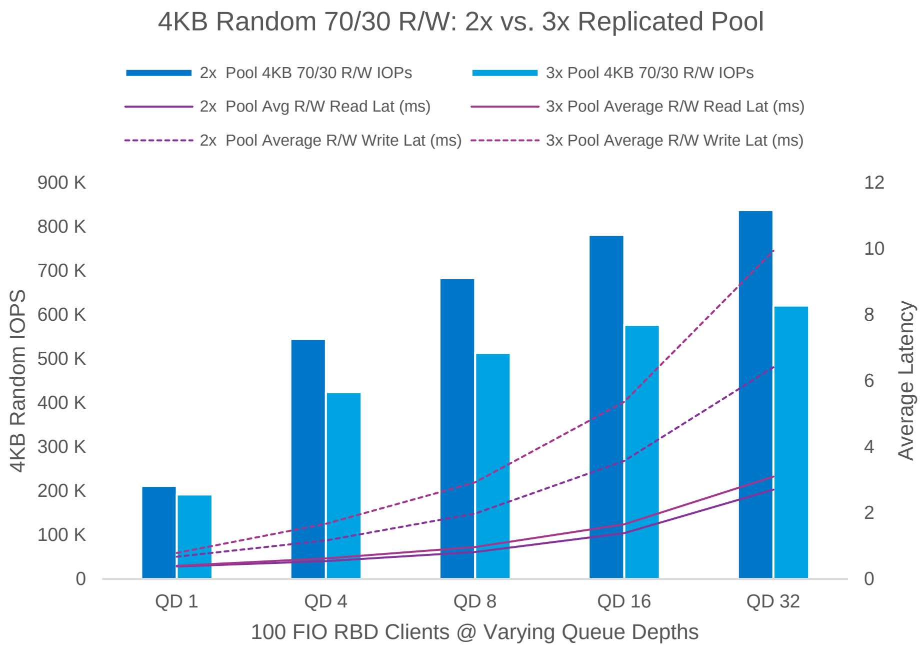


Figure 23: 2x vs 3x Replication Pool 4KB 70/30 R/W IOPS vs Average Latency

Figure 24 shows that tail latencies for read and write were 28% lower for the 3x replicated pool. This was due to the lighter load on the Micron 9200 MAX NVMe SSDs.

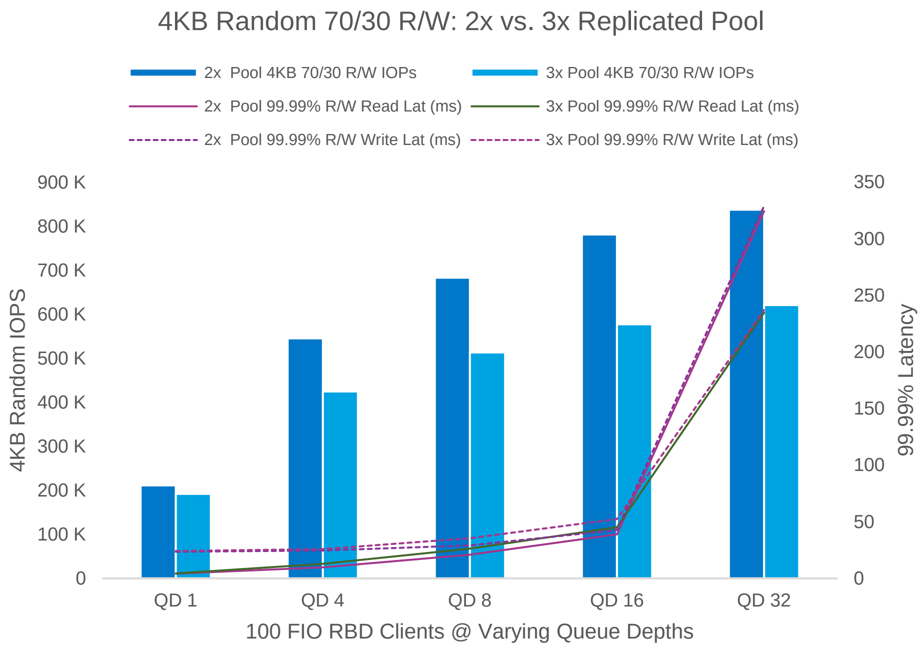


Figure 24: 2x vs 3x Replication Pool 4KB 70/30 R/W IOPS vs Tail Latency

Figure 25 shows CPU utilization was higher at lower queue depths for a 3x replication. Note too that it hit CPU saturation earlier.

