Vulnerability Assessment and Resilience Plan – Thomas Jefferson National Accelerator Facility

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Executive Summary

The U.S. Department of Energy is committed to managing the short and long-term effects of climate change on its mission and operations. To support this priority, DOE sites are expected to conduct vulnerability assessments and develop resilience plans within the next year. The vulnerability assessment and resilience plans (VARPs) will enable sites to identify, prepare for, and meet the challenges posed by climate change, and will build upon other existing DOE risk assessments processes.

Within the VARP processes, sites will identify a range of climate hazards for which they may be at risk. Plans must consider multiplier effects from compounding threats (e.g., droughts leading to increased wildfires) and the extent that vulnerabilities affect mission critical functions and operations. Throughout this process, sites will evaluate the potential life-cycle costs and consequences of inaction, both to DOE sites and external communities, including the assessment impacts on energy and environmental justice communities. To the extent possible, sites should evaluate the potential costs and benefits of proposed resilience solutions, including the quantification of key metrics that show changes to resilience, energy efficiency, and GHG emissions. This document provides a description of how each step of the VARP was undertaken at the Thomas Jefferson National Accelerator Facility (TJNAF).

Introduction

Site Description and Overview

Thomas Jefferson National Accelerator Facility (TJNAF) is a world-leading research institution for exploring the nature of matter in depth, providing unprecedented insight into the details of the particles and forces that build our visible universe inside the nucleus of the atom. TJNAF was established in 1984 in Newport News, Virginia, and is operated by Jefferson Science Associates (JSA), LLC, for the Department of Energy's (DOE) Office of Science (SC).

Research at TJNAF reveals the fine details of the constituents of matter, from the familiar protons, neutrons, and electrons in the atom, to the lesser-known quarks and gluons inside the atom's nucleus. These studies are revealing how fundamental universal forces build and shape matter and are opening a window into matter's inner universe.

Enabling these studies is TJNAF's world leadership in the development and deployment of large-scale superconducting radiofrequency (SRF) technology. SRF technology powers TJNAF's flagship facility, the Continuous Electron Beam Accelerator Facility (CEBAF). The technical and research successes accomplished with CEBAF as a unique SRF particle accelerator have made possible a wide array of applications, from ever more powerful free-electron lasers for research to life-saving advances in nuclear medicine, and from impactful applications in industry to real-world solutions for protecting our nation's borders.

In support of its scientific mission, TJNAF maintains core capabilities and expertise in Nuclear Physics; Accelerator Science and Technology; Large-Scale User Facilities/Advanced Instrumentation, and Advanced Computer Science, Visualization, and Data. TJNAF is exploring ways to capitalize on its expertise in the computational sciences to provide large-scale high-performance computing services to an array of research fields for accelerating and maximizing scientific insight in the future.

TJNAF actively partners with industry to advance critical technologies to benefit the nation. The lab is also investing in the next-generation science, technology, engineering, and math (STEM) workforce. Its dedicated research facilities enable one-third of U.S. PhDs in nuclear physics annually, and its outreach programs positively impact thousands of students and teachers while helping them build critical knowledge and skills for a brighter future.

VARP 2022 Scope

TJNAF is located on a 169-acre DOE-owned federal reservation. Adjacent to the federal reservation is the Virginia Associated Research Campus (VARC), a 5-acre parcel owned by the Commonwealth of Virginia and leased by Southeastern Universities Research Association (SURA) which sub-leases five acres to DOE for TJNAF use. Also adjacent is an 11-acre parcel owned by the City of Newport News that contains the Applied Research Center (ARC) where JSA leases additional office and lab space.

TJNAF consists of 69 DOE-owned buildings comprising 882,990 square feet (SF) of office, shop, technical, and storage space. Many of the key facilities are located underground. JSA leases additional office and lab space in the VARC (37,643 SF) and ARC (11,435 SF). JSA also leases two off-site storage warehouses (17,549 SF). TJNAF provides office and workspace for approximately 800 JSA contractor, JSA, and federal government employees plus nearly 1,700 transient users and visiting scientists. Since the entire TJNAF portfolio of assets and infrastructure described above are located in a common geographic region and climate zone, a single consolidated Vulnerability Assessment and Resilience Plan (VARP) was included in this scope.

