# STRATA Final Report: STudy of INL for RAdio naTional fAcility

**DECEMBER 2024**

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# EXECUTIVE SUMMARY

Spectrum is a valuable resource that is critical for a significant portion of modern society, including air travel, astronomy, wireless and satellite communications, and radar. The exponentially growing demand for spectrum requires a shift from traditional spectrum management. Dynamic spectrum sharing (DSS) has emerged as a viable solution to address spectrum demand. DSS allows users to operate on the same frequency in the same geographic region while limiting interference. Validating DSS techniques requires adequate and reproducible experimentation in representative scenarios. This validation builds the confidence necessary for governing authorities to realize policy changes that allow the deployment of DSS concepts.

The National Science Foundation (NSF) and the White House[a] have responded to the increasing demand for spectrum access with initiatives to facilitate the development of DSS technologies. NSF has initiated a program[b] to develop facilities that allow government, academia, and industry researchers to collaborate and collect data in a consistent and transparent manner. Foundationally, this program intends to enable DSS research by realizing a National Experimental Facility for Spectrum Innovation (NEFSI). In support, Idaho National Laboratory (INL) and the University of Southern California's (USC's) Information Sciences Institute (ISI) partnered to (1) define the requirements for the NEFSI, (2) outline the capabilities necessary for a minimally viable NEFSI, (3) evaluate INL as the NEFSI, and (4) recommend steps to realize this minimally viable NEFSI at INL.

The NEFSI must fulfill technical, economic, management, regulatory, and environmental requirements to effectively validate DSS technologies. The NEFSI must be available to researchers across industry, government, and academia. Further, a NEFSI should support reproducible, comparable, and transparent research to build trust with spectrum stakeholders. The approach to realizing the NEFSI should be modular to facilitate incremental deployment and upgrades of both hardware and software. We suggest leveraging open-source products where applicable to limit vendor lock-in, promote broad access, and enable technology transfer.

As we evaluate the viability of INL, much of the core investment necessary for the NEFSI has already been made. This constitutes a brownfield approach to realization. The cost in dollars and time to raise a brownfield site to a minimal viable NEFSI is significantly lower than developing a new site. We finish by proposing next steps to enable this minimally viable NEFSI, using INL as an example. To this end, we have also developed a NEFSI reference architecture to serve as a guide for potential deployment.

The NEFSI is fundamental in the long-term sustainment of our finite spectrum resource. As technology continues to evolve and new usages emerge, the NEFSI will allow the governing authorities to rapidly react to changes with science driven policies. The definition of what a NEFSI is and does constitutes an important step on the path forward.

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a     https://www.ntia.gov/issues/national-spectrum-strategy, accessed on 12/21/2023.

b     Spectrum Innovation Initiative: National Radio Dynamic Zones

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# FIGURES

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# ACRONYMS

| | |
|---|---|
| ACL | Access-control lists |
| AGL | Above-ground level |
| BEA | Battelle Energy Alliance, LLC |
| BYOD | Bring your own device |
| CDRL | Contract deliverable requirements lists |
| CIE | Cyber-Informed Engineering |
| COTS | Commercial off-the-shelf |
| CPU | Central processing unit |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DSS | Dynamic spectrum sharing |
| EIS | Environmental Impact Statement |
| EM | Electromagnetic |
| EMS | Experiment-management system |
| ESH&Q | Environmental, Safety, Health, and Quality |
| FCC | Federal Communications Commission |
| FFRDC | Federally Funded Research and Development Center |
| FISMA | Federal Information Security Modernization Act |
| GUI | Guided user interface |
| HF | High-frequency |
| Hz | Hertz |
| INL | Idaho National Laboratory |
| IP | Internet Protocol |
| IRON | Idaho Regional Optical Network |
| ISI | Information Sciences Institute |
| LAN | Local area network |
| LRS | Laboratory Review System |
| MNO | Mobile-network operators |
| MPLS | Multiprotocol Label Switching |
| MVP | Minimally viable product |
| NAS | Network-attached storage |
| NEFSI | National Experimental Facility for Spectrum Innovation |
| NEPA | National Environmental Policy Act |

| NRDZ | National Radio Dynamic Zone |
|------|------|
| NRDZCOM | NRDZ community of interest |
| NSA | Non-standalone |
| NSF | National Science Foundation |
| NTIA | National Telecommunications and Information Administration |
| O&M | Operations and management |
| ORAC | Office of Risk, Assurance and Compliance |
| OSM | Office of Spectrum Management |
| PRTG | Paessler Router Traffic Grapher |
| RAM | Random access memory |
| RDZ | Radio dynamic zones |
| RF | Radiofrequency |
| ROM | Rough-Order-of-Magnitude |
| SDR | Software-defined radio |
| SPHERE | Security and Privacy Heterogeneous Environment for Reproducible Experimentation |
| SPP | Strategic partnership program |
| STRATA | Study of INL for Radio National Facility |
| T&C | Terms and Conditions |
| UAV | Uncrewed aerial vehicle |
| UMS | User-management system |
| US | United States |
| USC | University of Southern California |
| VNE | Virtual network embedding |
| VPN | Virtual private networks |
| VXLAN | Virtual Extensible Local Area Network |
| WCRD | Wireless Communications Research Division |
| WTB | Wireless Testbed |
| XDC | Experimental development container |
| XIR | Experiment Intermediate Representation |
| ZMS | Zone management system |

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## 1. INTRODUCTION: A SPACE FOR SAFE INNOVATION

Spectrum is becoming both increasingly scarce and increasingly important. Access to the electromagnetic spectrum has become foundational to modern life as the key enabler for communications systems and sensors across a wide range of application areas. As a result, robust and trustworthy mechanisms for addressing spectrum scarcity are required to enable continued innovation and maintain United States' technological leadership.

Dynamic spectrum sharing (DSS) has emerged as the primary solution to spectrum scarcity. DSS represents a paradigm shift in spectrum management that increases the efficiency of spectrum usage. Under the DSS paradigm, multiple spectrum users operate on the same frequency in the same geographic area while actively adjusting their signals to avoid harmful interference. Importantly, this approach leverages the fundamentally ephemeral nature of spectrum usage to overcome the issues inherent to traditional spectrum management. Traditional spectrum management focuses on static separation of users through long term ownership of frequencies for a given geographic area. However, this approach to spectrum management artificially creates scarcity by ignoring the potential for dynamic, real-time coexistence.

Realizing DSS requires some means to validate that the dynamic controls of DSS systems are adequate to prevent harmful interference[c]. Given the emphasis on the interaction, validation of DSS technology must account for the complexities inherent to the radio frequency (RF) environment. Outdoor, over-the-air testing of RF equipment is required to accurately account for the complexities of the RF environment and the associated impacts on RF signals. Over-the-air testing builds on the foundation established through simulation and controlled laboratory experimentation. Together these elements provide a complete picture of the DSS performance.

The National Science Foundation (NSF) and the White House have acknowledged these research challenges. The White House has called for establishment of a "national testbed for dynamic spectrum sharing." "As a Nation, we must deepen our collective understanding of the electromagnetic (EM) spectrum… if we are to meet the demands of our spectrum-dependent world."[d] This national level focus further emphasizes the need for a testing capability to reproducibly characterize DSS effectiveness.

To enable the realization of DSS, the NSF has championed a National Experimental Facility for Spectrum Innovation (NEFSI). The NEFSI is envisioned as a facility to enable controlled spectrum research with limited impact to incumbents. The research conducted at this facility will build trust with spectrum stakeholders by reproducibly validating DSS concepts. As a fundamental part of building trust, the NEFSI will be broadly available for government, academic, and industry research. This approach allows collaboration and data collection to be consistent and transparent.

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[c]   Chapin, John (11/2023). Introduction to RDZ and NRDZ concepts. In NRDZ Program Community Open Meeting 3.

[d]   https://www.ntia.gov/issues/national-spectrum-strategy, Strategic Objective 3.2, accessed on 12/21/2023.

Our main contributions are:

- Identifying the requirements of NEFSI,

- Outlining the capabilities necessary for a minimally viable NEFSI,

- Evaluating the potential of Idaho National Laboratory (INL) as the NEFSI facility,

- Recommending the next steps for achieving this minimally viable NEFSI at INL, and

- Developing a reference architecture for the NEFSI that serves as a basis for future development and deployment.

When operational, the NEFSI not only will enable DSS experimentation, but provide a facility where broad spectrum research and innovation can be developed and validated. The conclusions, recommendations, and contributions of this report will help drive the NEFSI vision and grow the United States' technical leadership.

## 1.1. A View of National Experimentation

The concept of a radio zone is not new. The National Radio Quiet Zone (NRQZ) has enabled radio astronomy since 1958. The need for DSS has led to a concept like the NRQZ, but used for experimentation called a Radio Dynamic Zone (RDZ). A RDZ is a region that is focused on testing new and novel approaches to spectrum.

Fundamentally, a testbed sits at the heart of all RF testing. NSF has proposed creating a system of RDZs which may be non-contiguous with various emphases, including radio astronomy, Department of Defense (DoD) training or testing, and experimental research facilities. Known as the National Radio Dynamic Zone (NRDZ) this system of RDZs enables transferability of the spectrum experimentation to leverage the strengths of various RDZs to further the development of broad-spectrum concepts like DSS. The NEFSI is envisioned as a uniquely capable RDZ to accelerate innovation in advanced wireless and spectrum management by providing researchers with increased freedom in spectrum access and reduced experimental delays.

The NRDZ system would facilitate a broad scope of research and testing needed to leverage multiple locations to enable spectrum innovation. Initially, a wireless experiment might require testing in an anechoic chamber, followed by open-air testing at a remote RDZ site with low noise and low probability of interference. This would allow for a high degree of control of the experimentation and vetting of new technologies. Once that is complete the testing could be moved into an urban or other RDZ that would be more representative of the final usage. The transferability of the spectrum experimentation is ideal to rapidly prototype and assess whether the technology is viable. When fully operational the NRDZ will enable new spectrum usage models, sharing strategies, and technologies. As part of this larger research infrastructure, the NEFSI is envisioned as a well-controlled, low-risk and highly-capable RDZ to support any stage of spectrum experimentation.

Figure 1 illustrates the high-level concept of the NEFSI. Primarily, the NEFSI supports reproducible experimentation and testing for government, academic and industry researchers. This necessitates managing RF interference among research and non-research activities within the NEFSI as well as RF interference from outside of the NEFSI. In the figure, the Zone Management System (ZMS) monitors the environment to track interference and inform spectrum provisioning. The Experiment Management System (EMS) handles the control and provisioning of radios and

supporting hardware. The EMS provides overall management of the experimentation zone by incorporating the spectrum information provided by the ZMS as well as facilitating remote access to experiment resources and data. Together the EMS and ZMS capture both the configuration parameters and environmental conditions necessary to reproduce any experiment or testing conducted in the NEFSI.
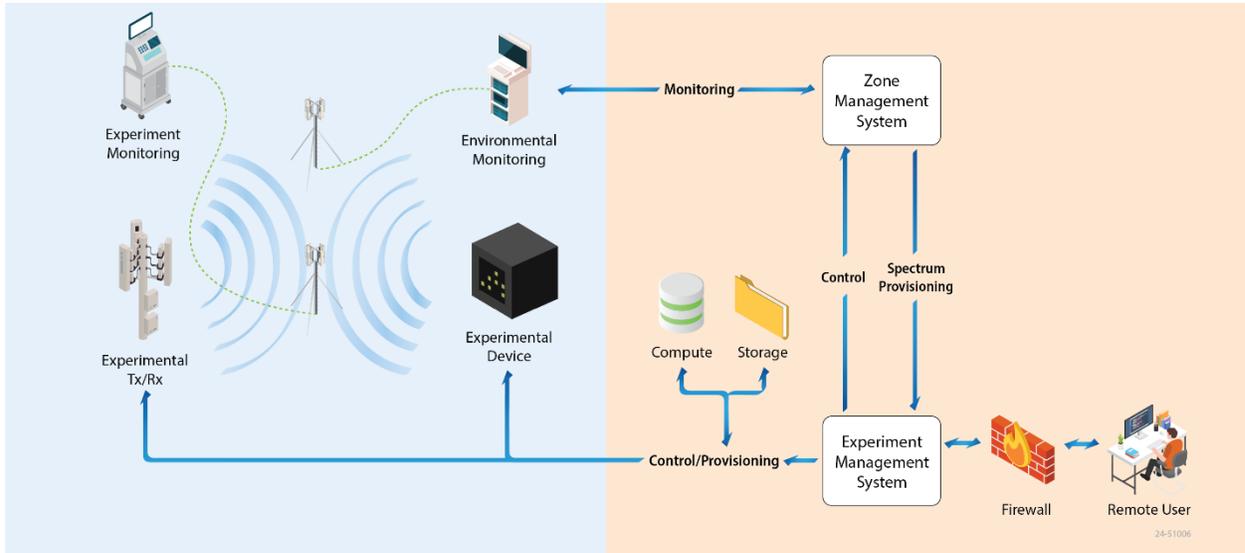


Figure 1. Simplified NEFSI Architecture.

Some research in spectrum innovation will delve into sensitive topics. Thus, the NEFSI's management must maintain a strong set of security capabilities and monitor for potential security violations. Protecting the intellectual property and security of work done at the NEFSI is critical to establishing trust in researchers.

Researchers across the community want to innovate leveraging as much spectrum as possible. This requires that the NEFSI provide access to both the spectrum regulated by the National Telecommunications and Information Administration (NTIA) and that under the Federal Communications Commission (FCC). Additionally, NEFSI RF management and monitoring capabilities would ideally span all bands. This involves monitoring and controlling signals entering, escaping, or occupying the NEFSI including rapid termination of experiments as necessary to avoid harmful interference. This control is foundational to maintaining both a reproducible environment within the NEFSI and preventing impact to spectrum users outside of the NEFSI.

The next section of this report shall define the requirements for a NEFSI to meet the needs of a diverse set of spectrum stakeholders, including researchers, regulators, law-makers, and so forth.

# 2. NEFSI CONDITIONS

We propose six high-level, critical conditions that any NEFSI site must satisfy to fully accomplish the NEFSI goals. These conditions are:

- *Location*. A NEFSI is an RDZ and so will require space for outdoor testing and structures necessary to house NEFSI components. Ideally, a NEFSI would provide indoor spectrum testing facilities for laboratory and anechoic chamber testing for innovative waveforms. Other ideal location characteristics include a range of landscape features relevant to spectrum research and physical separation from concentrations of non-participating wireless emitters.

- *Technical*. The required NEFSI technical capabilities include hardware resources, remote access, shared resource management, automation, experimental isolation, data storage, and system security. This includes setting up new technologies and maintenance of existing ones.

- *Management*. Smooth NEFSI operation demands mechanisms to provide expected maintenance and resolve any potential conflicts. Procedures are needed to ensure users are properly trained and maintain safe operation of equipment. NEFSI management must also enable long-term sustainability through thoughtful and timely technical enhancements.

- *Economic*. Diversity of funding streams would make a NEFSI resilient to changes in sponsors' interest over time and promote usage by communities with various monetary resources.

- *Regulatory/Political*. Every NEFSI must operate within the appropriate regulatory environment and be responsive to oversight. Ideally, a NEFSI holds broad spectrum authority to enable experimentation without placing additional requirements on researchers.

- *Environmental*. A NEFSI requires mechanisms to identify and mitigate environmental and cultural concerns.

We note that not all conditions must be exhaustively satisfied to enable initial testing of spectrum innovations like DSS and interference characterization. This allows us to define the capabilities of a minimally viable product (MVP) NEFSI. We propose that establishment of an MVP NEFSI would promote early testing, demonstrate capability, and enable gradual funding from multiple sources.

## 2.1. NEFSI Location

The location of a NEFSI must provide sufficient space to allow for broad access to reproducible testing in a controlled environment. Access to representative, outdoor, over-the-air testing is a primary value of the NEFSI concept. This implies that researchers should be able to deploy equipment in physical configurations that reflect their scenario of interest within the bounds of a NEFSI. Given the goal of broad accessibility and rapid prototyping, the location should be large enough to support multiple, simultaneous experiments without harmful interactions. Maintaining high accessibility across the full spectrum also implies that many of these simultaneous experiments will overlap in frequency and must therefore be widely separated. Beyond providing space for outdoor testing, a NEFSI location must provide enough space for the necessary infrastructure and in-door components. Ideally this includes both laboratories and anechoic chambers.

The characteristics of the NEFSI location impact both applicability and sustainability. As discussed in Section 1.1, remote sites with low probability of interference may be well suited to exploration of new spectrum technologies. However, the remote nature of the site increases the challenge of traveling to the site for experimentation. Additionally, some environments, such as urban settings, may provide particularly representative environments, but would also require more robust mechanisms to handle interference external to the NEFSI. Similarly, a large area for testing within a NEFSI could support representative tests of large-scale systems but acquiring and supporting a large area would increase sustainment costs. Thus, the location selected for a NEFSI may achieve maximum sustainability value through a multi-purpose mission.

## 2.2. NEFSI Technical Capabilities

Technical capabilities are required to successfully conduct experiments, monitor potential interference, and collect results. Robust, controlled, and repeatable experiments are key for gaining trust with stakeholders. A successful NEFSI would require these specific capabilities:

- Spectrum-monitoring resources,
- Wireless and wired infrastructure,
- Data collection, storage, and analysis tools,
- Experiment management tools,
- Remote and shared access mechanisms,
- Access control and experiment isolation techniques,
- Network administration and cybersecurity-monitoring tools, and
- Multiple sensitivity levels.

A NEFSI must be able to control and monitor spectrum experiments, as well as share results with remote stakeholders and control sensitive data. As technical requirements for validating spectrum innovations change, the NEFSI will need to evolve with it. This could be many things from frequency expansion to specialized test equipment. The technical staff will need to install, configure, and integrate new equipment for the emerging requirements as well as maintain existing infrastructure.

To help facilitate the development and deployment of the NEFSI technical capabilities, we have created a reference design discussed in Appendix A, Initial Reference Design. This design includes necessary hardware and software components and identifies missing components that will need to be developed.

### 2.2.1. Spectrum Monitoring Resources

Spectrum monitoring directly affects the reliability and reproducibility of spectrum innovation test results. Spectrum monitoring capabilities serve multiple purposes for DSS and spectrum innovation research.

- Baseline monitoring: collecting data from the surrounding environment to determine whether non-test signals are likely to affect test results.
- Data collection: monitoring both the system under test and general testing environment.
- Interference determination: tracking the allocated frequencies to quantify interference between experiments and incumbents.

Spectrum monitoring requires both spectrum-monitoring hardware and the software to actively observe spectrum and detect signals. Further, collecting spectrum baselines and experiment data

in standardized formats allows for comparable results.

