

# IPv6-Only HTCondor Integration with the Open Science Pool: The Viper Cluster at GW/CAAREN

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## 1 Introduction

In 2025, The George Washington University [1], in partnership with the Capital Area Advanced Research and Education Network (CAAREN) [2], successfully contributed a single-stack IPv6 HTCondor [3] cluster, Viper, to the Open Science Pool (OSPool) [4], a nationally distributed computing platform for data-intensive research. This demonstrates a path forward for institutions preparing for an IPv6-only future, reinforcing GW’s leadership in research cyberinfrastructure and open science.

There is some legitimate concern that integrating IPv6-only computational resources into the OSPool may have adverse effects on effective job throughput and be damaging to the Open Science Pool. These concerns break down into two broad categories of challenges,

1. Interoperability with OSPool and HTCondor
2. Interoperability with researcher jobs

A solution is required that bridges the gap for both of these sets of concerns for there to be any possibility of moving beyond legacy addressing. Because the way the OSPool CE’s match requests with resources is well-understood [5], the first set of challenges may be addressed systematically. However, the second set, owing to researcher workflows being much less predictable, requires a broadly-scoped solution that handles a variety of scenarios.

## 2 System Overview

Viper is a 12-node HTCondor cluster managed with Warewulf 4.6.1 [6] running Rocky Linux 9.5 and supported by a dedicated network-attached ZFS pool for backups and administrative workflows. Each node in the cluster is a Dell PowerEdge R730 with the following hardware specifications:

Component	Specification
Cores	2x14 Intel Xeon E5-2680 v4 @ 2.40GHz
RAM	8x16 GB DIMM ECC 2400 MT/s
Scratch Storage	1 TB SSD

There are two master nodes serving as redundant central-managers in an active-passive relation, one submit node, and nine execute points. Because Viper uses Warewulf’s stateless provisioning, nodes can be quickly repurposed or recovered after failure.

Viper is configured to advertise 4.5 GB of RAM per core to the Open Science Pool, allowing it to efficiently integrate with workloads of varying shapes.

### 3 About CAAREN

The Capital Area Advanced Research and Education Network (CAAREN) provides high-performance networking to support education, research, and innovation in the Washington, D.C. area. As a regional optical network and member of Internet2, CAAREN connects GW to other research institutions and to global science collaborations.

CAAREN has been a leader in routing security, being among the first US higher education institutions to implement Route Origin Authorization (ROAs). CAAREN implemented the first known production deployment of TCP-AO for advanced BGP session security [7].

Also available on CAAREN is an advanced content distribution test environment using Tree Distribution Networking (TreeDN) [8]. Employing a combination of native multicast and overlay tunneling technology (via Automatic Multicast Tunneling - AMT), multicast content can be delivered to any endpoint.

CAAREN's core network includes:

- Juniper MX480
- DWDM with optical protection to connect to Internet2
- Supplemental 10 Gbps access via secondary switches

Additional CAAREN services include:

- Cloud Connect: Dedicated links via Internet2's footprint to AWS, Azure, Google Cloud, and OCI, offering low-latency, secure access to cloud resources.
- The Things Network: A collaborative IoT sensor network initiative using LoRaWAN for low-power, long-range device communication.

These services position CAAREN as a leader for data-intensive science, advanced networking research, and the transition to secure, scalable IPv6-only architectures.

### 4 Network Architecture

Viper is integrated into the CAAREN research network using globally routable IPv6 addresses on all nodes. IPv6 is the sole transport protocol used for all HTCondor daemons and management tooling. Figure 1 illustrates the overall layout and connectivity of the Viper deployment.

#### 4.1 IPv6 Addressing and Interface Layout

Each node has a statically assigned IPv6 address from a globally routable /64 prefix delegated to GWU by CAAREN. The interface layout is as follows:

- **Primary interface:** `eno1`, used for HTCondor daemon communication and OSPool job I/O
- **Secondary interface:** `clat0`, a virtual interface created by CLATD to support legacy IPv4-only applications using 464XLAT translation

No IPv4 addresses are assigned to any interface on the system, and all name resolution, routing, and job submission are performed over IPv6.

## 4.2 Routing and Firewalling

Routing within Viper and upstream to the internet is handled via CAAREN's core routers. Internally, the cluster uses host-based firewalls to limit inbound IPv6 traffic. The following constraints are enforced:

- Inbound traffic from specific OSG ranges is allowed for HTCondor job and daemon communication
- Outbound traffic is unrestricted to allow for software installation, data transfer, and job staging
- ICMPv6 and multicast traffic necessary for neighbor discovery are explicitly allowed

There are no intermediate firewalls or NAT devices on the local network path. All firewall rules are managed and deployed via the stateless overlay system to ensure consistency across nodes.