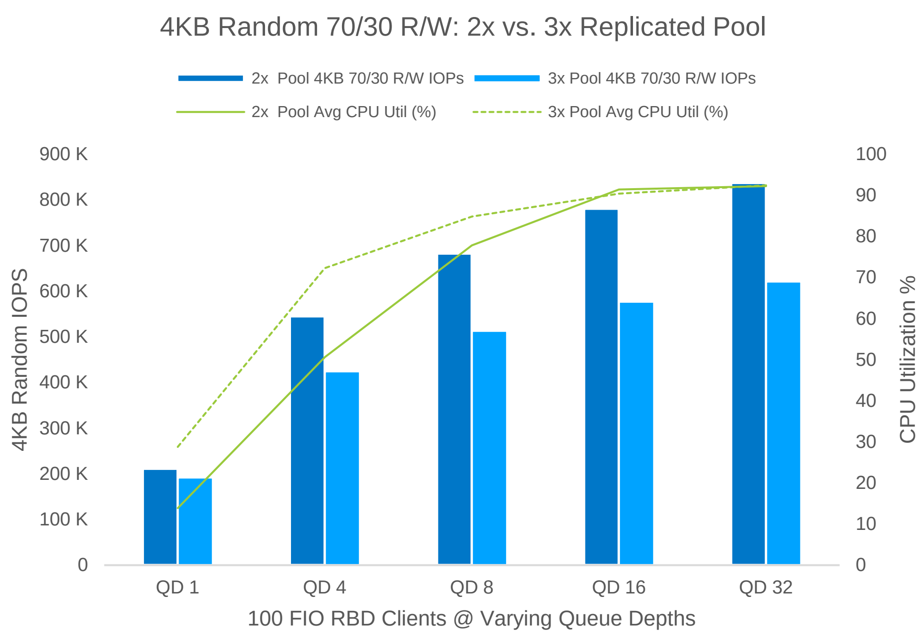


Figure 25: 2x vs 3x Replication Pool 4KB 70/30 R/W IOPS vs CPU Utilization

Table 17 compares 2x and 3x 70/30 R/W results. Note that for this IO profile, 4KB performance decreased 9% to 29% when replication increased from 2x to 3x.

	4KB Random 70/30 R/W Performance: 2x vs. 3x Replicated Pool						
Queue Depth	2x Pool 70/30 R/W IOPS	3x Pool 70/30 R/W IOPS	2x Pool Avg R/W Read Lat	3x Pool Avg R/W Read Lat	2x Pool Avg R/W Write Lat	3x Pool Avg R/W Write Lat	IOPS Decrease 2x to 3x
QD 1	211,322	191,918	0.38	0.40	0.68	0.79	9%
QD 4	545,172	424,426	0.54	0.62	1.17	1.67	22%
QD 8	682,920	513,150	0.82	0.97	1.98	2.92	25%
QD 16	781,002	577,047	1.39	1.66	3.57	5.36	26%
QD 32	837,459	620,901	2.71	3.10	6.41	9.93	26%

Table 17: 2x vs. 3x Replicated Pool Random 70/30 R/W Results

2x vs. 3x Replication Object Write

4MB object write performance was reduced by 35% going from a 2x pool replicated pool to a 3x replicated pool.