A fully capable NEFSI would require broad spectrum monitoring. While several spectrum monitoring technologies exist, these technologies focus on specific frequency ranges. Broad spectrum monitoring will most likely require leveraging multiple technologies covering different portions of the spectrum. An initial deployment plan would focus monitoring on portions of the spectrum of most interest to researchers. The total amount of spectrum monitoring required would be based on the target spectrum, transmission power, and geographic location.

Currently there is no single standardized output of spectrum monitoring technology. While In-Phase and Quadrature (I/Q) data is a common output, I/Q data is not universally available and often too granular for the needs of spectrum monitoring. Standards for higher level representation exist, such as the Signal Metadata Format Specification (SIGMF) and Hierarchical Data Format 5 International Telecommunications Union Radiocommunications Sector (HDF5-ITU-R). Beyond these, several monitoring systems use proprietary formats. Mechanisms will be required to translate formats to support broad accessibility.

Spectrum monitoring data is utilized by the ZMS to facilitate interference management. The ZMS receives information about the expected emissions for each experiment from the EMS and sends alerts when experiments operate outside expectations. Further, the ZMS processes all RF monitoring inputs to detect interference and anomalies. To ensure timely interference management, spectrum-monitoring should be highly automated. Run-time rules or controls in the DSS technology exist to automatically adjust its spectrum access depending upon external conditions. NEFSI monitors must also be able to quickly detect anomalies, and the ZMS must rapidly act on this input to protect experiment accuracy and incumbents.

## 2.2.2.   Relevant Wireless and Wired Infrastructure

DSS research requires a combination of wired and wireless infrastructure, adaptable to the testing needs of the experiments. We recommend that experiment control and data management leverage wired infrastructure, freeing the wireless infrastructure for experimentation. This approach preserves spectrum for experimentation and provides a robust control framework.

Wireless infrastructure can include traditional cellular deployments, mesh/MANET deployments, or other radios for experimentation. Ideally, a NEFSI would have access to SDRs or other flexible RF frontends that allow experimenters full transmission control. Researchers should also deploy hardware, enabling examination of novel spectrum usage. Remote and shared access to wireless radios is desirable to support broad accessibility.

Beyond wireless infrastructure, wired infrastructure that can interconnect all portions of the wireless infrastructure is required. A robust NEFSI would have wired infrastructure across four planes:

- A control plane to manage all experimental resources,
- An experimental plane that can emulate networks as needed by experimenters,
- A data plane that can operate at line-rate for storage, aggregation, and processing, and
- A physical access plane that enables connectivity for experimental devices in useful positions.

Ideally, the wired infrastructure would present a non-blocking, fully connected network that could be dynamically configured automatically, based on experimental needs. This wired

infrastructure would support the data rates required by DSS experiments as well as isolation and protection mechanisms that maintain confidentiality of customers' data.

Passing spectrum and experiment data demands high data rates that are most readily provided by wired infrastructure. Data rates for a single RF monitor typically range between 100 and 500 Mbps for 20 to 100 MHz of bandwidth. To support the upper end of this range, fiber cables of at least 40 Gbps must be deployed between the experimental equipment and the interconnect switches. The switches themselves need a non-blocking backplane of nearly 3 TB/s, with multiple high-capacity upstream ports. Further, network devices should support such common network-isolation technologies as Multiprotocol Label Switching (MPLS) and Virtual Extensible Local Area Network (VXLAN).

Achieving broad accessibility requires managing simultaneous RF tests to avoid logistical delays. Wired infrastructure would need to be adaptable to support a multizone testing infrastructure. A multizonal architecture would require sufficient wired infrastructure to connect each zone to the central backend. The structure of this infrastructure will be dependent on the communication requirements between the zones and to the backend.

Wired infrastructure also includes facilities with internet connectivity, lighting, heating and cooling for onsite researchers while they collect, analyze, display and share results. Electricity and fiberoptic cables at the physical access plane ease set-up for each experiment.

### 2.2.3. Data Collection, Storage, and Analysis Tools

Figure 1 notes the centrality of collection, storage and analysis capabilities. Spectrum experiments can generate large amounts of data. These data generation rates necessitate compute technology that can condition, process, provide near-real-time analysis, and save large amounts of data.[e] Achieving this capability must account for any associated burden on network and storage facilities. An expandable, large-scale storage cluster should be deployed to handle a variety of experiments, scaling both in size and duration. In a multizonal architecture, multiple storage clusters could be deployed, reducing backhaul throughput requirements and enabling data isolation between customers. We further recommend the use of edge-based and in-network processing to handle the anticipated data volume and reduce the burden on the storage clusters. We note that there will need to be a budget for regular hardware refresh.

### 2.2.4. Experiment Management Tools

Experiment management encompasses the entire life cycle of an experiment. The required capabilities in this area include:

1. Experiment Definition. While no universal wireless-experiment definition format exists, multiple open-source example experiment formats do, including XIR used by MergeTB and RSpec used by POWDER. Use of an existing format allows a NEFSI to build on existing capability and user base. In some cases, extensions to cover unique NEFSI capabilities, such as the target spectrum and the physical location of resources, may be required.

2. Plausibility Analysis. This analysis determines whether the described experiment is able to run within a NEFSI. This includes determining whether (1) the resources requested and connections between them can be mapped to the physical infrastructure, (2) the spectrum

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[e]   For example, a simple experiment with four spectrum monitors and three experimental Tx/Rx devices could potentially generate 280 Gb/s of data. If all that data were stored raw, it would generate 1 TB of data every 30 seconds.

requested is available/allowable, and (3) the RF power requested will result in unallowable interference. Tools exist to determine the plausibility of a virtual network embedding onto underlying physical resources.[f] Determining spectrum availability and potential interference are the responsibility of the ZMS. Spectrum availability analysis involves comparing the requested spectrum to the bands available within a NEFSI. Potential interference analysis is based on propagation modeling to determine whether interference is likely to be harmful to external incumbents or other experiments. This requires accurate propagation and terrain models of the given environment using tools, such as Hz Warfare, and validated with environmental measurements.

3. <u>Scheduling</u>. Experiment scheduling requires both spatial and temporal awareness. While many test infrastructures use a first-come, first-served model, the potential interference generated by RF experiments requires a more-robust scheduling mechanism. A fully capable NEFSI will employ a schedule that considers the type of experiments being conducted, staggering potential interferers while maintaining fairness. The schedule should be also account for security concerns, as discussed in Section 2.2.8. Finally, the schedule may need to consider dynamic spectrum availability outlined in agreements with local incumbents.

4. <u>Provisioning</u>. Given the scope and physical characteristics of NEFSI experiments, we recommend automated experiment provisioning as much as possible. Tools such as Ansible currently exist to enable automated provisioning and configuration of networks, switches, and computing resources. However, these tools will need to be extended to enable control of RF devices. Further, a common provisioning application programming interface (API) may ease integration of bring-your-own-device (BYOD) experiments or future devices to be controlled by the provisioning tools.

5. <u>Monitoring</u>. Experiment monitoring broadly covers maintaining and validating the health of an experiment. This focus on the experiment control and computational resource consumption as well as the ZMS-managed spectrum monitoring covered in Section 2.2.1. Here, monitors ensure that the control parameters sent to experiment resources are within the bounds set by the experiment definition and that computational resource consumption is within expected levels. Selecting infrastructure that can self-report constraint violations will improve experimental monitoring. This monitoring data is also analyzed to report any anomalies in the testing infrastructure.

6. <u>Termination and Cleanup</u>. Nominally, termination and cleanup would occur when an experiment reaches its natural conclusion. However, an important NEFSI capability is the rapid termination of an experiment when it exhibits unhealthy behavior or begins to generate interference. No matter the situation, the cleanup capability involves confirming that systems have returned to an idle state and resources were released.

The EMS provides these experiment management capabilities (see Figure 1). Several testbeds currently use automated EMSs, including the Merge Testbed Ecosystem. However, available EMSs will likely need extensions to support uncommon NEFSI requirements. For example, the physical location of NEFSI resources is an important scheduling consideration for multizone interference management that is not currently considered by existing EMSs. Additionally, the NEFSI EMS must coordinate with a ZMS for spectrum management.

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[f]  Zheng, Y., Ravi, S., Kline, E., Koenig, S., & Kumar, T. S. (2022, June). Conflict-based search for the virtual network embedding problem. In *Proceedings of the International Conference on Automated Planning and Scheduling* (Vol. 32, pp. 423-433).

## 2.2.5.    Remote and Shared Access Mechanisms

Remote access is critical to reduce scheduling delays for experiments, accelerate innovation, and provide researchers with more freedom to access NEFSI spectrum. Remote access also enables more researchers to utilize the NEFSI by reducing the burden of physically traveling to the site. Similarly, shared access allows several different users to access the facility without necessarily requiring a reservation or a complex schedule. While resources themselves will have to be reserved and potential conflicts resolved due to the broadcast nature of RF transmissions, different resource groups can potentially be used simultaneously, increasing the overall value of the facility.

The EMS and ZMS provide the support for multiple simultaneous users through resource reservation and interference analysis. Importantly, these capabilities must allow sharing between researchers if they are remote or local. Ideally, each NEFSI would also support various experimenter-assigned roles such as observers that could monitor an ongoing experiment without any control privileges. This also should allow either remote or local users to be specified as observers.

Remote access technologies have become common place, and standard technologies are readily applied to a NEFSI. A staple of remote access is strong authentication and zero-trust technologies that provide strong protections for both experimenters and the NEFSI. Supporting these technologies is likely to required dedicated resources within a NEFSI, but the expanded access that this offer is worth the additional cost.

## 2.2.6.    Access Control and Experiment Isolation Techniques
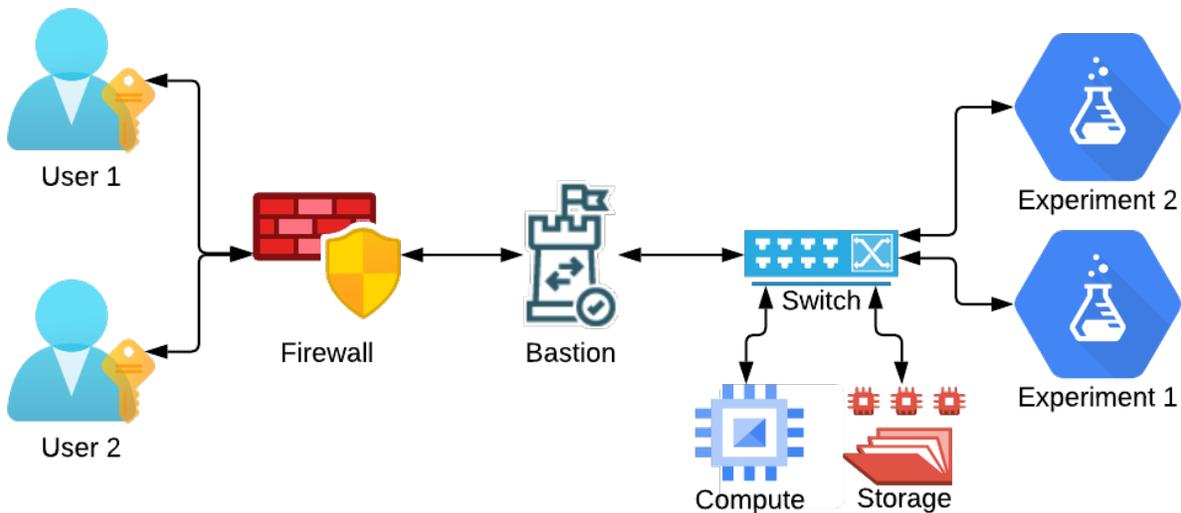


Figure 2. Example of Shared Access

Access control prevents users from interacting with systems without appropriate authorization. Modern access control methods, such as access-control lists (ACLs) and temporary access tokens, are applicable to a NEFSI. Configuration of these should employ recognized best practices such as zero-trust principles, deny-by default policies, and regulated access through bastion servers.

Experiment isolation ensures that one user cannot influence or observe another user's experiments or results. As shown in Figure 2, several infrastructure components are likely to be shared even if radios or spectrum are not. Virtual private networks (VPNs) are particularly

applicable to the isolation of network connection on a per experiment basis. Further, network segment isolation should be used with techniques such as MPLS or VXLAN to minimize cross-traffic interference. Virtualization and containerization provide a similar capability for shared compute platforms. Data storage should be dynamically allocated to a single experiment in addition to requiring user authentication.

Access control and experiment isolation technologies are readily available. Data-centers feature robust access-control and isolation capabilities for computational resources, networks, and data storage but do not provide the experimental fidelity mechanisms that the NEFSI would require. Several existing testbeds apply these principles for experiment resources, such as the Merge Testbed Ecosystem.

## 2.2.7. Network Administration and Cybersecurity-Monitoring Tools

Network administration requirements include detecting failures, congestion prediction, and continuous monitoring. Fortunately, multiple mature network management, fault-detection, and usage-tracking tools are available. Allowing broad accessibility necessitates establishing strong cybersecurity mechanisms. Beyond the discussions in Sections 2.2.4 and 2.2.6, every NEFSI requires continuous threat monitoring and intrusion detection. Maintaining certification of security mechanisms for the network in accordance with the Federal Information Security Modernization Act (FISMA)[g] is a fundamental requirement.

The design of a NEFSI ought to reflect Cyber-Informed Engineering (CIE) principles to achieve comprehensive and maintainable cybersecurity. CIE is an engineering approach that integrates cybersecurity considerations into the conception, design, construction, and operation of any physical system that has digital connectivity, sensors, monitoring, or control. Rather than add cybersecurity controls after the design is complete, CIE focusing eliminating or mitigating avenues for cyberattack starting from the earliest stage of design and continuing throughout the system's life cycle.[h] Adopting NSF's Trusted CI principles will also provide confidence for potential experimenters.[i]

## 2.2.8. Multiple Sensitivity Levels

We expect that customers will conduct testing with variable sensitivity requirements ranging from at least public access, to proprietary, to classified. Satisfying this need requires sufficiently mature management capabilities that are vetted across several sensitivity levels. This may also result multiple sets of equipment to physically separate different sensitivity levels. Further, classified experimentation may require enhanced scheduling to ensure temporal separation between classified and unclassified experiments. Physical-security systems are also required to protect wired infrastructure and facilities from tampering.

## 2.3. NEFSI Management Capabilities

Management capabilities enable a NEFSI to operate smoothly and sustainably. This begins with attracting, retaining and developing a knowledgeable and accessible test-support and management staff. Staff familiar with spectrum innovation and standards development would

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g    https://www.govinfo.gov/app/details/PLAW-113publ283/, accessed 11/22/2024.

h    US Department of Energy, Office of Cybersecurity, Energy Security, and Emergency Response, Cyber-Informed Engineering Implementation Guide, Version 1.0, INL/RPT-23-74072, 08/07/2023, pg 8.

i    https://www.trustedci.org/

enrich the NEFSI testing environment to achieve the White House's vision of maintaining US leadership.[j] At a minimum, proper test setup and experiment management involves NEFSI staff's directly supporting experimenters to address issues, assure safety, and promote fair usage.

NEFSI staff must also educate users and experimenters. Experimenters must be knowledgeable enough to prevent damage to the facility and equipment. They should also be aware of the facility's capabilities, rules, and relevant regulations. The staff may also need to vet users, only allowing access to acceptable users. How vetting is conducted will be left open to the NEFSI's operation policies, but may include internal vetting, application reviews, or even a third-party vetting service.

Beyond the technical capabilities, NEFSI staff also require skills to manage experiment resources. Due to the volatile nature of spectrum testing, NEFSI staff may need the ability to manually reset devices, tear-down isolation, and remove access in a timely manner. Staff will also need the ability to overcome technical issues users might experience, including lack of required access or resource starvation. Remote access also adds the challenge of helping users who are not physically present and may be in different time zones.

NEFSI staff must stay in tune with the trend and needs of spectrum innovation research. We expect some staff to participate in events and academic conferences to assess research trends and make the community aware of new NEFSI capabilities. Lastly, NEFSI staff will need to maintain the infrastructure, replace or upgrade equipment as necessary, and potentially develop new functionality as new capabilities become available.

Management must establish and maintain a safety culture to sustain significant testing capabilities. NEFSI operations will require traditional roles, including human resources, accounting, physical security, transportation, firefighting, legal and medical staffs, as well as associated equipment, vehicles, and policies. Depending on the location, other staff may be required to meet specific location-based needs.

## 2.4.  NEFSI Economic Capabilities

As a national asset, NEFSI technical capabilities must be sustainable long-term. This means that each NEFSI must be funded to plan for, track, maintain, and update equipment, infrastructure, and software. NEFSI facilities must also be maintained, including buildings and infrastructure. Furthermore, an enduring NEFSI will need to ensure periodic modernization of reference architecture and plan for retirement of disused technical capabilities.

Like any national facility, each NEFSI must understand its operational costs, costs per experiment, maintenance costs, and potential budgets for upgrades. Many of these costs will be derived from the size and scale of the NEFSI. We expect that economies of scale will benefit every NEFSI, with costs per experiment reduced as more experiments are executed. This is due to the experience gained from any given experiment, any leave-behinds from the experimenters, and overall streamlined operations.

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j    https://www.ntia.gov/report/2023/national-spectrum-strategy-pdf, accessed 11/22/2024.

For operational costs, a NEFSI could use several potential models:

- Direct Government Funding. In this model, the government directly funds the NEFSI with a fixed yearly budget. Costs are not passed on to experimenters or researchers, except in special circumstances (e.g., deployment of significant BYODs). This option provides the least burden on experimenters but will require significant legislative efforts. Examples of this model include the National Radio Quiet Zone and the National Cyber Range.

- Direct Industry Funding. Industry or industry groups most likely to benefit from a NEFSI come together to fund it with a fixed yearly budget. Like government funding, costs are not passed on to experimenters. However, given the funding mechanism, industry partners may expect priority access to the NEFSI. This may discourage some researchers from using the NEFSI. Lastly, industry priorities may change rapidly, resulting in a sudden loss of funding. The most-common example of this model is the pharmaceutical industry funding academic research labs.

- Industry/Government Cost Share. This is a combination of Models 1 and 2, where industry and government split the operational costs. This model gains many of the benefits of direct government funding while reducing the detriments of direct industry funding. There are multiple examples of cost-sharing between industry and government, including Department of Transportation's Safe Streets and Roads for All, FEMA's Hazard Mitigation Assistance, and NTIA's NOFO 2 for Open Radio Units.