## 4.3 DNS64/NAT64 Infrastructure

To support outbound connections to IPv4-only resources (e.g., public repositories or APIs), the cluster relies on:

- **DNS64 resolvers:** Provided via systemd-resolved on the submit node and propagated to all compute nodes
- **NAT64 gateway:** An external, stateless NAT64 service provided by CAAREN's upstream connectivity

This infrastructure allows IPv6-only nodes to resolve and connect to IPv4 services without needing dual-stack configurations. See Section 6.1.

## 4.4 464XLAT Translation Path

Each node runs a local instance of `clatd`, which invokes stateless NAT64 translation to handle IPv4-bound traffic. This includes glideins, containers, and research workflows that depend on IPv4. See Section 6.2.

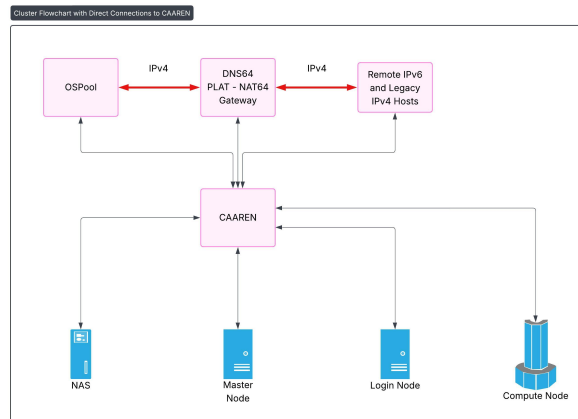


Figure 1: Network overview of the Viper IPv6-only implementation.

## 5 HTCondor Configuration and IPv6 Deployment

Network configuration is thoroughly discussed in the HTCondor documentation [11]. All HTCondor components are configured to operate only over IPv6. The following key values were set on each node via overlay.

### 5.1 Access Point and Central-Manager IPs

Note that the addresses below are reserved for documentation and used for illustrative purposes; they will need to be updated for site-specific networks.

Role	IPv6 Address
Central-Manager (CONDOR_HOST)	2001:db8:0:1::200
Submit/Access Point	2001:db8:0:1::100

### 5.2 /etc/condor/config.d/10\_ipv6.conf

Listing 1: IPv6 Override Settings

```
# submit/access point
UID_DOMAIN = 2001:db8:0:1::100

# central-manager
CONDOR_HOST = 2001:db8:0:1::200
COLLECTOR_HOST = [2001:db8:0:1::200]:9618

NETWORK_INTERFACE = eno1
ENABLE_IPV6 = true
PREFER_IPV6 = true
ENABLE_IPV4 = false

ALLOW_READ = 2001:db8:0:1::/64
ALLOW_WRITE = 2001:db8:0:1::/64
ALLOW_NEGOTIATOR = 2001:db8:0:1::/64
ALLOW_ADVERTISE_STARTD = 2001:db8:0:1::/64
```

By default, HTCondor sets `BIND_ALL_INTERFACES = true`. In a multi-interface environment, each with network routes, it may be necessary to be more selective. As each execute point on Viper has two interfaces (one being the virtual `clat` interface), routing tables are used to sidestep this issue. All IPv6 traffic between Condor daemons is bound to the appropriate interface.

## 6 DNS64, NAT64, and 464XLAT

Viper operates in an IPv6-only environment so some measures are required to enable connectivity to legacy IPv4 hosts and applications. This is achieved through a combination of DNS64, NAT64, and CLAT, an implementation of 464XLAT [9].

DNS64 and NAT64 are required for accessing upstream OSG services, Git repositories, and software mirrors that remain IPv4-only.

## 6.1 DNS64 and NAT64

- **DNS64:** When an IPv6-only host makes a DNS request for an A record (IPv4), a DNS64-enabled resolver synthesizes an AAAA record using a configured NAT64 prefix, often `64:ff9b::/96`, but in the case of Viper an external NAT64 gateway was used.
- **NAT64:** The NAT64 gateway intercepts IPv6 packets destined for these synthesized addresses and translates them to the corresponding IPv4 address, enabling IPv4 interoperability.

## 6.2 CLAT for Application Compatibility

Some applications do not support IPv6, including those that bind to literal, or hardcoded IPv4 addresses. To address this limitation, Viper utilizes the following:

- **CLAT (Customer-side Translator):** An open source implementation [10] of 464XLAT [9], CLATD allows IPv4-only applications to operate in Viper’s IPv6-only environment. CLATD orchestrates the translation of IPv4 socket calls into IPv6, which are then handled by Viper’s provider-side translator (PLAT)—the NAT64 gateway responsible for bridging to legacy IPv4 services.
- **Implementation:** On Viper, CLATD runs on each node and provides its own instance of TAYGA, an out-of-kernel stateless NAT64 daemon. CLATD (and TAYGA) are integrated at boot through systemd units within overlays.