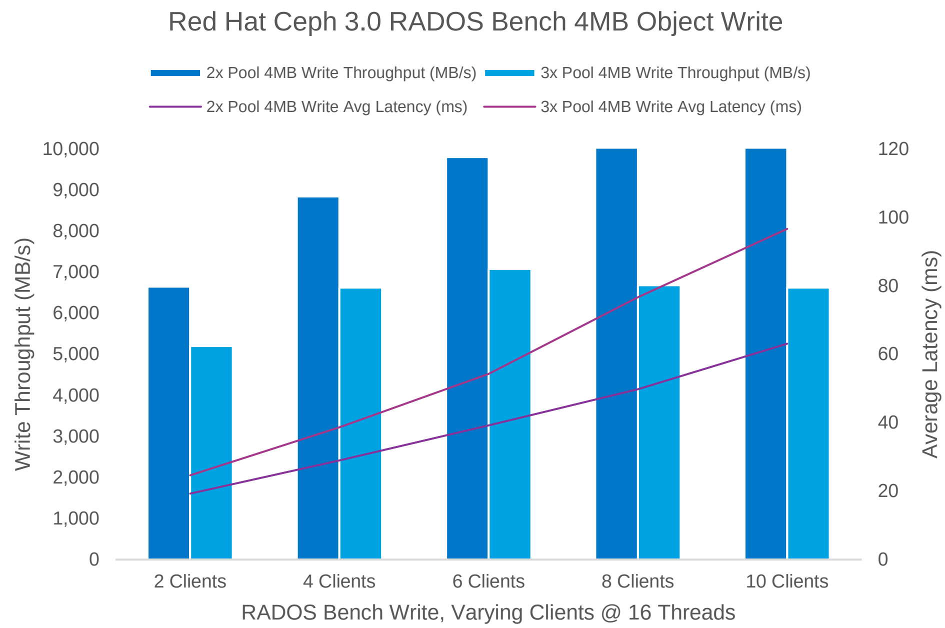


Figure 26: 2x vs 3x Replication Pool 4MB Object Write Throughput

Table 18 summarizes 4MB object write performance for 2x and 3x replicated pools. Note that with eight to 10 clients, 4MB object performance on a 2x replicated pool was lower than on a 3x replicated pool (reduction range from a low of 22% to a high of 35%).

4MB Object Write Performance: 2x vs. 3x Replicated Pool					
Clients @ 16 Threads	2x Pool Write Throughput	3x Pool Write Throughput	2x Pool Write Avg Lat	3x Pool Write Avg Lat	Throughput Decrease 2x to 3x
2 Clients	6.6 GB/s	5.2 GB/s	19 ms	24 ms	22%
4 Clients	8.8 GB/s	6.6 GB/s	28 ms	38 ms	25%
6 Clients	9.8 GB/s	7.0 GB/s	39 ms	54 ms	28%
8 Clients	10.3 GB/s	6.7 GB/s	49 ms	76 ms	35%
10 Clients	10.1 GB/s	6.6 GB/s	63 ms	96 ms	35%

Table 18: 2x vs. 3x Replicated Pool 4MB Object Write Throughput Results

2x vs. 3x Replication Object Read

Figure 27 shows 4MB Object read performance. Note that pool replication level did not affect these results.

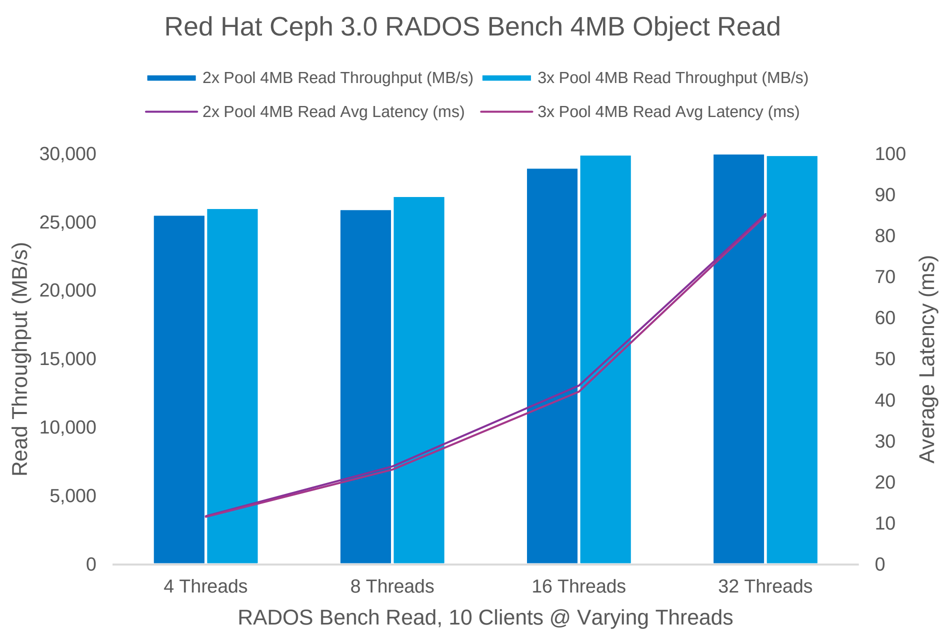


Figure 27: 2x vs 3x Replication Pool 4MB Object Read Throughput vs Average Latency

These results are also summarized in Table 19.