- Fixed-term Government Funding. Unlike Model 1, this has the government provide funding for a fixed-term, after which a NEFSI would need to reapply for funding. While there is little burden on experimenters, there is a significant chance that no funding may be provided after the initial term, reducing long-term sustainability of the facility. This model is heavily used for national research infrastructure with the most-relevant example being NSF's Mid-scale Research Infrastructure.

- Cost Recovery or Pay Ahead. These models follow a simple approach, the experimenters will pay to use the facility. Cost recovery assumes that users will pay after concluding their effort with some understanding of what their costs will be prior to beginning their experiments. Pay ahead has users pay upfront to use the facility; researchers can continue to use a NEFSI if they have outstanding credits. Both models are useful for promoting sustainability of the facility because the facility recuperate funding as it was used. Further, the facility's utility as research infrastructure and its revenue are directly proportional. That is, if the facility is useful, researchers will be more likely to use it. A significant challenge to this approach is the burden placed on researchers, specifically academics or underserved communities that might not be able to afford the costs. Another limitation would be the ability for capital investments to enhanced capabilities. Examples of this type of funding include many of the US national laboratories.

- Research Grant/Contract Rider. In this model, researchers who want to use the facility request funding to do so when writing a grant or contract proposal to a funding agency. If awarded, funding to use the facility is put aside and directed to the facility. A pool of funds for researchers to use the facility may be allocated at various funding agencies and provisioned on a per-application basis. Examples of this model include NSF's FABRIC and CloudBank capabilities.

- Donations. A donation-based model assumes that the facility has sufficient utility that individuals, corporations, or the government are willing to make regular donations to keep it functional. The fundamental challenge involved in this model is initial cost because the facility must prove its utility before donors are willing to donate. Donations may also be highly volatile from year to year. We could not find a direct example of donation-based research infrastructure. The most similar example were research charities, such as the American Cancer Society, which collects donations to fund research.

- Hybrid. A NEFSI is not required to have a single funding model, and a combination of any of the above models may be the best funding strategy. For example, government could directly fund a portion of a NEFSI, specifically for academic research. Industry researchers, on the other hand, would be expected to pay for use.

While this report identifies multiple possible funding models, we do not recommend a funding model at this point. The final model chosen would depend on the goals for a NEFSI, the target communities, the expected overall cost, and the appetite in Congress and industry to get involved. If the goal of the NEFSI is to have a facility open to industry, government, and academics, then we do recommend that the funding model be cognizant of the various economic factors at play in those different communities. We note that the funding model can change over time, based on the utility and capabilities of the NEFSI.

## 2.5. NEFSI Regulatory and Political Capabilities

A NEFSI needs authority to manage and approve experimental use of spectrum. This spectrum authority could be achieved through an Experimental Radio Station designation from the NTIA and/or an FCC experimental use license. Alternatively, Congress could legislatively define the NEFSI and direct spectrum regulators to delegate appropriate authorities for research and testing. Given that the NEFSI is intended to support both the public and private sectors, authority that spans both the NTIA and FCC would be ideal. Such broad-spectrum access directly aligns with the NEFSI goal of making spectrum research and innovation widely available and applicable.

Spectrum authority at a NEFSI should be embodied by a spectrum manager. This individual would maintain accountability to spectrum regulators, stakeholders, laws, and regulations. The spectrum manager would enable efficient test scheduling through close cooperation with spectrum regulators and local licensees. Technologies that automate scheduling, potential interference analysis, and spectrum allocation can minimize the burden on spectrum managers and enable faster experimentation.

Beyond spectrum authorities, any NEFSI must have adhere to several other laws and regulations. For example, NEFSI operation requires compliance with FISMA, as discussed in Section 2.2.7, and the National Environmental Policy Act (NEPA), as will be discussed further in Section 2.6. Each NEFSI will need well documented policies and processes that guide users to operations that align with NEFSI policies.

# 2.6. NEFSI Environmental Capabilities

The NEFSI will be a partner with the local environment and must be compliant with NEPA[k] in constructing or maintaining facilities for testing. This will allow long-term usage while not negatively impact the surrounding region or communities. It will also serve as a governance of physical resources allowing decisions to be made that promote long-term sustainability.

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k    https://www.epa.gov/nepa, accessed 11/22/2024.

# 3. CREATING A NEFSI

The STRATA team has identified that a trade-space may be defined between the capability considerations listed in Section 2 and the costs estimated to create a fully-capable NEFSI. In a cost-informed approach, the requirements of a fully capable NEFSI are defined by the research required at the NEFSI during the near-future. Therefore, the NEFSI may be iteratively refined from an initial MVP state to progressively meet gradually increasing testing demands for spectrum innovation.

## 3.1. NEFSI Minimum-Viable Product

Not all conditions must be fully satisfied to encourage innovative spectrum research. An MVP NEFSI supports early tests by prioritizing initial funding for NEFSI capabilities according to its reference architecture. The gradual development approach may delay some proposed tests while capabilities are deployed.

We postulate that an MVP NEFSI needs the following minimal capabilities:

1. Capacity for a single DSS experiment at any one time, including spatial, spectrum, and support capabilities,

2. Spectrum monitoring on the testing frequencies,

3. Mechanisms for experiment termination when interference or violations are detected,

4. Remote access with strong access controls to allow experimenters to control their experiments and retrieve or process results,

5. Compute with semi-persistent storage to process and maintain results,

6. User vetting to ensure only authorized and appropriate users can use the facility,

7. An initial economic model to provide seed funding for the facility and experiments, and

8. Appropriate management controls to comply with relevant laws and statutes.

Scaling beyond this MVP requires first adding capabilities for handling multiple experiments and then streamlining these. For example, scaling the MVP requires adding experiment isolation. Further scaling is likely to require automation of experiment control and scheduling. The reference architecture described in Appendix A, Initial Reference Design allows for linear scaling of infrastructure.

## 3.2. Greenfield vs. Brownfield NEFSI Deployments

Practically speaking, there are two options for the NEFSI: build fresh or modify existing facilities. A new construction on previously undisturbed land is often known as "greenfield" while a construction upon previously disturbed land is called "brownfield" (see Figure 3). Brownfield construction has advantages, including cost and time savings due to previous investments on the land. However, at least two risks exist with leveraging brownfield sites. First, rework of existing brownfield conditions can be expensive and time-consuming compared with greenfield construction. Second, prejudicial bias towards a brownfield location may occur if a site is already conducting a specific type of research. Alternatively, greenfield constructions benefit from a new design at a premium cost and bears additional risks such as attracting and retaining staff under a new management culture.
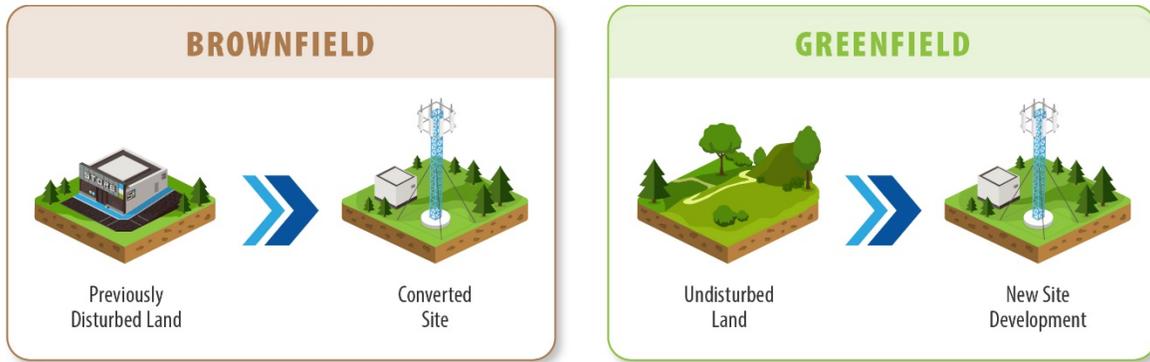
Figure 3. Brownfield vs. Greenfield construction.

## 3.3. NEFSI Greenfield Rough-Order-of-Magnitude Cost Estimate

We have produced a rough-order-of-magnitude (ROM) greenfield NEFSI cost estimate as a benchmark. Details of this ROM cost estimate are included in Appendix C. Several assumptions were made to estimate the upfront ROM cost of building an MVP greenfield NEFSI:

- Land is owned; acquisition costs for land were not included in ROM

- At least five square miles of land are needed for outlay of towers, infrastructure and facilities (Section 2.1)

- At least three roads, 50% gravel and 50% paved, are required

- Five necessary facilities, which may be combined in some fashion, will include a data center, office building, maintenance facility, medical clinic, and fire station

- Towers will include three fixed and two mobile towers.

- An environmental impact statement (EIS), including cultural and ecological studies, can reasonably be expected prior to building the assumed MVP greenfield NEFSI. Planning, research, stakeholder consultation, including public notices and hearings, and other EIS documentation and approvals are expected to require 2 years to complete, with costs toward the median of $1.5–7 million.[1]

- Full lifecycle costs were *not* included: operational costs, maintenance, salaries, etc.

Again, this cost estimate does not reflect costs for INL (as a brownfield) to provide MVP NEFSI capabilities. Instead, as a benchmark, a parameter-based ROM cost estimate found that total design and installation costs for a greenfield MVP NEFSI are about $124 million, with a low-end range of $100 million and a high-end range of $150 million. Further, 42 United States Code 16, §1862n–4 and Public Law 114-329 requires that the NSF director provide life-cycle cost estimates, which means that multiyear operational and sustainment costs would have to be added to the ROM cost estimate. Without identifying the site and desired scale of the NEFSI the sustainment cost is difficult to estimate at this stage.

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[1] The EIS estimate is based on discussion with the INL NEPA group.

# 4. IDAHO NATIONAL LABORATORY AS A BROWNFIELD NEFSI

The STRATA report was specifically awarded to assess INL as a national radio facility. Since award, the concept of a national radio facility has focused into defining the NEFSI. INL presents a brownfield option to realize the NEFSI by leveraging capabilities developed, refined and maintained over more than 20 years. We estimate that INL currently meets or exceeds 95% of MVP NEFSI criteria relevant to near-term DSS research. A small set of strategic investments made over time would allow INL to achieve all MVP NEFSI criteria.

## 4.1. INL's Location

The INL Site is 890 square miles with unrestricted airspace above 1500 ft above-ground level. The INL desert site (Figure 4) is situated in southeastern Idaho, with surrounding mountains that enable real-world environments and help to isolate RF emissions. The test range is at 5000 ft average elevation, with one radio site at 8628 ft elevation. There is limited impact from military bases, international airports, or urban areas, and the caldera landscape provides natural RF shielding.
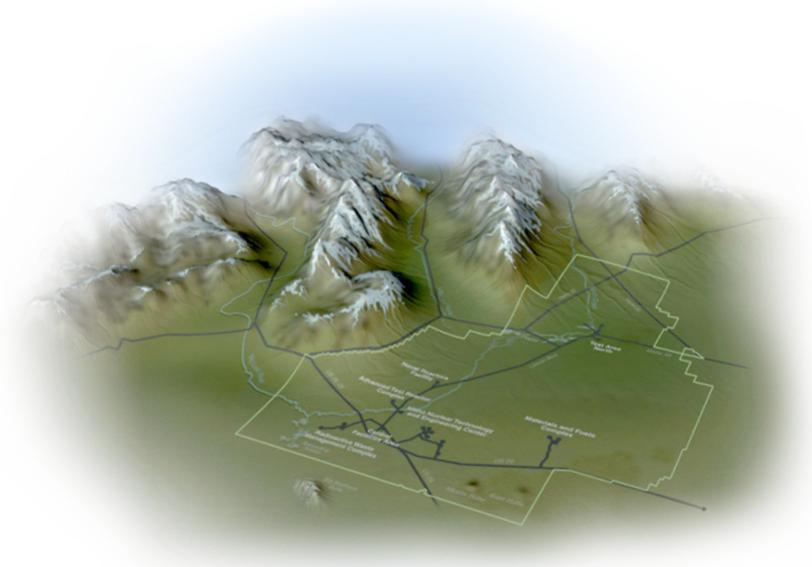


Figure 4. Aerial view of INL site and neighboring mountain range.

INL provides a quiet RF environment. INL researchers are also exploring methods for federation of spectrum-innovation testbeds, including data and methodology transparency between multiple interested spectrum-experimentation ranges. This allows for other ranges to have access to the natural conditions of the INL site. Geology and remoteness preserve a quiet RF environment. On average, and measured in 10-kHz binned channels, the Site's noise floor is less than -120 dBm (Figure 5).
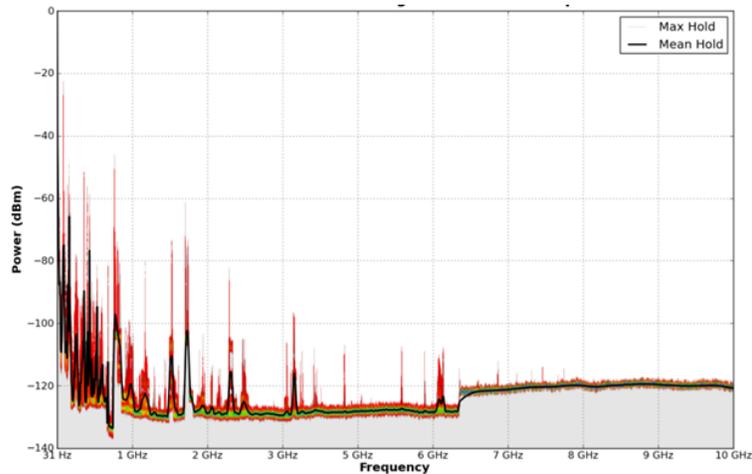
Figure 5. Measured spectrum at INL Range (31 Hz to 10 GHz).

The INL desert site has a wide range of complimentary capabilities. It has an uncrewed aerial vehicle (UAV) landing strip and routinely supports aerial-based tests on various platforms, payloads, and emitters. There is also a representative water and electrical distribution test facility allowing for integrated application-level testing of DSS.

The INL range is located about a 45-minute drive from the greater Idaho Falls area. Idaho Falls has a regional airport, hotels, and restaurants. Many transportation options and other services are already in place to support experimenters.

## 4.2. INL's Technical Capabilities

INL has attracted world-class staff who are pursuing spectrum, cybersecurity, modeling, and energy commutation related research areas. This allows for cross domain expertise facilitating DSS research and testing. Here we review INL's technical capabilities. INL has conducted research activities outlining the policy changes that would be needed to enable DSS.[m] Researchers often invest in INL by purchasing equipment and building infrastructure. This has allowed INL to accumulate resources over time that align with the needs of a NEFSI.

### 4.2.1. Spectrum Monitoring Resources

INL's current spectrum-monitoring capability leverages Tektronix Real-Time Spectrum Monitoring Kits, Tektronix Real-time Spectrum Analyzer, Field Fox spectrum analyzers, and Anritsu spectrum analyzers. Additionally, INL has conducted significant research into spectrum monitoring, interference detection, and spectrum sharing.[n] INL also operates a variety of RF wave-form analyzers and generators, protocol analyzers, and noise generators for controlled interference which can be made available for spectrum innovation testing.

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[m]   Kaminski, N. J., Smith, R. W., Beck, J. M., & Bhuyan, A. (2024, May). Toward Practical Federal Spectrum Sharing for Advanced Wireless Technologies. In *2024 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)* (pp. 157-162). IEEE.

[n]   Reese, R. D., & Quach, A. T. (2024). *YOLO for Radio Frequency Signal Classification* (No. INL/CON-23-73981-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States). IEEE. Kaminski, N. J., Smith, R. W., Beck, J. M., &

## 4.2.2. Wireless and Wired Infrastructure

Existing wireless infrastructure is primarily managed by the Wireless Test Bed (WTB) at INL which includes:

- the Isolated Satellite Backhaul Network (ISBN),

- HF fixed and mobile radios and antennas,

- a 2G Groupe Spécial Mobile (GSM) cellular network,

- a 3G Universal Mobile Telecommunications System (UMTS) cellular network,

- 4G Long-Term Evolution (LTE) Tier I carrier grade and Tier III networks,

- 5G non-standalone (NSA) and standalone (SA) Tier I cellular networks with commercial roaming capability,

- A series of 7 GHz point-to-point microwave links, and

- A WiMax network.

INL also has remote HF monitoring sites in Salt Lake City (at the University of Utah), Maryland, and Florida. Figure 6 shows the locations of INL's six cellular network sites.
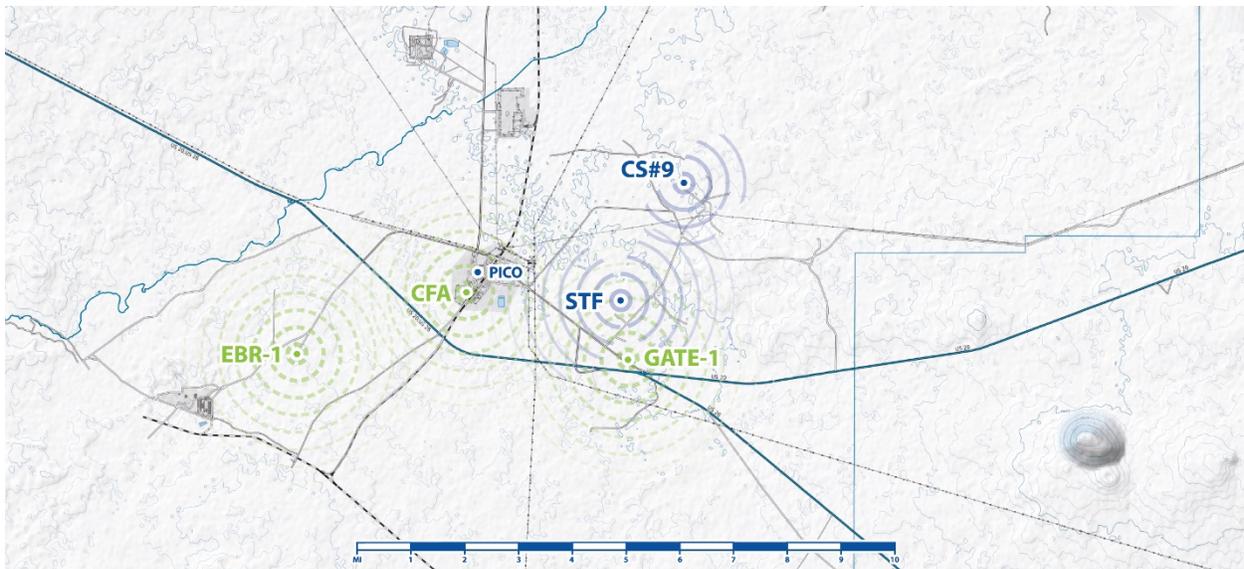


Figure 6. Six experimental cell sites—legacy (i.e., 2G–4G) sites in green, and 5G sites in blue.