Note, in a dual-stack environment (e.g., while transitioning from legacy to IPv6) it is important that HTCondor not attempt to bind to the virtual `clat` interface for intra-daemon communication. It is typically sufficient to specify the appropriate interface by setting `NETWORK_INTERFACE` and redirecting all other IPv4-bound traffic to the `clat` interface.

Together, DNS64, NAT64, and CLAT allow IPv6-only nodes to maintain operational capability with legacy IP hosts and applications.

## 7 Results and Discussion

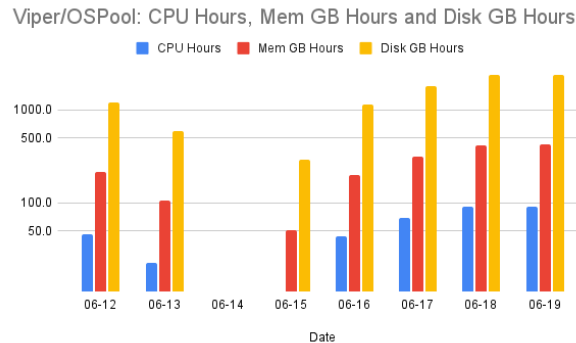


Figure 2: Eight days of processing jobs for the OSPool.

- Viper has been integrated successfully into the OSPool. See Figure 2.

- Despite signaling `ENABLE_IPV4 = false` and `PREFER_IPV6 = true`.
- **DISCUSS SITUATIONS THAT ARE PATHOLOGICAL OR PERNICIOUS**

## 8 Conclusions

Demonstrates that a single-stack IPv6-only resource can interoperate with the broader research ecosystem, legacy IPv4-only hosts.

## 9 Appendix: Site-Specific Notes

### 9.1 Installing CLATD

Due to the stateless nature of Viper's execute images, installing CLATD into an image presents an issue. The CLATD installation procedure doesn't handle TAYGA installation correctly if it cannot start or run daemons, as is the case with modifying an image. For installation on Viper, the CLATD Makefile was modified and TAYGA installed separately. Viper's minimal CLATD Makefile is,

Listing 2: Minimal Makefile for CLATD Installation

```
DESTDIR=
PREFIX=/usr
SYSCONFDIR=/etc

DNF_OR_YUM=/usr/bin/dnf
SYSTEMCTL=/usr/bin/systemctl

all:

install:
    install -D -m0755 clatd $(DESTDIR)$(PREFIX)/sbin/clatd
    pod2man --name clatd --center "clatd - a CLAT implementation for Linux" --section
        8 README.pod $(DESTDIR)$(PREFIX)/share/man/man8/clatd.8 && gzip -f9 $(DESTDIR)
        $(PREFIX)/share/man/man8/clatd.8 || echo "pod2man is required to generate
        manual page"
    if test -d "$(DESTDIR)$(SYSCONFDIR)/systemd/system"; then install -m0644 scripts/
        clatd.systemd $(DESTDIR)$(SYSCONFDIR)/systemd/system/clatd.service ; fi
    if test -d $(DESTDIR)$(SYSCONFDIR)/NetworkManager/dispatcher.d; then install -
        m0755 scripts/clatd.networkmanager $(DESTDIR)$(SYSCONFDIR)/NetworkManager/
        dispatcher.d/50-clatd; fi

installdeps:
    if test -x "$(DNF_OR_YUM)"; then $(DNF_OR_YUM) -y install perl perl-IPC-Cmd perl-
        Net-IP perl-Net-DNS perl-File-Temp perl-JSON iproute nftables; fi
```

### 9.2 HTCondor Configuration

Issues may arise from using short hostnames derived from `/etc/hosts` which we avoided by using IPv6 literals for `CONDOR_HOST`, `COLLECTOR_HOST`, and `UID_DOMAIN`.

## References

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- [8] Giuliano, L., Lenart, C., and Adam, R. (2025). *TreeDN: Tree-Based Content Delivery Network (CDN) for Live Streaming to Mass Audiences*. RFC 9706. <https://tools.ietf.org/html/rfc9706>
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- [11] HTCondor Project. *HTCondor IPv6 Support*. Available at: <https://htcondor.readthedocs.io/en/latest/admin-manual/networking.html#ipv6-support>. Accessed June 2025.