	4MB Object Read Performance: 2x vs. 3x Replicated Pool				
10 Clients @ Varied Threads	2x Pool Read Throughput	3x Pool Read Throughput	2x Pool Read Avg Lat.	3x Pool Read Avg Lat.	Throughput Decrease 2x to 3x
4 Threads	25.6 GB/s	26.0 GB/s	11 ms	11 ms	2%
8 Threads	26.0 GB/s	26.9 GB/s	23 ms	23 ms	4%
16 Threads	29.0 GB/s	30.0 GB/s	43 ms	42 ms	3%
32 Threads	30.1 GB/s	29.9 GB/s	85 ms	85 ms	0%

Table 19: 2x vs. 3x Replicated Pool 4MB Object Read Throughput Results

Summary

With 1.9+ million 4KB random reads in four rack units with 256TB total storage, this RA is designed for massive amounts of small block random workloads, and is the most performant Ceph architecture we've tested. With 367K random writes in 4U, it also has the highest random write performance we've measured with Ceph Storage to date.

Testing proves that the performance penalty between a 2x and 3x replicated storage pool is about 35% for writes and 0% for reads (as seen in Figure 28). This is expected and is a good data point to have because of differing data protection needs across organizations.

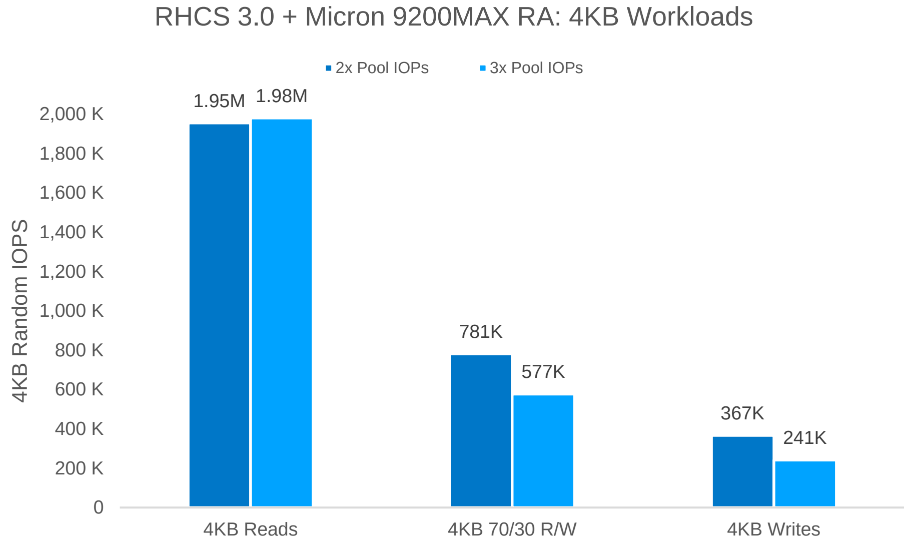


Figure 28: 2x vs 3x Replication Pool 4KB Mixed IO Performance

Appendix A: Configuration Details

Ceph.conf

```
[global]
fsid = <fsid>
public network =
cluster network =
auth client required = none
auth cluster required = none
auth service required = none
auth supported = none
mon host =
ms_type = async
rbd readahead disable after bytes = 0
rbd readahead max bytes = 4194304
filestore xattr use omap = true
mon compact on trim = False
mon_allow_pool_delete = true
osd pg bits = 8
osd pgp bits = 8
osd_pool_default_size = 2
mon pg warn max object skew = 100000
debug_RADOS = 0/0
debug_asok = 0/0
debug_auth = 0/0
debug_buffer = 0/0
debug_context = 0/0
debug_crush = 0/0
debug_filer = 0/0
debug_finisher = 0/0
debug_heartbeatmap = 0/0
debug_lockdep = 0/0
debug_mon = 0/0
debug_monc = 0/0
debug_ms = 0/0
debug_objecter = 0/0
debug_paxos = 0/0
debug_perfcounter = 0/0
debug_rbd = 0/0
debug_rgw = 0/0
debug_throttle = 0/0
debug_timer = 0/0
debug_tp = 0/0
perf = True
mutex_perf_counter = True
throttler_perf_counter = False
rbd cache = false
mon_max_pg_per_osd = 800
[mon]
mon_osd_max_split_count = 10000
[osd]
osd journal size = 20480
osd mount options xfs =
noatime,largeio,inode64,swalloc
osd mkfs options xfs = -f -i size=2048
osd_op_threads = 32
filestore_queue_max_ops = 5000
filestore_queue_committing_max_ops = 5000
journal_max_write_entries = 1000
journal_queue_max_ops = 3000
objecter_inflight_ops = 102400
filestore_wbthrottle_enable = False
osd mkfs type = xfs
filestore_max_sync_interval = 10
osd_client_message_size_cap = 0
osd_client_message_cap = 0
osd_enable_op_tracker = False
filestore_fd_cache_size = 64