Existing wired infrastructure at INL includes:

- fiber distribution network with over 30 power-pole-mounted fiber patch panel breakouts and

- public Internet connectivity to cellular networks at speeds up to 10 Mbps through the Idaho Regional Optical Network.

In addition to the fixed cellular towers shown above, the INL test range provides four mobile towers and a moveable 5G picocell. Tests on the INL test range can connected to internal or external network operations centers as well as other INL resources to further augment experiments.

### 4.2.3. Data Collection, Storage, and Analysis Tools

INL uses network-attached storage arrays for real-time storage of test data. Currently INL has Synology and QNAP rack devices deployed for this purpose. These arrays are configured for onsite data access and via remote-access options through INL Box web-based sharing. These resources are configured to provide access controls. Associated IP routing and switching to the devices are performed by WTB staff and certified network engineers. Data connections to the network-attached storage devices are up to 10 Gbps over copper and optical connections.

### 4.2.4. Experiment Management Tools

INL supports DSS and spectrum experiments as a full-service test facility. INL can assist customers with defining the scope of work, identifying success criteria, and generating experiment plans. Through these steps, INL helps researchers to realize the experiment definition and plausibility analysis of the experiment life cycle. INL then schedules the experiment. Experiment provisioning at INL includes receiving any necessary external equipment, deploying that equipment, configuring it, and confirming functionality. This process includes identifying test leads, engineers, and technicians to support the experiment execution and documentation of results. Experiments are then executed and monitored. Post-experiment activities include the decommissioning of equipment, teardown of infrastructure, return shipping, and final-report generation.

Nearly the entirety of INL's experiment management capabilities is manual and rely on technicians and experts. Multiple processes are in place to ensure proper experiment operation and execution with rigorous monitoring in place. Any failures, errors, or anomalies are acted on quickly by the monitoring personnel.

Long-term field trials can be arranged to allow the equipment and support infrastructure to remain deployed and readily available. This allows a series of experiments to leverage equipment with minimal effort.

### 4.2.5. Remote and Shared Access Mechanisms

INL can support remote access through a VPN. INL uses Fortinet security products and has dedicated staff who review logs and enforces our policies for remote and shared access. The VPN can be tailored based upon access requirements. To facilitate multiple simultaneous users, INL separates users by VLAN, time, physical location, and/or frequency to prevent resource conflict and segment access.

### 4.2.6. Access Control and Experiment Isolation Techniques

INL experiment isolation is accomplished through scheduling and network configuration. INL also has two faraday cages and an anechoic chamber, with plans to install a second anechoic chamber in 2025. This capability would allow for enhanced RF isolation if required.

### 4.2.7. Network Administration and Cybersecurity-Monitoring Tools

INL uses Paessler Router Traffic Grapher (PRTG) network monitoring and FortiGate logging. PRTG is primarily used to detect potential hardware failures. FortiGate collects logs and feeds FortiAnalyzer for anomaly detection, threat monitoring, and intrusion detection, and to create alerts or automatic actions.

### 4.2.8.    Multiple Sensitivity Levels

INL has a history of operating at various sensitivity levels and multiple controls in place to support sensitive operations.  INL staff are experienced with adjusting to the security and control requirements of various federal and non-federal stakeholders, including DoD and DOE orders. INL's current capabilities include:

- Controlled test-range access,
- Controlled access facilities,
- Secure connectivity via Comsec safes,
- Classified compute,
- Secure storage, and
- Security police officer patrols.

## 4.3.  INL's Management Capabilities

As Section 2.1 described trade-offs between remoteness and accessibility, and Section 2.3 discussed management's role to attract and retain qualified staff, it's important to note that INL is currently home to more than 6,100 researchers and support staff[o] focused on innovations in nuclear research, renewable-energy systems, and national security solutions that are changing the world.[p]

Developed over decades, INL's workforce includes all of the traditional roles encouraged in Section 2.3 and has wireless research-specific management. INL recently established the Wireless Communications Research Division (WCRD) within the National and Homeland Security Directorate. With some 80 staff & researchers, the WCRD focuses on the research, testing, and development of communications innovations, including DSS. The WCRD contains the WTB, Wireless Security Institute, and associated staff with significant experience supporting spectrum experiments at INL. The creation of WCRD shows INL's focus to advance communications and spectrum innovation.

## 4.4.  INL's Economic Capabilities

INL, as a Federally Funded Research and Development Center (FFRDC), reporting to DOE's Office of Nuclear Energy, may perform work for non-federal customers that aligns with and drives DOE missions. Note that advancing the resiliency of critical infrastructure includes wireless communications systems as part of the mission.

Recently, an independent, non-profit 501(c)(3) organization not directly affiliated with the INL was created to bridge the gap between INL and its donors to advance the lab's energy research, development and innovations that enhance the nation's leadership in the energy industry. The INL Foundation provides research and project risk reduction and liability protection for partners by the Foundation accepting ACT/CRADA/SPP (government contracts) liability terms. It also allows for more flexible terms with the private sector.[q]

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[o]    INL Headcount growth reflects continual growth year after year since 2013. (https://inl.gov/content/uploads/2023/05/FY22-FY26-INL-Workforce-Projections.pdf; accessed 12/7/2024)

[p]    https://inl.gov/about-inl/; accessed on 6 November 2024.

[q]    https://inlfoundation.org/; accessed on 12/7/2024.

Projects accepted by INL must be aligned with laboratory capabilities, must not interfere with work directed by DOE, cannot compete with the private sector, and must be paid for at full-cost recovery. Also, sponsors are required to provide a sufficient advance payment prior to the start of the work. Moreover, work scope, the cost estimate, and other internal reviews and approvals of the project must be approved by DOE's Idaho Operations Office (ID) and signed off by the DOE-ID contracting officer before work can begin. In some cases, the INL Foundation will be able to act as an intermediary bridging gaps in terms and conditions (e.g., advanced payment) by representing the Sponsor to INL.

## 4.5.  INL's Regulatory and Political Capabilities

For more than 20 years, INL has supported spectrum tests and experimentation under NTIA experimental radio station authority.[r] INL's spectrum manager has authority delegated by DOE's Office of Spectrum Management to use any radio frequencies under a blanket assignment without prior authorization so long as harmful interference is avoided.[s] INL's spectrum manager must review all experiments prior to execution. Researchers may leverage INL's existing spectrum authority by submitting a spectrum request. Alternatively, researchers may leverage their own spectrum authority through coordination with the INL spectrum manager. If necessary, the spectrum manager coordinates with local licensees to prepare for upcoming events.

INL's Office of Risk, Assurance and Compliance protects the laboratory's people, property, and mission by supporting laboratory leadership's efforts to identify, manage, and minimize risks. INL provides General Counsel, internal audits, and documented policies and procedures to help operate in compliance with all applicable federal and state laws and regulations. Staff regularly participate in training, and personnel are available to advise with compliance to relevant laws and best practices, including FISMA, Risk Management Framework, NEPA, Davis-Bacon, etc.

## 4.6.  INL's Environmental Capabilities

INL is committed to protecting the public and the environment. An excerpt from INL's Environmental Policy States:

> *INL balances research, development, and demonstration activities in support of the mission with the protection and preservation of human health and the environment and compliance with applicable laws, regulations, and other requirements. The INL is committed to environmental protection, compliance, pollution prevention, and continual improvement.*

The Environmental, Safety, Health, and Quality (ESH&Q) Organization exists to ensure INL's compliance with all environmental laws, regulations, requirements, and any agreements with government entities or stakeholders. We describe the ESH&Q offices below that handle the most relevant aspects.

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[r]     U.S. Dept. of Commerce, National Telecommunications and Information Administration: For sale by the U.S. G.P.O. Supt. of Docs, Manual of regulations and procedures for Federal Radio Frequency Management, Jan 2023 Revision of the Jan 2021 Edition. Washington, D.C. Section 7.11 and Appendix C.

[s]     Manual of Regulations and Procedures for Federal Radio Frequency Management. January 2023 Revision of the January 2021 Edition; U.S. Department of Commerce, National Telecommunications and Information Administration (NTIA); Section 7.11.1

### 4.6.1.   Monitoring and Natural Resources Services

This group conducts environmental and biological sampling and surveying on and off the INL Site to ensure that all INL operations and research are conducted in a manner that minimizes impact to the environment or the public. The group is split into the Monitoring Services and the Natural Resources Groups. The Monitoring Services Group conducts monitoring and sampling to observe levels of radionuclides and other contaminants in the local environment. The Natural Resources Group monitors and collects data on vegetation and wildlife habitats that have the potential to be or are currently being affected by INL operations on the INL Site.

### 4.6.2.   Cultural Resources Office

This office exists to ensure INL conducts work in a manner that is compliant to federal laws and regulations, state laws, DOE policies, and DOE-Idaho legal commitments to the Shoshone-Bannock Tribes, state of Idaho, and the federal Advisory Council on Historic Preservation. The Cultural Resource Office is uniquely positioned to provide the services, products, and expertise necessary to integrate effectively cultural-resource considerations into project and land-use planning and to implement INL projects and programs.

### 4.6.3.   Environmental Management Services and NEPA

Environmental Management Services and NEPA Group are responsible for ensuring the INL is compliant to multiple regulations: NEPA, the Clean Air Act, Clean Water Act, Emergency Planning and Community Right-to-Know Act (EPCRA), National Emission Standards for Hazardous Air Pollutants (NESHAP), and others. NEPA planning and reporting requirements are aligned with project- and contract-approval processes at INL, so compliance is assured by existing processes.

# 5. GAP ANALYSIS TO MEET MVP NEFSI CAPABILITIES

We examined INL's current ability to provide the capabilities necessary for a NEFSI MVP by examining planned DSS experiments at INL. Here, we discuss these planned experiments and then describe INL's gaps. For a risk assessment of each of the gaps below please see Appendix B.

## 5.1. Description of Planned FY-25 DSS Field Trials

During FY-25, INL is planning two DSS field trials: (1) an extended field trial of a secondary user and (2) an examination of potential interference.

The first experiment is a 6–12-month field trial of an INL-developed dynamic spectrum-access method. Figure 7 displays the concept for this experiment. This technology senses spectrum and avoids any sensed interferers. In prior testing, this technology demonstrated the ability to reconfigure in less than 20 ms when interference was detected.
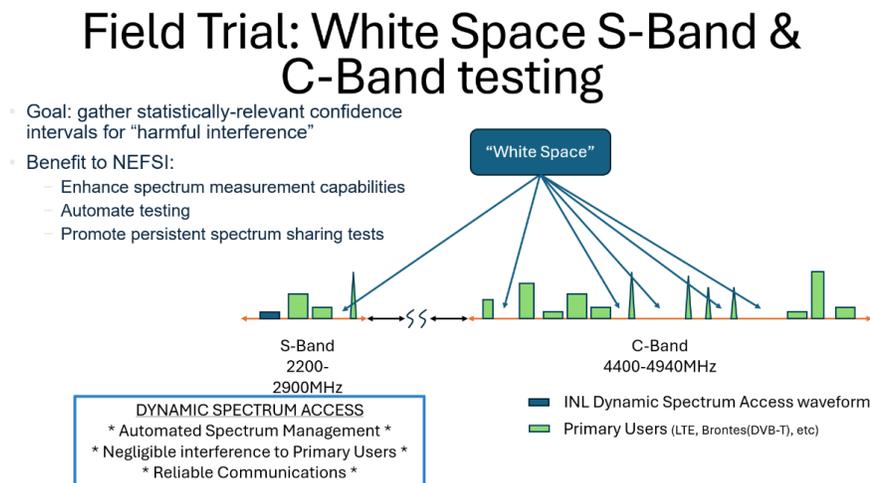


Figure 7. FY-25 planned dynamic-spectrum access field-trial description.

The second experiment evaluates potential interference to primary users in 7 GHz from Wi-Fi and 5G that may result from emerging spectrum policy. This experiment focuses on producing scientifically grounded data to inform later development of DSS technology and policy. Thus, this experiment will test many configurations of potential interferers against a variety of incumbent equipment. Running the large number of trials for this experiment will push INL to automate testing. Conducting these extended field trials concurrent with other FY-25 wireless tests constitutes a form of multizonal architecture.

## 5.2. Technical Gaps

Though INL has many features to support a NEFSI there are a few core elements that are required for the MVP. The main areas that INL will need to develop are dedicated spectrum monitoring, enhanced data analysis, automated experiment management, and expanded remote access.

### 5.2.1. Spectrum Monitoring Gaps

INL's current approach to spectrum monitoring is based on tailoring available equipment to an experiment. A NEFSI requires a more dedicated approach to achieve the necessary reproducibility

and comparability of spectrum experimentation. While INL can do reconfigurable spectrum monitoring what it lacks is permanent spectrum monitoring. Permanent spectrum monitoring needs towers and fiberoptic connectivity installed to support spectrum sensors. There are many commercial off-the-shelf SDRs that would be a good fit for spectrum monitoring. A good balance of features for the price point is the Signal Hound[t].

## 5.2.2. Data Collection, Storage, and Analysis Gaps

INL currently lacks a tight integration of cloud computing accessible to external researchers for spectrum experimentation. Specifically, INL has not implemented a containerized approach to data processing. This limits the degree to which INL can scale the compute made available to experiments and researchers. Container deployments would expedite deployment of externally developed code. Additionally, INL's current network attached storage may not support the required data rates for broad DSS experimentation.

Also, building a robust NEFSI with a permanent multizonal network architecture will require installation of additional networks, possibly with physical-infrastructure investments. For instance, INL currently operates an airstrip that is regularly used for UAV operations. The airstrip lacks fiberoptic connectivity, and multiple internal and external customers would benefit from availability of a new test laboratory collocated there for spectrum-innovation research. The Spectrum Innovation Testbed, as part of a multizonal architecture, would require rack, switches, uninterruptible power sources, network storage, heating, cooling, and other investments.

A large-scale, multi-zonal architecture will also have to support many of the experimental isolation and shared access capabilities highlighted in Sections 2.2.5 and 2.2.6. While INL has traditionally used temporal scheduling to promote isolation, this mechanism will most likely be insufficient for the large-scale NEFSI use-case. To this end, as the NEFSI grows, INL will investigate the various isolation, sharing, and security capabilities discussed previously and as part of the reference architecture.

## 5.2.3. Experiment Management Gaps

INL currently handles experiments on a case-by-case basis. Generally, the researchers come to INL, and our focus is on success for their specific experiment. INL does not currently have robust mechanisms for experiment automation. This includes provisioning, monitoring, and termination. Currently some of the processes are done manually. If interference or anomalies are detected in an experiment, the experiment lead is notified, and the experiment is manually ended.

The processes used by INL are well documented but are also complex. For example, the spectrum approval process shown in Figure 8. INL's Spectrum Approval Process has multiple steps, some of which refer to other processes. Several of these steps also require external communications and approvals. The result is that the process for approving and operating experiments can be time consuming, a potential detriment for low-budget researchers or those with tight deadlines. These overall limitations don't preclude INL from acting as a NEFSI, but it limits higher risk experimentation for DSS that might cause interference or anomalous behavior.

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[t]    https://signalhound.com/products/usb-sa124b/. SDR with frequency range: 100 kHz to 12.4 GHz.
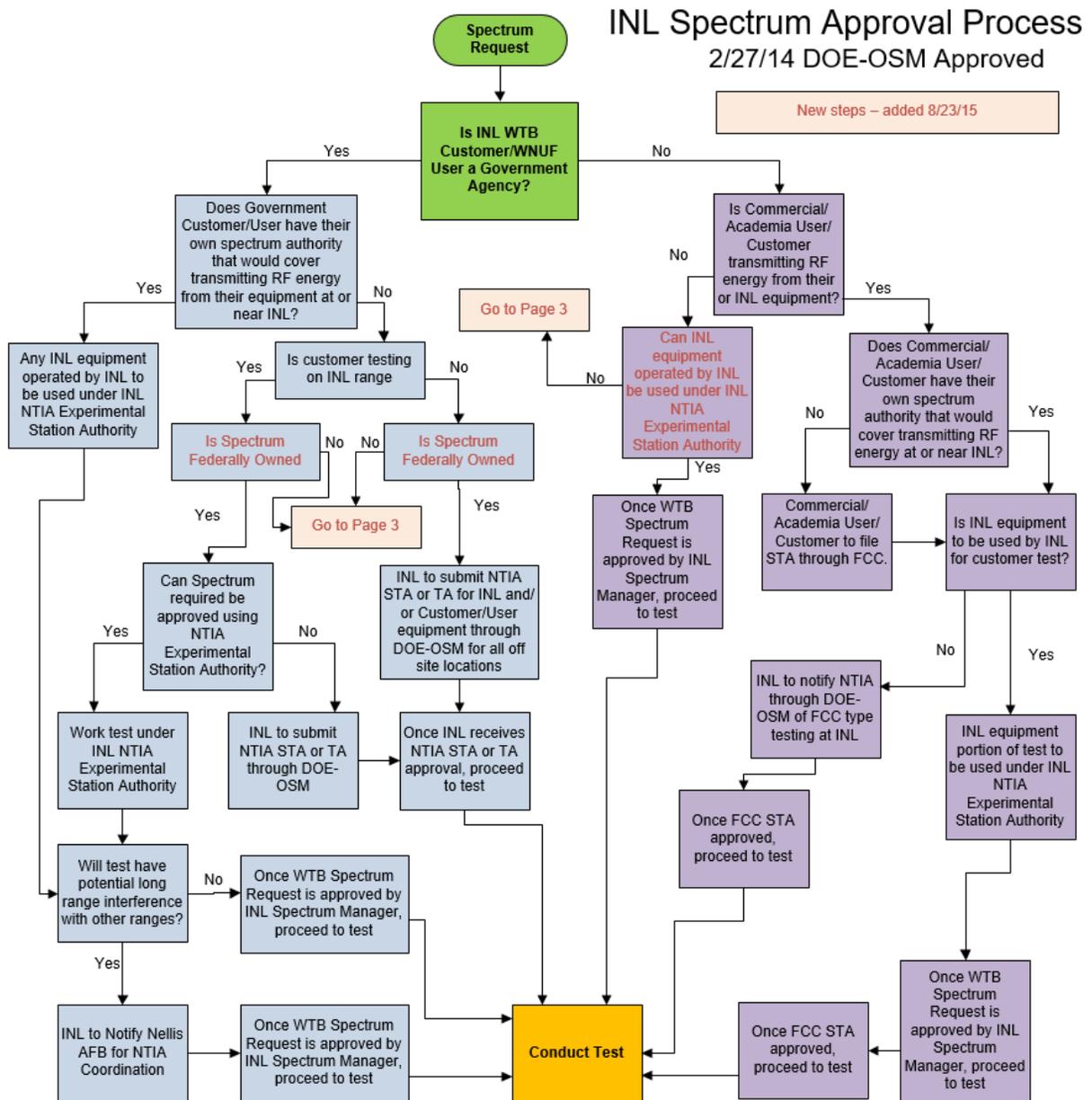
Figure 8. INL's Spectrum Approval Process

## 5.2.4. Remote Access Gaps

During INL's 20 year history of supporting wireless RF testing, researchers usually physically come to INL to do testing. The expected outcomes are either raw data that is collected or an aggregated report of findings. A NEFSI will need to provide remote accessibility for all aspects of an experiment's lifecycle. This will require a design that follows CIE principals such that the attack vectors are limited, and the data is sufficiently protected. A dedicated security focused engineer would allow for the deployment and active monitoring of analysis compute as well as remote access to be done safely and securely giving broad confidence to researchers as they conduct experiments.