VARP Planning Team (VARP Step 1)

The core VARP planning team consisted of site planning and sustainability program staff. The team looked at historical weather data, climate projections, and the latest climate science to understand baseline and future climate scenarios. A previous climate screening document from 2014 was also thoroughly reviewed. Potential impact of extreme weather events and climate change on the site-specific operational viability of critical assets, infrastructure, and programs were assessed. This assessment considered both near-term climate impacts, as well as long-term impacts over the expected lifespan of critical assets and infrastructure systems.

To provide a baseline for understanding historical hazards that could be affected by climate change, the team consulted the Federal Emergency Management Agency's (FEMA) National Risk Index (NRI) and the Potential Hazards tool within FEMP's Technical Resilience Navigator.

Future climate hazards were evaluated using the climate scenarios represented by Representative Concentration Pathway (RCP) 4.5 and RCP 8.5. RCP 4.5 represents the Intergovernmental Panel on Climate Change's (IPCC) scenario for lower concentrations of GHG emissions, while RCP 8.5 represents a scenario of higher GHG emissions resulting in greater projected impacts (e.g., temperature extremes, sea level rise and storm surge, droughts and extreme precipitation events) that lead to severe consequences and higher costs. Regional reports from the National Climate Assessment (NCA) that describe specific climate hazards projected for geographic regions as well as tools, information, graphs, maps, downloadable data of observed and projected climate variables, and subject matter expertise in the Climate Resilience Toolkit, Climate Explorer, and National Oceanic and Atmospheric Administration's (NOAA) State Climate Summaries were also used to identify and manage climate-related risks and increase resilience.

Subsequently, several interviews with TJNAF staff were conducted to identify a comprehensive list of potential vulnerabilities associated with projected hazards resulting from climate change. The participants were selected based on their depth of expert knowledge about TJNAF systems and included members from operational divisions such as Environmental, Safety and Health (ESH) and Facilities Management and Logistics (FM&L) as well as science and technology divisions such as Accelerator (ACC), Computational Science and Technology (CST), Engineering (ENG), and Experimental Nuclear Physics (ENP).

Critical Site Assets and Infrastructure (VARP Step 2)

Critical site assets and infrastructure analyzed in this VARP based on the scope are described in Table 1 below:

Table 1: Critical Site Assets and Infrastructure

List of Asset and Infrastructure System Types	Asset or Infrastructure Name or Identifier	Description: Scale/Size/Footprint
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Service Buildings	01 - North Linac: 12,850 GSF 02 - South Linac: 12,850 GSF 21 - North Extractor Service: 460 GSF 82 - South Extractor Service: 2,289 GSF 38 - South Access: 8,332 GSF 67 - North Access: 8,332 GSF 39 - East ARC Service (E2): 460 GSF 40 - West ARC Service (W4): 460 GSF 45 - West ARC Service (W5): 548 GSF 49 - East ARC Service (E3): 548 GSF 50 - East ARC Service (E5): 548 GSF 56 - West ARC Service (W3): 460 GSF 63 - East ARC Service (E4): 460 GSF 68 - West ARC Service (W2): 1,673 GSF 200 - Service Building: 3,636 GSF 53 - Injector Service: 3,402 GSF 92 - Service Building: 2,487 GSF 91 - Hall A Beam Dump Cooling: 630 GSF 95 - Hall C Beam Dump Cooling: 630 GSF
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Cryogenics Plants	08 - Central Helium Liquefier (CHL): 22,038 GSF 102 - End Stage Refrigeration (ESR): 2,991 GSF 104 - End Stage Refrigeration 2 (ESR2): 6,638 GSF 201 - Cryo Plant: 903 GSF 57 - Cryogenics Test Facility (CTF): 4,098 GSF
Water and Wastewater Systems	Cooling Towers	08-CT02 CHL Cooling Tower 2: 7,125 Tons 200-CT01 Hall D Complex Cooling Tower 1: 933.3 Tons 38-CT02 South Access Cooling Tower 2: 4,175 Tons 57-CT02 CTF Cooling Tower 2: 812.5 Tons 58-CT01 Test Lab Cooling Tower 1: 5,925 Tons 67-CT02 North Access Cooling Tower 2: 5,325 Tons 92-CT02 Building 92 Cooling Tower 2: 2,050 Tons