filestore_fd_cache_shards = 32
filestore_op_threads = 6
filestore_queue_max_bytes=1048576000
filestore_queue_committing_max_bytes=1048576
000
journal_max_write_bytes=1048576000
journal_queue_max_bytes=1048576000
ms_dispatch_throttle_bytes=1048576000
objecter_infilght_op_bytes=1048576000
```

Ceph-Ansible Configuration

All.yml

```
---
dummy:
fetch_directory: ~/ceph-ansible-keys
ntp_service_enabled: true
upgrade_ceph_packages: True
ceph_repository_type: cdn
ceph_origin: repository
ceph_repository: rhcs
ceph_rhcs_version: 3
fsid: <insert-fsid-here>
generate_fsid: false
cephx: false
rbd_cache: "false"
monitor_interface: enp131s0
ip_version: ipv4
journal_size: 20480
public_network:
cluster_network:
osd_mkfs_type: xfs
osd_mkfs_options_xfs: -f -i size=2048
osd_mount_options_xfs:
noatime,largeio,inode64,swalloc
osd_objectstore: filestore
ceph_conf_overrides:
 global:
  ms_type: async
  rbd readahead disable after bytes: 0
  rbd readahead max bytes: 4194304
  mon compact on trim: false
  osd pg bits: 8
  osd pgp bits: 8
  mon pg warn max object skew: 100000
  mon pg warn min per osd: 0
  osd_pool_default_size: 2
  osd_pool_default_min_size: 1
  mon_compact_on_trim: false
  perf: true
  mutex_perf_counter: true
  throttler_perf_counter: false
  rbd cache: false
 mon:
  mon_max_pool_pg_num: 166496
  mon_osd_max_split_count: 10000
 osd:
  osd_op_threads: 48
  filestore_queue_max_ops: 5000
  filestore_queue_committing_max_ops: 5000
  journal_max_write_entries: 1000
  journal_queue_max_ops: 3000
  objecter_inflight_ops: 102400
  filestore_wbthrottle_enable: false
  filestore_max_sync_interval: 10
  osd_client_message_size_cap: 0
  osd_client_message_cap: 0
  osd_enable_op_tracker: false
  filestore_fd_cache_size: 64
  filestore_fd_cache_shards: 32
  filestore_op_threads: 6
disable_transparent_hugepage: true
os_tuning_params:
  - { name: kernel.pid_max, value: 4194303 }
  - { name: fs.file-max, value: 26234859 }
  - { name: vm.zone_reclaim_mode, value: 0 }
  - { name: vm.swappiness, value: 1 }
  - { name: vm.min_free_kbytes, value:
1000000 }
  - { name: net.core.rmem_max, value:
268435456 }
  - { name: net.core.wmem_max, value:
268435456 }
  - { name: net.ipv4.tcp_rmem, value: 4096
87380 134217728 }
  - { name: net.ipv4.tcp_wmem, value: 4096
65536 134217728 }
ceph_tcmalloc_max_total_thread_cache:
134217728
```

Osds.yml

The osds.yml file is left mostly blank since we want to deploy 2 OSDs per drive. Deploying with ceph-ansible and this osds.yml will install ceph and all its dependencies on the monitor and storage nodes then it will fail at the storage deployment step. Run “ansible-playbook site.yml --limit clients” to install client software.

```
---
dummy:
osd_scenario: collocated
```