Remote access will also require additional hardware and software to be purchased and deployed at INL. This new infrastructure would provide managed and reliable access to experimental resources, compute, and data. Further, INL's current 10 Gbps external Internet connection may be insufficient for transferring data generated in DSS and spectrum innovation experiments.

## 5.3. Economic Gaps

As a result of the current funding model, INL is focused on supporting Government spectrum research. Both industry and academia have limited access to spectrum experimentation at INL. Industry is often unwilling to work under the terms and conditions (T&Cs) imposed by INL. As mentioned in Section 4.4, INL Foundation may provide a helpful bridge for future Industry-INL partnerships. Also, academic institutions are often unable to directly pay the cost of spectrum research at INL; so we typically seek joint funding opportunities instead.

To better support academia and industry, exploration of the alternative funding models listed in Section 2.4 will be needed. For instance, direct government funding, cost recovery, and research grants each partially address the cost-structure barrier limiting academic testing at INL. However, a hybrid approach may be most effective to address annual operating expenses to incrementally adapt the NEFSI's capabilities to research needs and to attract non-federal testing. This hybrid approach could be creation of a NEFSI working-capital fund or investment in the INL Foundation.

Developing the concept of a NEFSI working-capital fund a little further, a government sponsor could fund INL as the NEFSI at the beginning of each fiscal year indexed to an expected amount of non-federal DSS testing for the year. The working-capital fund would then enable INL to maintain remote-access and network-security capabilities to make test scheduling easier. This working-capital fund would reduce individual costs borne for academic tests and provide advanced payment for industry tests. Reimbursement in full and in arrears would be expected for industry researchers. Reimbursement to the working-capital fund from academic researchers may be a combination of project funding and research grants.

Another economic consideration for future DSS experimentation includes the cost of research on licensed frequencies. For instance, C-band is heavily researched for 5G communications. While some negotiation with local mobile-network operators (MNOs) has been possible until now, we must expect at some point that commercial MNOs will be required to pay for use of spectrum. In that case, direct government funding or the NEFSI working-capital fund may be crucial to enable relevant DSS research.

## 5.4. Regulatory and Political Gaps

Currently, INL only has experimental authority through the NTIA Experimental Radio Station. Lack of FCC experimental authority limits INL's ability to enable experiments for academics or industry. While this does not prevent INL from acting as a NEFSI, obtaining FCC experimental authority would expand INL's capabilities as a NEFSI.

# 6. RECOMMENDATIONS AND PATH FORWARD

Here we discuss recommendations and next steps for NSF to enable the creation of a NEFSI.

## 6.1. Recommendations

First, STRATA provides a list of recommendations to realize a NEFSI. This list is not ordered and should not be considered a ranked list of priorities.

### 6.1.1. Brownfield vs Greenfield

We recommend that NEFSI utilize brownfield sites wherever possible. Our analysis indicates that the cost of building a new site is too high for the marginal benefits gained from greenfield development. Brownfield sites, such as INL, offer access to desirable locations with foundational capabilities for a NEFSI. The ideal brownfield site for a NEFSI would already have facilities and personnel with experience running RF experiments and managing interference.

### 6.1.2. Technology

We recommend investing in the development of experiment automation. Many DSS and RF experiments are manually tuned and deployed, limiting repeatability and verification while placing a heavy burden on experimenters. This limits the scale of DSS that can be effectively accomplished at a NEFSI.
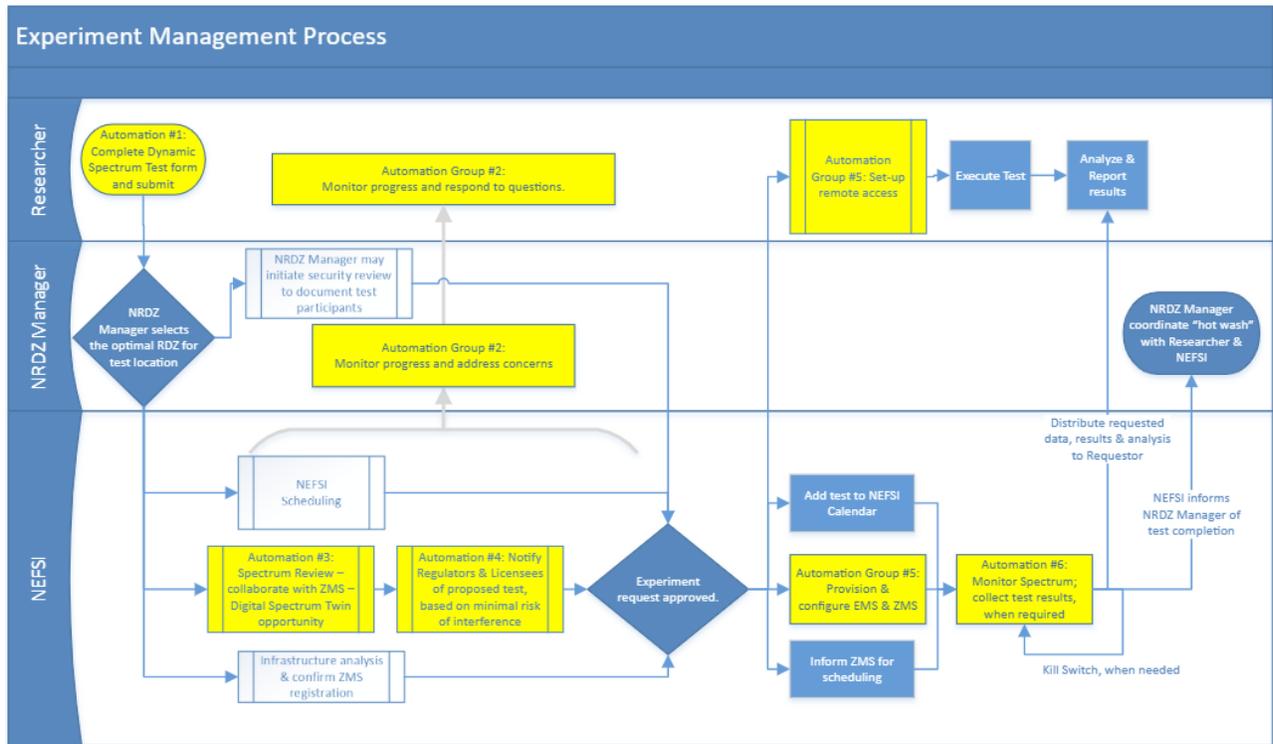


Figure 9. Automation Opportunities

We note that experiment automations can be deployed incrementally at a NEFSI. This allows development to focus on specific automation capabilities with the highest impact to research efficiency. Figure 9 highlights (in yellow) multiple candidates for potential automation. Each automation candidate can be developed independently and incrementally without impact to any other function.

A potential focus candidate is automated experiment termination and experiment configuration, as they will be highly impactful. Incremental deployment also allows for leveraging existing technologies and tailoring them to NEFSI requirements. We believe that OpenZMS and Merge are particularly good candidates for foundational automation technologies.

A second technological investment opportunity is more robust spectrum monitoring and interference detection. Current spectrum monitors focus primarily on a small range of frequencies and are incapable of monitoring spectrum broadly. This limitation requires a NEFSI to have multiple monitors across various spectrum to provide sufficient coverage. Further, the monitors are designed to detect spectrum usage, not "interference". Monitors that can be configured to detect interference (i.e., specific spectrum usage above an expected threshold) and can alert on those detections will greatly facilitate a NEFSI's spectrum protection function, especially when coupled with automated experiment termination.

### 6.1.3. Spectrum Policy and Authority

Broadly, testing of DSS violates the agreements that NTIA and FCC have issued for experimental sites. This needs to be addressed at the policy level. We recommend that policy be updated to clearly define (1) what harmful interference means, (2) how a spectrum manager would determine impact to incumbents, and (3) an acceptable threshold of impact from an experiment. The ability to quantify the risk of DSS testing, leverage a policy to determine impact, and have decision authority are required for a NEFSI to be successful. These issues will also be present for broad spectrum research, beyond DSS.

A roadmap should be developed prioritizing spectrum bands, features, and capabilities for DSS research. An analysis of the set of laws and regulations that impact the NEFSI should be conducted and recommendations for potential changes should be made. This effort will take time and should be one of the highest priorities enabling successful DSS experimentation, or spectrum innovation in general.

### 6.1.4. Trust Building

For a NEFSI to advance DSS, it must be viewed as a trustworthy resource by all spectrum stakeholders. Incumbents have invested significantly in dedicated spectrum licenses. Similarly, new spectrum entrants have invested significantly in developing technology for emerging bands and spectrum sharing approaches. A NEFSI must demonstrate results that reproducibly reflect real-world operations to protect the investments of both groups.

We recommend holding a series of events focused on building trust at the NEFSI. These events should encourage collaboration among researchers, regulators, new entrants, and incumbents. We suggest accomplishing this through field trials that highlight NEFSI capabilities to demonstrate the applicability of DSS research to new entrant, incumbent, and policy maker concerns. These trials should apply a scientifically grounded approach to generate reproducible results in a transparent manner. If done correctly these trials will build a community of spectrum stakeholders around a mutual understanding of DSS, grounded in practical experimentation.

## 6.1.5. Funding Model

A NEFSI requires a funding model that promotes academic, industrial, and government experimentation. Each NEFSI is likely to have a slightly different model, but they all must support broad accessibility. We anticipate that hybrid approaches will be particularly useful to NEFSI funding.

Specifically, a working-capital fund as described in Section 5.3 might augment the NEFSI sufficiently to allow for research equality. A government sponsor would fund the NEFSI at the beginning of each fiscal year to support non-federal DSS testing. A grant type system could be in place allowing researchers from academia and industry to leverage NEFSI. This approach could also be used to increase the representation of financially disadvantaged groups in the DSS community.

# 6.2. Path Forward for NSF

As stated above, our research indicates that the brownfield development of an MVP NEFSI is a viable and cost-informed path to accelerate spectrum innovation. Therefore, the primary action for the NSF in the next 24 months should be recognizing an existing spectrum test range as a formal NEFSI. Following that the recognized site will require some funding to realize the capabilities required for a NEFSI. We explore the next steps for the selected site and the associated costs using INL as an example in the subsections below. Other brownfield sites will differ in capability compared to INL and an appropriate site-specific evaluation will need to be completed.

NSF could also advance establishment of NEFSI during the next 24 months by pursuing the following initiatives, not listed in any particular order:

a) Assisting NTIA and FCC to define DSS as an activity that can be conducted under experimental-spectrum authorities (Section 6.1.3)

b) Identify RDZs and support applications to FCC and NTIA for experimental use authorities (Section 1.1 & 2.5)

c) Prioritize funding models for the NEFSI as discussed in Sections 2.4, 5.3, and 6.1.5

d) Explore the T&Cs under which a chosen NEFSI would support federal government, as well as academic and industry spectrum testing

e) Evaluate with FCC and NTIA the pros and cons of the delegated spectrum authorities discussed in Section 2.5, particularly whether congressional designation of NRDZ and NEFSI better meets the national urgency for spectrum innovation research and testing than RDZs' applications

## 6.2.1. Next Steps for INL to achieve MVP NEFSI

If selected as the NEFSI, the STRATA team would recommend that the following steps be taken by INL within the first year. Cost estimates are provided in the next section.

- Define requirements for future automation investments;
- Test and evaluate existing automation solutions;
- Formalize the reference architecture described in Appendix A;

- Support an initial DSS field trial tailored to available funding and capabilities;
- Identify and prioritize the solutions that would help DSS testing be more effective at the NEFSI; and
- Schedule recurring programmatic reviews with stakeholders to discuss accomplishments, research needs, and current risks to spectrum innovation testing.

The second year of funding would prioritize the following:

- Identify data formats and mechanisms to standardize interactions with other RDZs and spectrum regulators to share data or results;
- Schedule demonstrations and collaboration events;
- Integrate selected automation suite and complete a DSS test event with it; and
- Partner with an academic institution interested in DSS and work with them to resolve funding issues and schedule a test event.

## 6.2.2.  Cost Estimate

The ROM cost identified in Table 1Table 2 are the rough labor estimate USC-ISI and INL put together to be representative of a brownfield site that has much of the infrastructure in place. This partnership is critical in the estimation as single institutions rarely have all the resources needed. Much of the automation software would be handled by USC-ISI while the location, maintenance, and contract management would fall to INL. The two years are broken up as most of the cost to bring the site up to the MVP NEFSI is covered in the first year, while much of the second year is running tests and working out issues to be fully operational.

Table 1. First-year ROM cost estimates for the NEFSI path forward.

| USC-ISI Labor | $683,859 |
|---|---|
| INL Labor | $833,713 |
| Materials, Subcontracts, Travel | $482,371 |
| Project Management | $121,300 |
| Management Reserve | $222,000 |
| * FAC | $23,437 |
| Total Cost | $2,367,146 |

Table 2. Second-year ROM cost estimates for the NEFSI path forward.

| USC-ISI Labor | $438,071 |
|---|---|
| INL Labor | $484,527 |
| Materials, Subcontracts, Travel | $247,808 |
| Project Management | $210,693 |
| Management Reserve | $120,000 |
| * FAC | $15,013 |
| Total Cost | $1,516,365 |

* FAC is Federal Administrative Charge: 1% additional charge established by DOE Order 522.1A.

# 7. CONCLUSIONS

The STRATA report has advanced NSF's goal to advance the use of DSS. Our main contributions are:

- Identifying the requirements of the NEFSI,

- Outlining the capabilities necessary for a minimally viable NEFSI,

- Evaluating the potential of Idaho National Laboratory (INL) as the NEFSI facility, and

- Recommending the next steps for achieving a minimally viable NEFSI at a brownfield site such as INL.

- Providing a reference architecture to help drive NEFSI development and deployment

A NEFSI should prioritize reproducible, comparable, and transparent research to build trust with spectrum stakeholders. This necessitates fulfilling technical, economic, management, regulatory, and environmental requirements. We also have found that a NEFSI needs a modular approach to facilitate incremental deployment and upgrades of both hardware and software. We suggest leveraging open-source products where applicable to limit vendor lock-in, promote broad access, and enable technology transfer.

After evaluating the capabilities required for a NEFSI, we have determined that a brownfield approach represents the most efficient way ahead. The cost in dollars and time necessary to adapt an existing, capable spectrum test range is significantly lower than would be required to develop a new site. We believe that INL is a good candidate for realizing a NEFSI, though other sites exist and should not be overlooked.

Once a NEFSI is established, it must continue to adapt to the evolving needs of spectrum researchers. We have assessed that developing experiment automation will be particularly important for the future of a NEFSI. Keeping up with emerging spectrum technologies is critical for a NEFSI to enable governing authorities to rapidly react to changes with science driven policies.

# Appendix A, Initial Reference Design

This section presents an initial reference design for a NEFSI, including a simple physical-architecture design, software-architecture design, and APIs. We present the designs (Figure 10) to help identify necessary components, missing capabilities, and future development directions. To facilitate ease of development and deployment, this design will assume use of Merge[u] and OpenZMS[v] as base components.
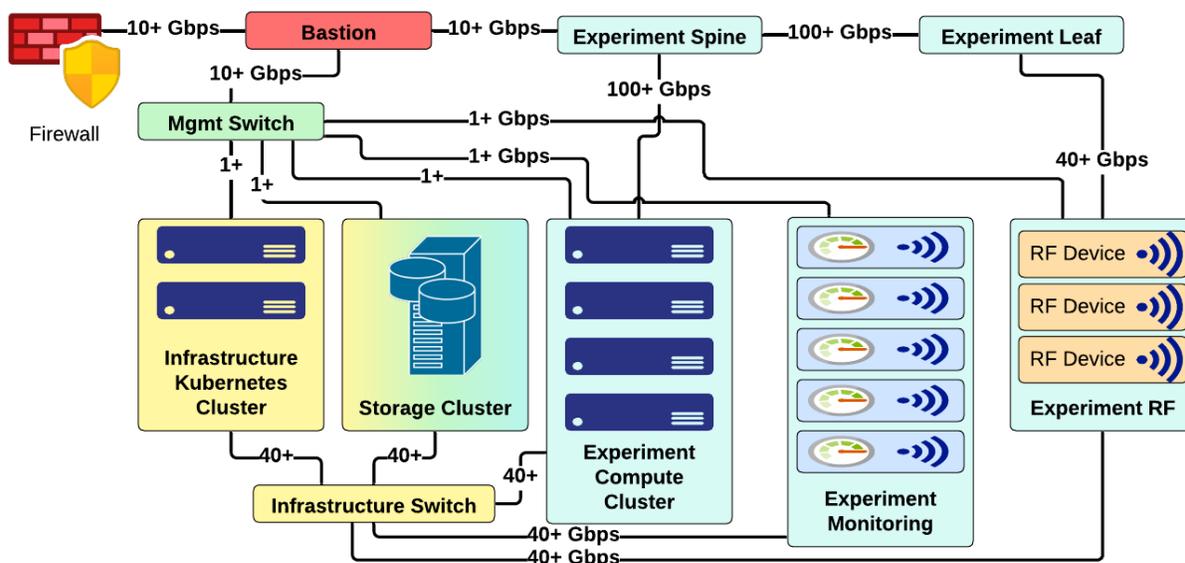


Figure 10. Simple reference infrastructure.

Figure 10 provides a high-level diagram of the software and hardware capabilities in an entire, fully-capable NEFSI. Many of these capabilities can be scaled down to achieve an MVP, such as, the Management Systems presented (see 3.1).

# A1.    Physical Infrastructure

NEFSI infrastructure can be broken down into four components:

1.  Access network
2.  Infrastructure network and services
3.  Management network
4.  Experiment network and services.

We leverage the terminology established by Merge here, because the Merge Testbed Ecosystem uses a similar design.