List of Asset and Infrastructure System Types	Asset or Infrastructure Name or Identifier	Description: Scale/Size/Footprint
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Experimental Halls	101 - Experimental Hall A: 34,861 GSF 203 - Experimental Hall D: 11,110 GSF 94 - Experimental Hall B: 17,706 GSF 96 - Experimental Hall C: 28,415 GSF
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	Control Rooms	202 - Counting House: 3,601 GSF 97 - Counting House: 16,948 GSF 85 - Machine Control Center (MCC): 7,579 GSF
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	18 - Low Energy Recirculator Facility (LERF)	33,812 GSF
IT and Telecommunication Systems	205 - Canon Communications Hut	240 GSF
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	51 - Hadron Guard House	330 GSF
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	54 - Radcon Calibration	1,017 GSF
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	Laboratory/Fabrication Buildings	55 - Technology & Engineering Development: 74,300 GSF 58 - Test Lab: 142,010 GSF 90 - Experimental Equipment Lab (EEL): 54,788 GSF 98 - Physics Fabrication: 6,164 GSF 36 - General Purpose Building (GPB): 19,199 GSF 23 - Experimental Staging: 18,000 GSF
Water and Wastewater Systems	60 - Chiller Building	4,148 GSF
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Accelerator Tunnel	999 - Accelerator Tunnel: 113,868 GSF 204 - Tagger Area: 6,654 GSF

List of Asset and Infrastructure System Types	Asset or Infrastructure Name or Identifier	Description: Scale/Size/Footprint
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	Exit Stairs	04 - Exit Stair 4: 728 GSF 07 - Exit Stair 1: 728 GSF 37 - Exit Stair 2: 728 GSF 42 - Exit Stair 6: 497 GSF 61 - Exit Stair 3: 497 GSF 70 - Exit Stair 5: 728 GSF 99 - Exit Stairwell: 461 GSF
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Gas Sheds	96B - Hall B Gas Shed: 693 GSF 96C - Hall C Gas Shed: 96 GSF 101A - Hall A Gas Shed: 360 GSF
Water and Wastewater Systems	AWN - Acid Waste Neutralization	15,000 Gallons/Day
Energy Generation and Distribution Systems	ELEC - Electrical Distribution	1 Each
Transportation and Fleet Infrastructure	ROADS – Roads	4.290 Miles
Water and Wastewater Systems	Water and Wastewater System	SEWER - Sanitary Sewer: 20,739 Feet WATER - Potable Water: 25,659 Feet
Site Workforce (outdoor workers, researchers, office staff, etc.)	Employees	800 persons
Supply Chains for Critical Material	Cryogenic Deliveries	Nitrogen Deliveries: 3 deliveries per day Helium Deliveries: 1 delivery per day
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	Data Center	5,366 GSF
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	Office Buildings	12 - CEBAF Center: 122,145 GSF 19 - Facilities Maintenance Shop: 2,904 GSF 28 - Support Service Center (SSC): 34,739 GSF 52 - ES&H Building: 11,777 GSF 87 - Accelerator Maintenance Support Bldg. (AMSB): 6,691 GSF 89 - Cryogenics Engineering: 10,152 GSF ARC - Applied Research Center: 11,435 GSF

Historical Hazard Events and Impacts (VARP Step 3)

Extreme events that have impacted the site within the last twenty years are described in :

Table 2 below:

Table 2: Extreme Events

Event Type and Date(s) (Month and Year)	Describe Event	Financial Impact (estimated $ and/or work hours)
Hurricane Isabel (September 2003)	Category-1 Hurricane passed through central Virginia on September 18, 2003 with winds up to 75 mph. The storm affected 99 counties and cities in the state, destroying thousands of trees and leaving approximately 1.8 million without power. Thomas Jefferson National Accelerator Facility was without power for approximately 3 and a half days. Without power, the Central Helium Liquefier could not run and the superconducting radiofrequency (SRF) insulating vacuum, crucial for the accelerator, could not be maintained. As a result, all SRF cavities warmed to ambient temperature and the laboratory had to vent approximately 65,000 liters of liquid helium.	6 weeks to return to operations; lost approximately $200,000 worth of Helium; 4 out of 300 cryomodule cavities were damaged, which accounted for at most 1% of the accelerator's energy reach
Heavy Rain Event (May 2012)	During business hours on May 15, 2012, the laboratory received approximately 1.69 inches of rain in a one-hour period. Two hours into the event, it was reported that the accelerator was down. Six inches of flooding was found in Experimental Hall B. Despite preparing for storm-related flooding by inspecting on-site drainage infrastructure for blockages and inspecting culverts for maximum flow, the heavy rain event filled the downstream drainage ditches resulting in flood damage.	No financial impact data available; Event resulted in creation of on-site early notification system.