Deploying 2 OSDs per Drive

Driveprep.sh

Run this script on the storage nodes to partition drives into 2x journal partitions and 2x data partitions:

```
#! /bin/bash
for num in {0..9}; do
sudo sgdisk -Z /dev/nvme${num}n1
done
sleep 10
echo "Partitioning Drives"
for drivenum in {0..9}; do
sudo parted /dev/nvme${drivenum}n1 mklabel gpt
sudo parted -a optimal /dev/nvme${drivenum}n1 mkpart primary 0% 1%
sudo parted -a optimal /dev/nvme${drivenum}n1 mkpart primary 1% 2%
sudo parted -a optimal /dev/nvme${drivenum}n1 mkpart primary 2% 51%
sudo parted -a optimal /dev/nvme${drivenum}n1 mkpart primary 51% 100%
sudo mkfs -t xfs -f -i size=2048 /dev/nvme${drivenum}n1p3
sudo mkfs -t xfs -f -i size=2048 /dev/nvme${drivenum}n1p4
done
```

10Drive_2Osd_pernode.sh

Run this script to deploy 2 OSDs per drive:

```
#!/bin/bash
for i in {0..9}; do
for j in {40..43}; do
ssh ceph${j} sudo ceph-disk prepare --cluster ceph --cluster-uuid 36a9e9ee-a7b8-4c41-
a3e5-0b575f289379 --fs-type xfs --crush-device-class NVME --filestore
/dev/nvme${i}n1p3 /dev/nvme${i}n1p1
ssh ceph${j} sudo chown ceph:ceph /dev/nvme${i}n1p1
ssh ceph${j} sudo ceph-disk activate /dev/nvme${i}n1p3

ssh ceph${j} sudo ceph-disk prepare --cluster ceph --cluster-uuid 36a9e9ee-a7b8-4c41-
a3e5-0b575f289379 --fs-type xfs --crush-device-class NVME --filestore
/dev/nvme${i}n1p4 /dev/nvme${i}n1p2
ssh ceph${j} sudo chown ceph:ceph /dev/nvme${i}n1p2
ssh ceph${j} sudo ceph-disk activate /dev/nvme${i}n1p4
done
done
```

Drive Readahead Settings

For 4KB random tests, the following was run on the storage nodes to set readahead to 0:

```
for i in {0..9};do sudo echo 0 > /sys/block/nvme${i}n1/queue/read_ahead_kb;done
```

For 4MB object tests, the following was run on the storage nodes to set readahead to 128:

```
for i in {0..9};do sudo echo 128 > /sys/block/nvme${i}n1/queue/read_ahead_kb;done
```

Spectre/Meltdown Patch Settings

Due to the potential performance impact and changing release status of Spectre/Meltdown updates, the variant #2 (Spectre) and variant #3 (Meltdown) patches were disabled (see the instructions in this article https://access.redhat.com/articles/3311301).

```
echo 0 > /sys/kernel/debug/x86/pti_enabled
echo 0 > /sys/kernel/debug/x86/ibrs_enabled
echo 0 > /sys/kernel/debug/x86/ibpb_enabled
```

About Micron

Micron Technology (Nasdaq: MU) is a world leader in innovative memory solutions. Through our global brands—Micron, Crucial® and Ballistix®—our broad portfolio of high-performance memory technologies, including DRAM, NAND and NOR memory, is transforming how the world uses information. Backed by more than 35 years of technology leadership, Micron's memory solutions enable the world's most innovative computing, consumer, enterprise storage, data center, mobile, embedded, and automotive applications. Micron's common stock is traded on the Nasdaq under the MU symbol. To learn more about Micron Technology, Inc., visit micron.com.

About Red Hat Ceph Storage

Red Hat Ceph Storage is an open, massively scalable storage solution for modern workloads like cloud infrastructure, data analytics, media repositories, and backup and restore systems. It can:

- Free you from the expensive lock-in of proprietary, hardware-based storage solutions.
- Consolidate labor and storage costs into 1 versatile solution.
- Introduce cost-effective scalability on self-healing clusters based on standard servers and disks.

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