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[u]    https://mergetb.org/

[v]    https://openzms.net/

# 1. Access Network

The access network is responsible to provide and control remote access to the NEFSI. A firewall regulates all incoming and outgoing connections while a bastion server is the primary landing and access-control point for users. In Merge, the bastion is called a portal, and each logged-in user is placed within a containerized environment called an experimental development container (XDC). Further, the portal hosts a web-based user interface through which experimenters can interact with the testbed ecosystem.

The access network requires sufficient bandwidth for multiple users to simultaneously access the NEFSI without conflict. However, the network is not designed for users to send or receive experimental data in real time. Such a data requirement might be very large, as discussed previously. Instead, we expect users to stage data prior to an experiment and retrieve it after the fact. To this end, a 1 Gbps access network may be sufficient, but we recommend at least 10 Gbps to promote data post-processing and network sharing.

The portal server itself requires enough memory, CPU, and storage to enable multiple simultaneous XDCs to operate. Most commodity hardware can facilitate this within a reasonable budget. The large Security and Privacy Heterogeneous Environment for Reproducible Experimentation (SPHERE) testbed at ISI[w] uses a portal with an AMD EPYC 9354P processor, 192 GBs of RAM, and 1 TB of internal NVMe storage.

# 2. Infrastructure Network and Services

The infrastructure network and services comprise the backbone of the NEFSI. These services include the ZMS and EMS for the overall management of the site. They also include other common services such as shared storage, Dynamic Host Configuration Protocol, Domain Name System, Network Time Protocol or Precision Time Protocol, etc. The network connects all these services and plumbs them into experiments. The network is also responsible for sending control messages to each device.

The infrastructure network requires enough bandwidth to handle the volume of traffic created by these services. While many of the services do not require much bandwidth, core infrastructure responsibilities include storage and RF monitoring. Both capabilities may generate significant data rates; thus, the infrastructure network shown requires at least 40 Gbps of bandwidth with an appropriately scaled backplane.

Infrastructure servers require the capability to deploy Kubernetes clusters and run the required services atop them. In this reference design, we have provided two servers for redundancy. This assumes each server is relatively powerful with at least 256 GB of RAM and 2+TB of internal NVME storage, as provided by SPHERE.

# 3. Management Network

The management network allows NEFSI administrators to control, maintain, and monitor all NEFSI components. It is best practice to have a separate management network that allows access to devices in case of network or device failure. Typically, management networks connect to a device's management interface using technologies such as Intelligent Platform Management

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[w]    https://sphere-testbed.net/

Interface[x]. Note that not all devices may have a management interface or adhere to a single standard. Alternate management mechanisms may be required, such as IP-controllable power strips that allow basic power control over any device. Generally speaking, the management network does not require significant bandwidth but may be scaled up if it is used in remote software deployment.

## 4. Experiment Network and Services

The experiment network and services includes computing and storage resources available to experimenters, monitoring services deployed as part of the experiment, and the RF resources deployed to conduct the experiment. In this basic design, we allocate four virtualizable computing resources for experimenters to use. These machines have similar specifications to the infrastructure servers provided.

Experimental monitoring should be scaled to allow for monitoring at transmission sites as well as edge monitors for detecting potential (internal or external) interference.

We expect DSS experiments to require at least three RF devices. Because DSS inherently requires sharing, at least two devices must attempt to transmit at the same time. A third device acts as the receiver to ensure transmission worked as expected. Clearly, this can be scaled to support more devices. The simplest design would leverage small SDRs, such as Ettus B310s or X410s.

The exact devices the NEFSI would use depends on the goals, frequency ranges, and regulatory authority of the NEFSI. Experimentation needs would also drive consideration of innovative wideband spectrum-sampling techniques, as demonstrated by SweepSense[y] or MITRE's Photon for GPU-accelerated signal processing.

As noted in the previous sections, RF experimentation can create significant data. Any storage cluster will require the capacity to both absorb incoming data and promote mid-term storage for post-experiment processing. The STRATA team expects that a petabyte storage cluster will be required at minimum. Network capabilities will also need to support these data rates, providing at least 40, if not more than 100 Gbps.

## 5. Infrastructure Caveats

There are a few caveats to this design. First, the design itself is relatively linearly scalable. Because most services are hosted as virtual machines or containers, they can be added redundantly to support larger deployments. Similarly, Kubernetes clusters are designed to promote scalability through the addition of machines and network connectivity. The primary scalability challenge is network connectivity. While more-powerful switches exist, eventually the purchase and deployment of additional switches will be necessary. The Merge ecosystem leverages a spine-and-leaf topology to promote scalability, where additional spines and leaves can be added to enable the required capacity.

The other caveat regards the number of networks. The design uses multiple networks to promote strong isolation of different NEFSI services. However, this may be a burden when deploying network equipment to the open-air, remote site of the NEFSI. For the portion of the services that exist within an indoor facility—i.e., everything except spectrum monitoring and

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[x]   https://www.intel.com/content/dam/www/public/us/en/documents/specification-updates/ipmi-intelligent-platform-mgt-interface-spec-2nd-gen-v2-0-spec-update.pdf

[y]   https://www.usenix.org/conference/nsdi19/presentation/guddeti, accessed 11/27/2024.

experimental equipment—we recommend having separate networks. For remote equipment, shared network resources using network isolation could enable the separation of networks. Whenever possible, separate-network infrastructure should be used to promote experimental fidelity, security, and best practices.

# A2. Management Services

For the NEFSI, management services encompass all the capabilities required to operate an experiment. The STRATA team, in conjunction with members of the community, have effectively split the management responsibilities into two subsystems—ZMS and EMS. At a high level, the ZMS is responsible for spectrum allocation, usage, and monitoring. Everything else—e.g., resource allocation, provisioning, monitoring, and experimental termination—is the responsibility of the EMS. A high-level system architecture is provided in Figure 11. This figure also highlights two additional systems: the user-management and the administrator systems. Specific interfaces are called out, which are discussed in Section A3.1. The locks on these interfaces indicate that some security function occurs, be it encryption, user validation, or system verification. In this section, we'll discuss each system's capability, as shown.

## 1. Zone Management System

The role of the ZMS is to manage all spectrum usage. As shown in Figure 11, this breaks down into a set of ZMS functionalities. When given a new experiment description, the ZMS must first determine whether the requested spectrum is available. If so, the ZMS conducts an interference analysis, determining whether the experiment will cause external interference or potentially interfere with another experiment. If the experiment is viable from both a spectrum and infrastructure perspective, then the ZMS will schedule the experiment based on available spectrum resources and other potential experiments that could interfere with the new experiment. During operations, the ZMS is also responsible for spectrum monitoring and usage tracking. In this section, we briefly describe how each capability may be accomplished.
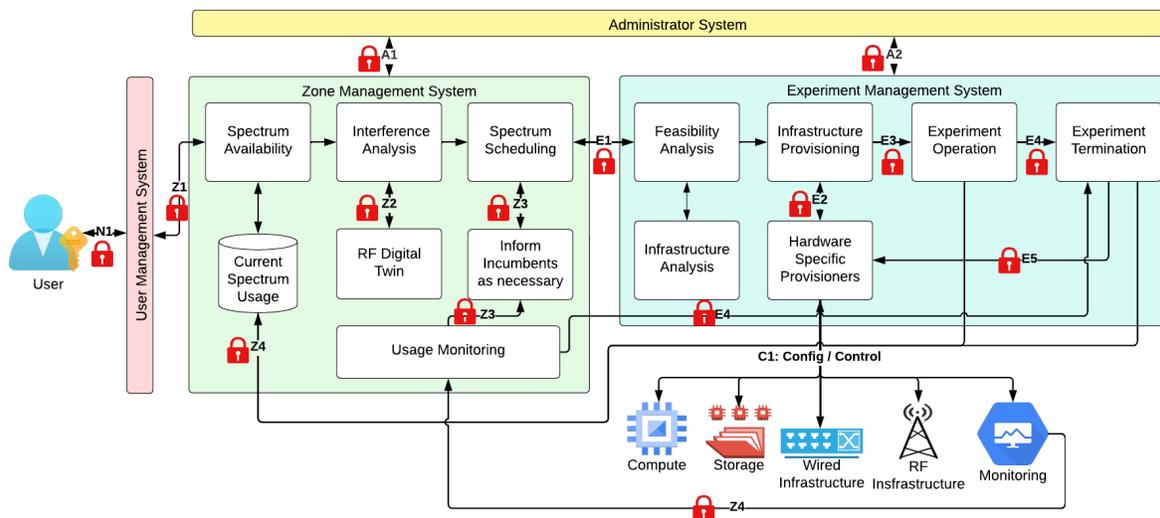


Figure 11. Management architecture.

The first function of the ZMS is to determine spectrum availability given the description of a spectrum experiment. This is primarily based on whether the NEFSI has regulatory authorization over the requested spectrum. This may be constrained by the body requesting the experiment because spectrum regulation for government is regulated by NTIA while the FCC is responsible for non-government spectra. This means that different requesters may have access to different spectra. Spectrum availability is also governed by the experimental timeframe. That is, a requester may desire to conduct an experiment immediately, but that spectrum may not be available due to another ongoing experiment.

The second function, and one of the most important, is to determine whether any experiment will cause interference. Interference can be split into two categories: internal interference, where one experiment may harm another, and external interference, where the experiment may harm other stakeholders. Internal interference can be mitigated by separating experiments adequately or by operating them at different times. External interference, however, may require moving the experiment, additional coordination with stakeholders, or denying the experiment altogether.

Calculating potential interference requires robust propagation models for available frequencies, detailed inventories of external stakeholders, and accurate experiment descriptions. None of these requirements are trivial, and many have presented significant challenges in the past. For example, creating precise, error-free propagation models has routinely been a challenge because they require detailed understanding of specific RF material interactions, local terrain, and atmospheric conditions. Some commercial products attempt to provide accurate models, but experience has shown they remain error prone. Similarly, maintaining stakeholder inventories has been a challenge because government databases are often out of date, and some stakeholders are mobile.

OpenZMS attempts to overcome this problem by using an RF digital twin to calculate potential interference. The digital twin combines the best-available propagation model for a given spectrum with known-terrain topographical models to determine potential interference. The NEFSI can expand on the digital-twin concept in several ways:

- The NEFSI is a fixed site that is expected to change slowly; therefore, detailed topographical models can be built and maintained
- The NEFSI can validate the results of various propagation models with measurement campaigns, resulting in more-accurate models
- These measurement campaigns can be expanded to measure temporal changes in both propagation and spectrum usage, potentially identifying non-interfering times
- The NEFSI team can reach out personally to stakeholders to build strong relationships and maintain accurate inventories.

The third function of the ZMS is to conduct experiment scheduling. Given a set of experiments that users want to conduct, this function determines where and when these experiments should occur. The MVP NEFSI infrastructure design, highlighted in Section 0, would only enable one experiment at a time. Thus, scheduling would simply be temporal. Scheduling would include experiment duration, priority, any fairness considerations—e.g., how often has this experimenter operated previously—and any temporal interference possibilities. A more-advanced NEFSI, with multiple zones or even sites, would require a scheduler that can handle simultaneous experiments across these locations. The STRATA team expects the ZMS would interface with the EMS to

understand the plausibility of placing an experiment at any location. That is, some experiments may not be viable at a given location, and the EMS will be required to make this determination.

The final, and perhaps most-critical function of the ZMS is to handle spectrum monitoring. The ZMS will receive all outputs from the deployed spectrum monitors. This may include raw I/Q outputs from the monitors or specific alerts from the monitors after they have processed the I/Q and detected potential interference. The exact data received by the ZMS will depend heavily on the types of monitors deployed, any collocated processing resources, and process-data formats.

Once the ZMS has detected interference, the ZMS must determine mitigation actions. In nearly all cases, this will involve asking the EMS to terminate the experiment because interference will either invalidate results or be harmful to stakeholders. The ZMS will inform experimenters of their experiment's termination. Depending on the type of interference, the ZMS may need to contact external stakeholders to report potential interference. Further, the ZMS may deny further experimental runs if the experiment was the cause of interference until the experimenter can demonstrate that the cause has been corrected.

## 2. Experiment Management System

The EMS is responsible for all the non-spectrum parts of the experiment, as shown in Figure 11. This includes determining experimental viability, resource provisioning, experimental operation and monitoring, and termination and cleanup. As with our infrastructure design in Section 3.1, the EMS architecture will leverage the Merge Testbed Ecosystem which already has most of the functionality required. Enhancements will be needed to support specific NEFSI equipment, but the modular design of Merge should readily promote this.

Merge determines experimental viability through a process called "realization." Given an experiment description, realization determines whether resources can be mapped to the available infrastructure. The process Merge uses is shown in Figure 12. Put simply, the realization process uses two steps. The first asks, given a set of requested resources, whether the facility has available resources to satisfy the request. If it does, the process determines whether sufficient network connectivity is available to connect all requested resources with sufficient bandwidth.
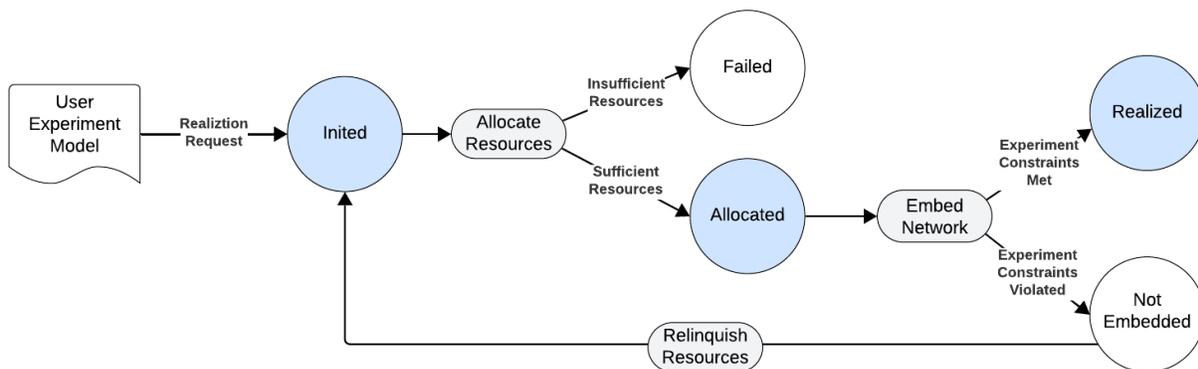


Figure 12. Realization process.

Determining sufficient bandwidth involves solving a graph-theory problem called the virtual network embedding (VNE) problem. Succinctly, the VNE problem determines the optimal set of physical nodes and network links to provision to support a virtual network—i.e., a requested set

of computing and bandwidth resources. Fortunately, members of the STRATA team have developed the state-of-the-art algorithm for solving the VNE problem, the iVNE-CBS algorithm.[z] If sufficient resources are available, the iVNE-CBS algorithm finds a satisfiable solution. Once the solution is found, resource provisioning can occur. If no satisfiable solution exists, then an error can be returned to the experimenter that modification of the experiment is needed.

After determining the viability of the experiment, the EMS must provision all relevant resources. In Merge parlance, this is called materialization because the underlying experiment is "materialized" into existence. Merge has a materialization API that sends provisioning commands to the underlying tools that handle the varied hardware within any given infrastructure. These tools handle the provisioning instructions and take appropriate actions, as necessary. All materialization actions are asynchronous, with the various tools taking their actions and sending status updates back via the materialization API.

The overall process flow can be seen in Figure 13. This process diagram highlights the multitude of individual provisioning tools that are required as part of a NEFSI. Currently, Merge supports automatic provisioning of network switches, compute nodes, underlying infrastructure capabilities, and network emulation servers[aa]. This diagram highlights that additional provisioning tools for the RF devices and monitors will be required for the NEFSI. As noted previously, some
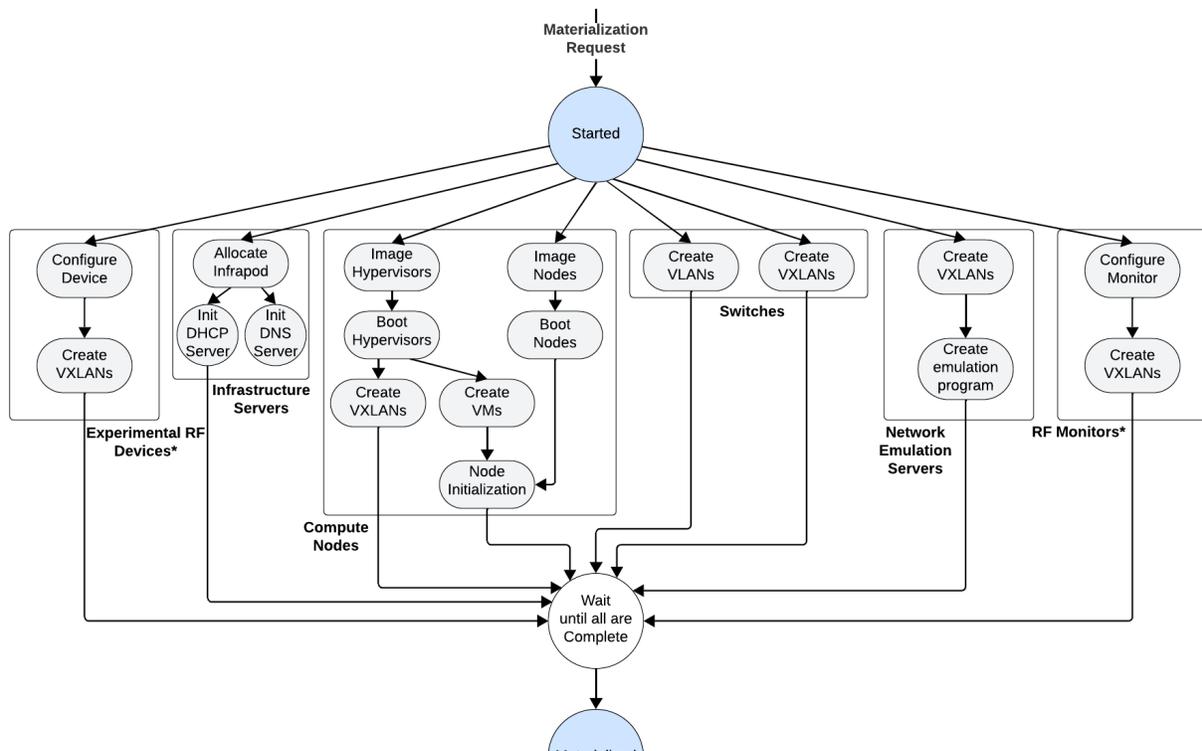


Figure 13. Materialization process.

z   Zheng, Y., Ravi, S., Kline, E., Thurlow, L., Koenig, S., & Kumar, T. S. (2023, July). Improved Conflict-Based Search for the Virtual Network Embedding Problem. In 2023 32nd International Conference on Computer Communications and Networks (ICCCN) (pp. 1-10). IEEE.

aa  Network emulation is generally required in many test infrastructures where underlying network conditions are relevant. This capability will not be necessary for all DSS experiments but may be relevant for a few. The initial infrastructure design does not provide any emulation capabilities, but an expanded version may desire them.

of these devices may have limited remote provisioning options, thus local software or hardware wrappers may need to be developed to enable automatic, remote provisioning. The realization process continues until all provisioners report success or failure. If any report failure, recovery is attempted, depending on the specific failure. If recovery is not possible, then the termination and cleanup process are executed, as discussed below.

The next step after materialization is for the experiment to execute. The EMS is not responsible for the execution of the overall experiment, but it can execute experimental scripts provided by the experimenter. The EMS will monitor experimental health, as specified in the experimental description. This includes monitoring for unacceptable packet loss on network links, oversubscription of CPU or RAM on computing nodes, and any failure states on devices. Depending on the experimenter's policy, health problems may simply result in a warning to the experimenter, could provide a note *ex post facto*, or may terminate the experiment.

When the experiment has reached conclusion, the final EMS component is exercised: termination and cleanup. The termination and cleanup process is effectively the inverse of the materialization process highlighted in Figure 13. Through the provisioning API, each provisioning tool "de-provisions" the relevant devices and resets them to their default state. For computing resources, this involves removing any virtual machines and deconstructing VXLANs. For switches, this is deconstructing the network-isolation mechanisms used. For RF devices, this may include resetting to a default configuration and powering off the device. The specific actions taken for any device is dependent on what the default state for that device should be, based on NEFSI policy. The EMS must also conduct verification, ensuring all devices are following the cleanup policy and procedures.

## 3. User-Management System

Any complex system like the NEFSI requires a user-management system (UMS). Multiple UMSs exist with POWDER, COSMOS, and Merge all having UMS implementations. Here, we present a brief UMS architecture that highlights the functionality the NEFSI would require. Additional functionality may be required as the NEFSI is developed, deployed, and operated.

At a high level, the UMS is responsible for all user-management functions. This includes presenting a frontend interface through which users operate, allowing them to manage their accounts, create or delete experiments, control those experiments, and control access to any equipment and data. The UMS must also support administrative control over users. These controls are user vetting and authorization, administrative account management, and user or project-level access controls. An exemplar architecture is illustrated in Figure 14.

An important caveat is that, while access control is critically important to the NEFSI, how it is accomplished is left open. This diagram uses ACLs as a stand-in for all access control, but multiple different access-control mechanisms may be sufficient for the NEFSI. Similarly, this diagram assumes a NEFSI with internal user management. If, however, users are managed externally (perhaps through a federated system or government agency), the UMS will mainly be a shell for accessing that external system.
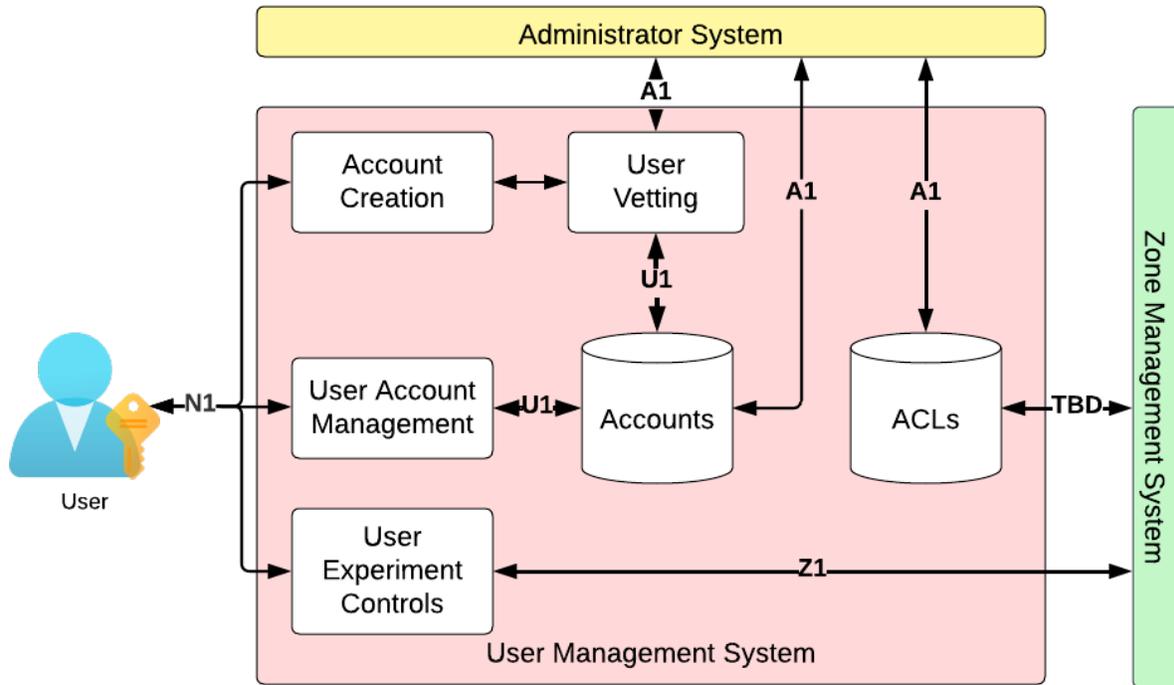
Figure 14. User Management System

# 4. Administrator System

The administrator system is the final systemic component of the NEFSI. It is responsible for all administrative functions of the NEFSI, although exactly what all those functions are is left open. However, a set of functions are clearly required to administer the NEFSI:

- User account management. Administrators will need to vet new users, approve new accounts, and terminate old accounts. Further, administrators may need to add or remove users from different projects or groups.

- Project or group management. Users will certainly want to work together across projects or groups. Thus, administrators will need to approve new projects or groups, potentially manage users within them, and remove old projects.

- Access controls. Users and projects will have various levels of privilege, which will be provided by administrators through access controls.

- Spectrum control. Spectrum managers will have authority over what spectra are available to the NEFSI and specific users. This control will certainly be fine grained. For example, specific spectra may be available only at specific transmit power levels or below.

- Resource commissioning and decommissioning. During the life cycle of any test infrastructure, new resources are added, and old resources are removed. Administrators must have the ability to ensure available resource inventories are accurate and up to date.

- Maintenance. As with any system, administrators need the ability to maintain the NEFSI.

As noted, this list of administrative functions may not be exhaustive. As the NEFSI develops, additional administrative functions will become clear and will be added to the administrator system.

# A3. Experiment Description Language

The NEFSI needs a common experiment description language that can be easily used to describe the resources, connectivity, and topology a given experiment requires. OpenZMS uses RSpec as its language while Merge uses XIR. Neither of these languages currently captures all salient aspects of an experiment that would be required for the NEFSI. Both are extensible with RSpec using XML to enable extensions while XIR is fully programmable with library support in Python and Go. While the STRATA team makes no specific recommendation on the description language, we do recommend choosing either RSpec or XIR.

# 1. APIs

Throughout Section A2, multiple APIs are identified. The list of potential NEFSI interfaces and high-level description of their functionality are provided in Table 3. Further, the security requirements for each interface are identified. All APIs should use *encryption* to protect their communications and *verify* each API endpoint.

Table 3. Potential NEFSI interfaces.

| API ID | API Name | API Description |
|---|---|---|
| **N1** | Frontend Interface | User presented frontend interface that allows users to create and manage their accounts and experiments |
| | | Security requirements: user verification |
| **A1** | User Administration | Administrative interface for managing user accounts and user-access controls |
| | | Security requirements: administrator verification |
| **A2** | ZMS Administration | Administrative interface for managing the ZMS to enable the spectrum manager to allocate, control, and remove spectra |
| | | Security requirements: administrator verification |
| **A3** | EMS Administration | Administrative interface for managing the EMS to allow the commissioning or decommissioning of resources and provide controls for system maintenance |
| | | Security requirements: administrator verification |
| **Z1** | User Experiment Controls | Allow users to request a new or execute an existing experiment, provided in the experiment description language |
| | | Security requirements: user verification, user and project spectrum-access credentials |

| API ID | API Name | API Description |
|--------|----------|-----------------|
| **Z2** | RF Digital Twin | Interface for requesting and receiving interference analysis from a RF digital twin that should be flexible enough to allow multiple different digital twins to exist within the ZMS.<br><br>Security requirements: endpoint verification |
| **Z3** | Incumbents | Communicate with incumbents about any potential or actual interference and agree upon mitigations<br><br>Security requirements: NEFSI, incumbent and endpoint verification |
| **Z4** | Spectrum Usage | Update the current spectrum being used by the NEFSI<br><br>Security requirements: spectrum-usage signature |
| **E1** | Plausibility | Determine whether a given experiment can be provisioned on the available NEFSI resources<br><br>Security requirements: user verification, user and project resource-access credentials |
| **E2** | Provisioning | Provision and configure NEFSI resources for the given experiment<br><br>Security requirements: configuration signatures |
| **E3** | Operations | Initiate and monitor the experiment<br><br>Security requirements: provisioning validation |
| **E4** | Termination | Terminate an experiment<br><br>Security requirements: user or interference verification |
| **E5** | Deprovisioning | Clean up experiment and return resources to available pool<br><br>Security requirements: validated termination request |
| **C1** | Hardware Control | Hardware-specific interfaces for provisioning, configuration and control, governed by specific equipment and perhaps requiring additional third-party controls<br><br>Security requirements: device dependent |
| **U1** | User Account Control | Interface for user-based account management<br><br>Security requirements: user verification |
| **TBD** | Access Control | Undecided mechanism for verifying user, project, and administrator access control—could be an interface or other access control mechanism |

# Appendix B, Risk Assessment of Gaps

Here we assess the risks associated with closing the gaps for INL to operate as an MVP NEFSI. Risks associated with INL's operation as a NEFSI are out of scope for the discussion here because they would depend on the specific approach taken to close the gaps discussed above. For each risk identified here, we propose a mitigation strategy. Figure 15 summarizes the probability and impact of each risk as well as the utility of the proposed mitigation strategy.

1. **Risk 1:** No suitable solution for dedicated spectrum monitoring can be identified, acquired, and installed at INL. This will result in INL operating as an MVP NEFSI with only the currently available spectrum monitoring capabilities.

   **Mitigation Strategy 1:** Current INL spectrum monitoring capabilities can be used to provide robust spectrum data, even without providing the long-term consistency and reproducibility of dedicated, stationary spectrum monitoring. Additionally, INL is actively updating spectrum monitoring toward a more dedicated and stationary approach as part of the planned FY 25 field trials.

2. **Risk 2:** A mechanism for terminating experiments automatically based on detected interference or anomalies cannot be realized for the complete scope of spectrum experiments at INL. This will prevent rapid experiment termination in the case of interference or anomalies, increasing the chances for data corruption or interfering with external incumbents.

   **Mitigation Strategy 2:** INL will continue to use the current, proven approach to terminating experiments as needed. While this method has additional delays compared to an automatic approach, it does provide protection for other experiments and incumbents. INL will also schedule experiments to minimize the potential for harmful interactions. In parallel, INL will explore more automated solutions for experiment termination. INL plans to deploy automated solutions iteratively, starting with approaches applicable to a small subset of experiments and scaling to include more over time.

3. **Risk 3:** Automated configuration of experiment isolation and security cannot be deployed at INL. This will reduce the number of experiments that can be supported by INL relative to a more automatic approach.

   **Mitigation Strategy 3:** INL will continue the more manual approach currently in place. As demand for experiments at INL increases, INL anticipates increasing the staff supporting these experiments. In parallel, INL is being to explore automation of experiment configuration as part the FY 25 field trials. This automation will initial target a small subset of experiment capabilities at INL and iteratively expand over time.

4. **Risk 4:** A streamlined process to rapidly enable remote access to experiment resources at INL is not possible. This will limit the number of new researchers that INL can support relative to a streamlined approach.

   **Mitigation Strategy 4:** INL is exploring methods to standardize and streamline providing remote access to external researchers. These methods will be supported manually initially. INL anticipates increasing the staff supporting experiments as demand increases. INL also

anticipates integrating streamlined methods for remote access into the automated experiment configuration tools mentioned in mitigation strategy 3.

5. **Risk 5:** The funding model of INL is not adapted to ease access for industry and academia. This will limit the potential pool of researchers that INL can support relative to other options.

   **Mitigation Strategy 5:** INL has recently established the INL Foundation to support alternative funding models. INL will explore the utility of this organization to support industry and academia access to DSS experimentation at INL.
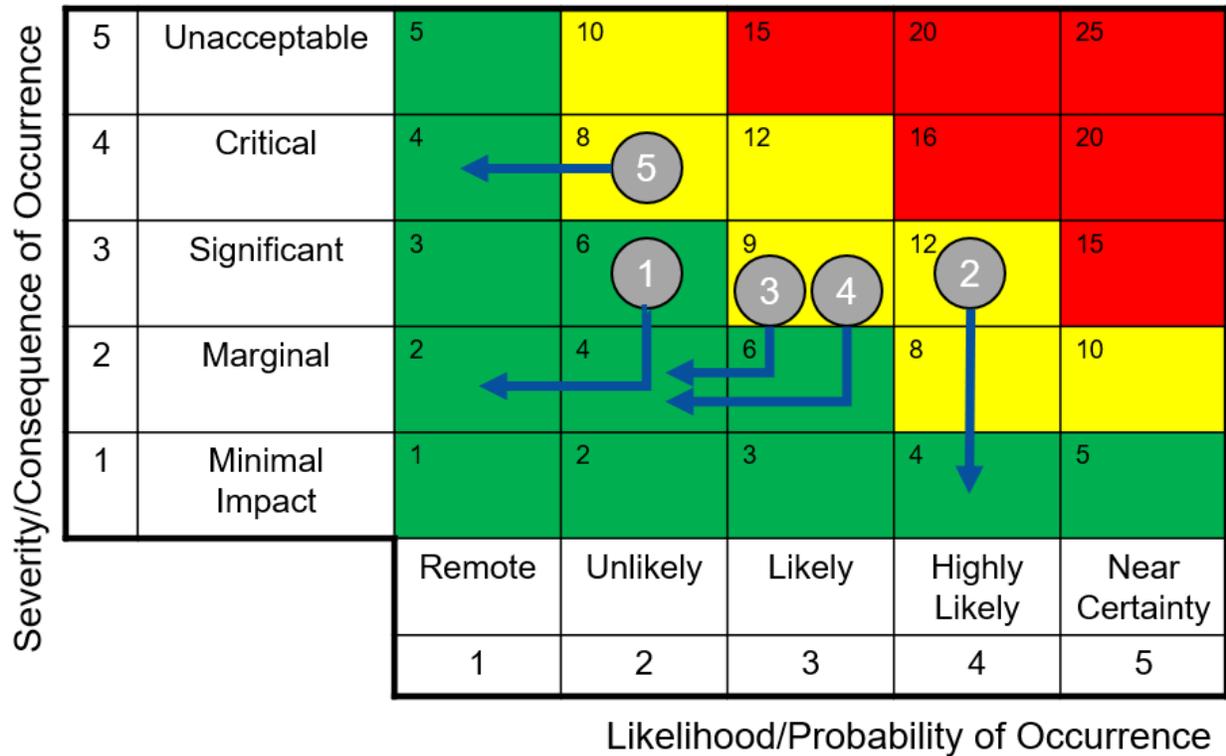


Figure 15. Risk summary associated with closing MVP NEFSI gaps at INL. The blue arrows show the anticipated impact of mitigation strategies.

# Appendix C, Greenfield ROM Cost Estimate

# Interoffice Memorandum

**INL** Idaho National Laboratory

| | |
|---|---|
| **Date:** | November 11, 2024 |
| **To:** | S. Z. Edwards, Project Manager |
| **From:** | G. R. Clark, Cost Estimator |
| **Subject:** | Greenfield National Spectrum Facility |

Garrett Clark

Digitally signed by Garrett Clark
DN: C=US, E=Garrett.Clark@inl.gov, O=PMO,
OU=Cost Estimating, CN=Garrett Clark
Reason: I am the author of this document
Date: 2024.11.11 08:37:47-07'00'

Per your request, Cost Estimating prepared a cost estimate Rough Order of Magnitude (ROM) package for the above-mentioned subject.

The estimated ROM cost range, excluding escalation and management reserve, is as follows:

| | |
|---|---|
| Low-end range value | $100,000,000 |
| ROM point value | $124,000,000 |
| High-end range value | $150,000,000 |

Please note the following:
A. If this estimate is used to establish or request funding or to be used as a proposal for this project, it is recommended and a best practice that the high-end range value be used.
B. The following costs/methods were explored and employed for performing this ROM:
1. Estimating industry recognized 6/10's rule for unit cost parametric.
2. Parametric modeling from online resources for similar projects.
3. Parametric modeling from previous projects completed at Idaho National Laboratory (INL).
C. Per the requester, this work will be direct funded. Battelle Energy Alliance, LLC (BEA) adders for this type of funding are not included in this estimate.
D. This estimate only reflects subcontract cost and does not include Battelle Energy Alliance, LLC (BEA) project support or adder costs.
E. A review of this cost estimate was held on November 6, 2024, with you and this cost estimator. This review allowed the estimator to discuss, in detail, the scope, basis of estimates, assumptions, project risks, and the resources that make up this cost estimate. Comments from this review have been incorporated into this estimate to reflect a project team consensus of this document.

Refer to the cost estimate summary, detail, and markup with the cost breakdowns.

This estimate is based on the limited information and hours allotted, provided to this estimator as the scope of work to be completed. Any changes to the methodology used to prepare this estimate could have a significant effect on the cost estimate and should be reviewed by me. If you have any questions or comments, do not hesitate to contact me by e-mail Garrett.Clark@inl.gov.

Attachments

cc:    Estimate File MC24

Uniform File Code:  8309
Disposition Authority:  A16-1.6-a

SCOTT WASLEY (Affiliate)

Digitally signed by SCOTT WASLEY (Affiliate)
Date: 2024.11.11 12:52:55 -07'00'

Retention Schedule:  Cut off annually. Destroy 10 years after cutoff.

NOTE:  Original disposition authority, retention schedule, and Uniform Filing Code applied by the sender may not be appropriate for all recipients. Make adjustments as needed.

# BEA - Report 1 - Summary Report

Project Name: Greenfield National Spectrum Facility
Project Location: Unknown
Estimate Number: MC24

Requester: S. Z. Edwards
Estimator: G. R. Clark
Estimate Classification: Rough Order Magnitude (ROM)

| Charging Practice | Item Description | Total Cost |
|---|---|---|
| **ROM** | **Rough Order of Magnitude** | **$124,058,174** |
| | **Grand Total** | **$124,058,174** |

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| | | Remarks: |
|---|---|---|
| Type of Estimate: | Rough Order Magnitude (ROM) | |
| Estimator: | G. R. Clark | |
| Checked By: | BRANDON FINCH Digitally signed by BRANDON FINCH DN: C=US, E=Brandon.Finch@INL.Gov, O=Cost Estimating, OU=F522, CN=BRANDON FINCH Date: 2024.11.11 09:05:15-07'00' | |
| Approved By: | SCOTT WASLEY (Affiliate) Digitally signed by SCOTT WASLEY (Affiliate) Date: 2024.11.11 12:53:22 -07'00' | |

**BEA**
11/11/2024  8:19AM

**iNL**
Idaho National Laboratory

# BEA - Report 2 - Project Summary

| WBS Code | Item Description | Total Cost |
|---|---|---|
| **1** | **Project Management** | **$7,121,240** |
| **1.05** | **Project Management** | **$6,103,920** |
| 1.05.15 | Project Management During Execution | $6,103,920 |
| **1.10** | **Cost & Schedule Management** | **$1,017,320** |
| 1.10.15 | Cost & Schedule Management During Execution | $1,017,320 |
| **2** | **Management Services** | **$5,035,734** |
| **2.10** | **Other Construction Management Support** | **$5,035,734** |
| 2.10.05 | Environmental Impact Statement | $4,272,744 |
| 2.10.05.10 | Environmental Impact Statement | $4,272,744 |
| 2.10.10 | Safety | $508,660 |
| 2.10.10.10 | Safety Oversight During Execution | $508,660 |
| 2.10.20 | Subsurface | $254,330 |
| 2.10.20.10 | Subsurface Oversight During Execution | $254,330 |
| **4** | **Design/Engineering** | **$10,173,200** |
| **4.05** | **Subcontract Design/Engineering** | **$10,173,200** |
| 4.05.02 | Design/Engineering Support During Preliminary Design | $4,069,280 |
| 4.05.03 | Design/Engineering Support During Final Design | $4,069,280 |
| 4.05.04 | Design/Engineering Support During Execution | $2,034,640 |

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# BEA - Report 2 - Project Summary

| WBS Code | Item Description | Total Cost |
|---|---|---|
| **6.05.01.05** | **Contractors General Requirements** | **$101,728,000** |
| **6.05** | **Construction Execution - Subcontracted Work** | **$101,728,000** |
| 6.05.01 | General Conditions | $9,248,000 |
| 6.05.01.05 | Contractors General Requirements | $9,248,000 |
| 6.05.02 | Utilities | $21,000,000 |
| 6.05.02.01 | Sewer System | $500,000 |
| 6.05.02.02 | Fire/Potable Water System | $500,000 |
| 6.05.02.03 | Power Distributions System | $12,000,000 |
| 6.05.02.04 | Telecommunication System | $8,000,000 |
| 6.05.03 | Clear & Grub/Roadways | $48,100,000 |
| 6.05.03.01 | Clear & Grub Facility Sites | $100,000 |
| 6.05.03.02 | Roadways | $48,000,000 |
| 6.05.04 | Facilities | $22,400,000 |
| 6.05.04.01 | Facilities | $22,400,000 |
| 6.05.05 | Towers | $180,000 |
| 6.05.05.01 | Fixed Towers | $120,000 |
| 6.05.05.02 | Mobile Towers | $60,000 |
| 6.05.06 | Maintenance Equipment Procurement | $800,000 |
| 6.05.06.01 | Maintenance Equipment Procurement | $800,000 |
| | **Grand Total** | **$124,058,174** |

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Project Name: Greenfield National Spectrum Facility
Project Location: Unknown
Estimate Number: MC24

Requester: S. Z. Edwards
Estimator: G. R. Clark
Estimate Classification: Rough Order Magnitude (ROM)

| Item Description | Labor Total | Mat Total | Equip Total | Subs Total | Sub Markups | BEA Adders | Escalation | Est Subtotal & Escalation | MR Total | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|
| **Prime Contractor** | - | - | - | **$101,728,000** | - | - | - | **$101,728,000** | - | **$101,728,000** |
| **Construction Management** | - | - | - | **$12,156,974** | - | - | - | **$12,156,974** | - | **$12,156,974** |
| **Off Site Design Services** | - | - | - | **$10,173,200** | - | - | - | **$10,173,200** | - | **$10,173,200** |
| **Grand Total** | - | - | - | **$124,058,174** | - | - | - | **$124,058,174** | - | **$124,058,174** |

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# BEA - Report 5 - Detail Item Report

Project Name: Greenfield National Spectrum Facility
Project Location: Unknown
Estimate Number: MC24

<div align="right">

Requester: S. Z. Edwards
Estimator: G. R. Clark
Estimate Classification: Rough Order Magnitude (ROM)

</div>

| WBS Code | Item Description | QTY | Unit | Contractor | WDC | Labor Unit | Labor Hours | Labor Total | Exp Type | Mat Price | Mat Total | Equip Rate | Equip Total | Subs Unit Price | Subs Total | Sub Markup Total | BEA Adders | Est Subtotal With Sub Markup | Escalation | Est Subtotal & Escalation | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Project Management | - | | | | - | - | - | | - | - | - | - | - | $7,121,240 | - | - | $7,121,240 | - | $7,121,240 | $7,121,240 |
| 1.05 | Project Management | - | | | | - | - | - | | - | - | - | - | - | $6,103,920 | - | - | $6,103,920 | - | $6,103,920 | $6,103,920 |
| 1.05.15 | Project Management During Execution | - | | | | - | - | - | | - | - | - | - | - | $6,103,920 | - | - | $6,103,920 | - | $6,103,920 | $6,103,920 |
| 1.05.15 | Project Management During Execution | 0.06 | % | 04-CM | | - | - | - | | - | - | - | - | $101,732,000 | $6,103,920 | - | - | $6,103,920 | - | $6,103,920 | $6,103,920 |
| 1.10 | Cost & Schedule Management | - | | | | - | - | - | | - | - | - | - | - | $1,017,320 | - | - | $1,017,320 | - | $1,017,320 | $1,017,320 |
| 1.10.15 | Cost & Schedule Management During Execution | - | | | | - | - | - | | - | - | - | - | - | $1,017,320 | - | - | $1,017,320 | - | $1,017,320 | $1,017,320 |
| 1.10.15 | Cost & Schedule Management During Execution | 0.01 | % | 04-CM | | - | - | - | | - | - | - | - | $101,732,000 | $1,017,320 | - | - | $1,017,320 | - | $1,017,320 | $1,017,320 |
| 2 | Management Services | - | | | | - | - | - | | - | - | - | - | - | $5,035,734 | - | - | $5,035,734 | - | $5,035,734 | $5,035,734 |
| 2.10 | Other Construction Management Support | - | | | | - | - | - | | - | - | - | - | - | $5,035,734 | - | - | $5,035,734 | - | $5,035,734 | $5,035,734 |
| 2.10.05 | Environmental Impact Statement | - | | | | - | - | - | | - | - | - | - | - | $4,272,744 | - | - | $4,272,744 | - | $4,272,744 | $4,272,744 |
| 2.10.05.10 | Environmental Impact Statement | - | | | | - | - | - | | - | - | - | - | - | $4,272,744 | - | - | $4,272,744 | - | $4,272,744 | $4,272,744 |
| 2.10.05.10 | Environmental Impact Statement | 0.04 | % | 04-CM | | - | - | - | | - | - | - | - | $101,732,000 | $4,272,744 | - | - | $4,272,744 | - | $4,272,744 | $4,272,744 |
| 2.10.10 | Safety | - | | | | - | - | - | | - | - | - | - | - | $508,660 | - | - | $508,660 | - | $508,660 | $508,660 |
| 2.10.10.10 | Safety Oversight During Execution | - | | | | - | - | - | | - | - | - | - | - | $508,660 | - | - | $508,660 | - | $508,660 | $508,660 |
| 2.10.10.10 | Safety Oversight During Execution | 0.01 | % | 04-CM | | - | - | - | | - | - | - | - | $101,732,000 | $508,660 | - | - | $508,660 | - | $508,660 | $508,660 |
| 2.10.20 | Subsurface | - | | | | - | - | - | | - | - | - | - | - | $254,330 | - | - | $254,330 | - | $254,330 | $254,330 |
| 2.10.20.10 | Subsurface Oversight During Execution | - | | | | - | - | - | | - | - | - | - | - | $254,330 | - | - | $254,330 | - | $254,330 | $254,330 |
| 2.10.20.10 | Subsurface Oversight During Execution | 0.00 | % | 04-CM | | - | - | - | | - | - | - | - | $101,732,000 | $254,330 | - | - | $254,330 | - | $254,330 | $254,330 |
| 4 | Design/Engineering | - | | | | - | - | - | | - | - | - | - | - | $10,173,200 | - | - | $10,173,200 | - | $10,173,200 | $10,173,200 |
| 4.05 | Subcontract Design/Engineering | - | | | | - | - | - | | - | - | - | - | - | $10,173,200 | - | - | $10,173,200 | - | $10,173,200 | $10,173,200 |
| 4.05.02 | Design/Engineering Support During Preliminary Design | - | | | | - | - | - | | - | - | - | - | - | $4,069,280 | - | - | $4,069,280 | - | $4,069,280 | $4,069,280 |
| 4.05.02 | Design/Engineering Support During Preliminary Design | 0.04 | % | DESIGN | | - | - | - | | - | - | - | - | $101,732,000 | $4,069,280 | - | - | $4,069,280 | - | $4,069,280 | $4,069,280 |
| 4.05.03 | Design/Engineering Support During Final Design | - | | | | - | - | - | | - | - | - | - | - | $4,069,280 | - | - | $4,069,280 | - | $4,069,280 | $4,069,280 |
| 4.05.03 | Design/Engineering Support During Final Design | 0.04 | % | DESIGN | | - | - | - | | - | - | - | - | $101,732,000 | $4,069,280 | - | - | $4,069,280 | - | $4,069,280 | $4,069,280 |
| 4.05.04 | Design/Engineering Support During Execution | - | | | | - | - | - | | - | - | - | - | - | $2,034,640 | - | - | $2,034,640 | - | $2,034,640 | $2,034,640 |
| 4.05.04 | Design/Engineering Support During Execution | 0.02 | % | DESIGN | | - | - | - | | - | - | - | - | $101,732,000 | $2,034,640 | - | - | $2,034,640 | - | $2,034,640 | $2,034,640 |
| 6.05.01.05 | Contractors General Requirements | - | | | | - | - | - | | - | - | - | - | - | $101,728,000 | - | - | $101,728,000 | - | $101,728,000 | $101,728,000 |
| 6.05 | Construction Execution - Subcontracted Work | - | | | | - | - | - | | - | - | - | - | - | $101,728,000 | - | - | $101,728,000 | - | $101,728,000 | $101,728,000 |
| 6.05.01 | General Conditions | - | | | | - | - | - | | - | - | - | - | - | $9,248,000 | - | - | $9,248,000 | - | $9,248,000 | $9,248,000 |
| 6.05.01.05 | Contractors General Requirements | - | | | | - | - | - | | - | - | - | - | - | $9,248,000 | - | - | $9,248,000 | - | $9,248,000 | $9,248,000 |
| 6.05.01.05 | Wastewater Treatment System | 0.10 | % | 02-PRIME | | - | - | - | | - | - | - | - | $92,480,000 | $9,248,000 | - | - | $9,248,000 | - | $9,248,000 | $9,248,000 |
| 6.05.02 | Utilities | - | | | | - | - | - | | - | - | - | - | - | $21,000,000 | - | - | $21,000,000 | - | $21,000,000 | $21,000,000 |
| 6.05.02.01 | Sewer System | - | | | | - | - | - | | - | - | - | - | - | $500,000 | - | - | $500,000 | - | $500,000 | $500,000 |
| 6.05.02.01 | Wastewater Treatment System | 1.00 | LS | 02-PRIME | | - | - | - | | - | - | - | - | $500,000 | $500,000 | - | - | $500,000 | - | $500,000 | $500,000 |
| 6.05.02.02 | Fire/Potable Water System | - | | | | - | - | - | | - | - | - | - | - | $500,000 | - | - | $500,000 | - | $500,000 | $500,000 |
| 6.05.02.02 | Fire/Potable Water System | 1.00 | LS | 02-PRIME | | - | - | - | | - | - | - | - | $500,000 | $500,000 | - | - | $500,000 | - | $500,000 | $500,000 |
| 6.05.02.03 | Power Distributions System | - | | | | - | - | - | | - | - | - | - | - | $12,000,000 | - | - | $12,000,000 | - | $12,000,000 | $12,000,000 |
| 6.05.02.03 | Power Distributions System | 1.00 | LS | 02-PRIME | | - | - | - | | - | - | - | - | $12,000,000 | $12,000,000 | - | - | $12,000,000 | - | $12,000,000 | $12,000,000 |
| 6.05.02.04 | Telecommunication System | - | | | | - | - | - | | - | - | - | - | - | $8,000,000 | - | - | $8,000,000 | - | $8,000,000 | $8,000,000 |
| 6.05.02.04 | Telecommunication System | 1.00 | LS | 02-PRIME | | - | - | - | | - | - | - | - | $8,000,000 | $8,000,000 | - | - | $8,000,000 | - | $8,000,000 | $8,000,000 |
| 6.05.03 | Clear & Grub/Roadways | - | | | | - | - | - | | - | - | - | - | - | $48,100,000 | - | - | $48,100,000 | - | $48,100,000 | $48,100,000 |
| 6.05.03.01 | Clear & Grub Facility Sites | - | | | | - | - | - | | - | - | - | - | - | $100,000 | - | - | $100,000 | - | $100,000 | $100,000 |
| 6.05.03.01 | Clear & Grub | 20.00 | acres | 02-PRIME | | - | - | - | | - | - | - | - | $5,000 | $100,000 | - | - | $100,000 | - | $100,000 | $100,000 |

<span style="color:red">Material costs, where applicable, include Idaho state sales tax</span>

# BEA - Report 5 - Detail Item Report

Project Name: Greenfield National Spectrum Facility
Project Location: Unknown
Estimate Number: MC24

<div align="right">

Requester: S. Z. Edwards
Estimator: G. R. Clark
Estimate Classification: Rough Order Magnitude (ROM)

</div>

| WBS Code | Item Description | QTY | Unit | Contractor | WDC | Labor Unit | Labor Hours | Labor Total | Exp Type | Mat Price | Mat Total | Equip Rate | Equip Total | Subs Unit Price | Subs Total | Sub Markup Total | BEA Adders | Est Subtotal With Sub Markup | Escalation | Est Subtotal & Escalation | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.05.03.02 | **Roadways** | | | | | - | - | - | | - | - | - | - | - | $48,000,000 | - | - | $48,000,000 | - | $48,000,000 | $48,000,000 |
| 6.05.03.02 | Paved Roadways | 10.00 | Miles | 02-PRIME | | - | - | - | | - | - | - | - | $4,200,000 | $42,000,000 | - | - | $42,000,000 | - | $42,000,000 | $42,000,000 |
| 6.05.03.02 | Gravel Roadways | 10.00 | Miles | 02-PRIME | | - | - | - | | - | - | - | - | $600,000 | $6,000,000 | - | - | $6,000,000 | - | $6,000,000 | $6,000,000 |
| 6.05.04 | **Facilities** | | | | | - | - | - | | - | - | - | - | - | $22,400,000 | - | - | $22,400,000 | - | $22,400,000 | $22,400,000 |
| 6.05.04.01 | **Facilities** | | | | | - | - | - | | - | - | - | - | - | $22,400,000 | - | - | $22,400,000 | - | $22,400,000 | $22,400,000 |
| 6.05.04.01 | Office Facility | 8,000.00 | SF | 02-PRIME | | - | - | - | | - | - | - | - | $800 | $6,400,000 | - | - | $6,400,000 | - | $6,400,000 | $6,400,000 |
| 6.05.04.01 | Maintenance Facility | 5,000.00 | SF | 02-PRIME | | - | - | - | | - | - | - | - | $600 | $3,000,000 | - | - | $3,000,000 | - | $3,000,000 | $3,000,000 |
| 6.05.04.01 | Medical Facility | 5,000.00 | SF | 02-PRIME | | - | - | - | | - | - | - | - | $1,000 | $5,000,000 | - | - | $5,000,000 | - | $5,000,000 | $5,000,000 |
| 6.05.04.01 | Fire Station Facility | 5,000.00 | SF | 02-PRIME | | - | - | - | | - | - | - | - | $800 | $4,000,000 | - | - | $4,000,000 | - | $4,000,000 | $4,000,000 |
| 6.05.04.01 | Data Center Facility | 5,000.00 | SF | 02-PRIME | | - | - | - | | - | - | - | - | $800 | $4,000,000 | - | - | $4,000,000 | - | $4,000,000 | $4,000,000 |
| 6.05.05 | **Towers** | | | | | - | - | - | | - | - | - | - | - | $180,000 | - | - | $180,000 | - | $180,000 | $180,000 |
| 6.05.05.01 | **Fixed Towers** | | | | | - | - | - | | - | - | - | - | - | $120,000 | - | - | $120,000 | - | $120,000 | $120,000 |
| 6.05.05.01 | 60' Fixed Tower | 3.00 | EA | 02-PRIME | | - | - | - | | - | - | - | - | $40,000 | $120,000 | - | - | $120,000 | - | $120,000 | $120,000 |
| 6.05.05.02 | **Mobile Towers** | | | | | - | - | - | | - | - | - | - | - | $60,000 | - | - | $60,000 | - | $60,000 | $60,000 |
| 6.05.05.02 | 60' Mobile Tower | 2.00 | EA | 02-PRIME | | - | - | - | | - | - | - | - | $30,000 | $60,000 | - | - | $60,000 | - | $60,000 | $60,000 |
| 6.05.06 | **Maintenance Equipment Procurement** | | | | | - | - | - | | - | - | - | - | - | $800,000 | - | - | $800,000 | - | $800,000 | $800,000 |
| 6.05.06.01 | **Maintenance Equipment Procurement** | | | | | - | - | - | | - | - | - | - | - | $800,000 | - | - | $800,000 | - | $800,000 | $800,000 |
| 6.05.06.01 | Maintenance Equipment Procurement | 1.00 | LS | 02-PRIME | | - | - | - | | - | - | - | - | $800,000 | $800,000 | - | - | $800,000 | - | $800,000 | $800,000 |
| | **Grand Total** | - | | | | - | - | - | | - | - | - | - | - | **$124,058,174** | - | - | **$124,058,174** | - | **$124,058,174** | **$124,058,174** |

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