Event Type and Date(s) (Month and Year)	Describe Event	Financial Impact (estimated $ and/or work hours)
Heavy Rain Event (August 2012)	On August 25, 2012, a severe storm resulted in flash floods causing equipment and facility damage to Experimental Halls A, B, and C. Storm onset and intensity were such that the Experimental Halls were flooded even before a Severe Thunderstorm Warning and a Flash Flood Watch were received. Flooding levels in the halls varied from 6 - 18 inches.	Highest flood level was located in Hall C at 30 inches. Due to pump issues, the flooding in Hall C continued into the next day. Overall, damages in the Halls had an impact on the accelerator upgrade schedule; Actual costs for repairs totaled $135,687

Responses to past extremes indicate TJNAF has the capacity for institutional learning and adaptation. TJNAF has back-up power generation capacity, including sufficient fuel for five days, which provides enough time for controlled warm-up of sensitive equipment in the event of another prolonged general power outage. TJNAF has also installed floodgates on the ramps leading down to the experiment halls to reduce sensitivity to future extreme precipitation.

Climate Change Projections for Hazards Affecting the Site (VARP Step 4)

TJNAF identified 10 climate hazards with historical impact to the region utilizing the National Risk Assessment and Technical Resilience Navigator. Using the interview method described in Step 1, TJNAF was able to refine the list of climate hazards and focus on 5 hazards known to historically impact the site. Leveraging the National Climate Assessment (NCA) and Climate Explorer, TJNAF determined that all of the climate hazards that historically impacted the site were projected to increase for both the 4.5 and 8.5 Representative Concentration Pathway (RCP) scenarios with various levels of confidence. The likely impact of climate change on the identified hazards is summarized below:

- **Precipitation**: TJNAF has historically experienced at least 1 major precipitation event every 10 years; climate change is anticipated to make this more frequent and severe going forward with high confidence in the model.
- **Hurricane**: TJNAF has historically experienced 1 major hurricane every 10 years; climate change is anticipated to make this more frequent and severe going forward with high confidence in the model.
- **Strong Wind**: TJNAF has historically experienced at 6 major strong wind events every 10 years; climate change is anticipated to make this more frequent and severe going forward with low confidence in the model due to limited available trend data.
- **Lightning**: TJNAF has historically experienced a least 20 major lightning events per year that disrupt accelerator operations; climate change is anticipated to make this more frequent going forward with low to medium confidence in the model due to limited available trend data.

- **Heat Wave:** TJNAF has historically experienced at least 1 major heat wave event per year; climate change is anticipated to make this more frequent and severe going forward with high confidence in the model.

Characterizing Current and Future Impacts of Climate Change (VARP Step 5)

Hazards with High Impact

Temperatures, precipitation, and storm strength and frequency are all likely to have the greatest impact to asset and infrastructure systems at TJNAF. TJNAF is projected to experience warmer temperatures in all seasons along with an increase of the freeze-free season and warm nights. TJNAF is projected to experience a slight increase in annual precipitation and heavy rainfall events are likely to occur more frequently. Projections of temperature and precipitation trends have a higher level of confidence due to the availability of trend data and consistency across models while storm severity trend data is limited by the difficulty of monitoring and modeling small-scale and short-lived events, such as lightning and strong wind (NCA 2018). In all modeled projections, historically observed data will be represented by gray, RCP 4.5 will be represented by blue, and RCP 8.5 will be represented by red. In each projection, there will be a color shaded region indicating the projected range and a color coordinated line indicating the projected average.

Average annual temperatures are projected to increase (Figure 1):

Figure 1: Projection for Annual Average Daily Maximum Temperature for Newport News, VA

The historical 1961-1990 average daily maximum temperature was 69°F. While average annual temperatures have already been observed above this historical threshold, temperatures are projected to continue increasing. The summer months are projected to see the greatest increases throughout the 21st century with the highest temperatures occurring in July. Depending on the RCP scenario, July temperatures at TJNAF are projected to increase by 2.1-2.3°F (1.2-3°C) within the next two decades alone. By 2090, July temperatures are projected to increase between 4.5°F (2.5°C) and 7.4°F (4.1°C) depending on the RCP 4.5 and 8.5 scenarios, respectively (Figure 2).

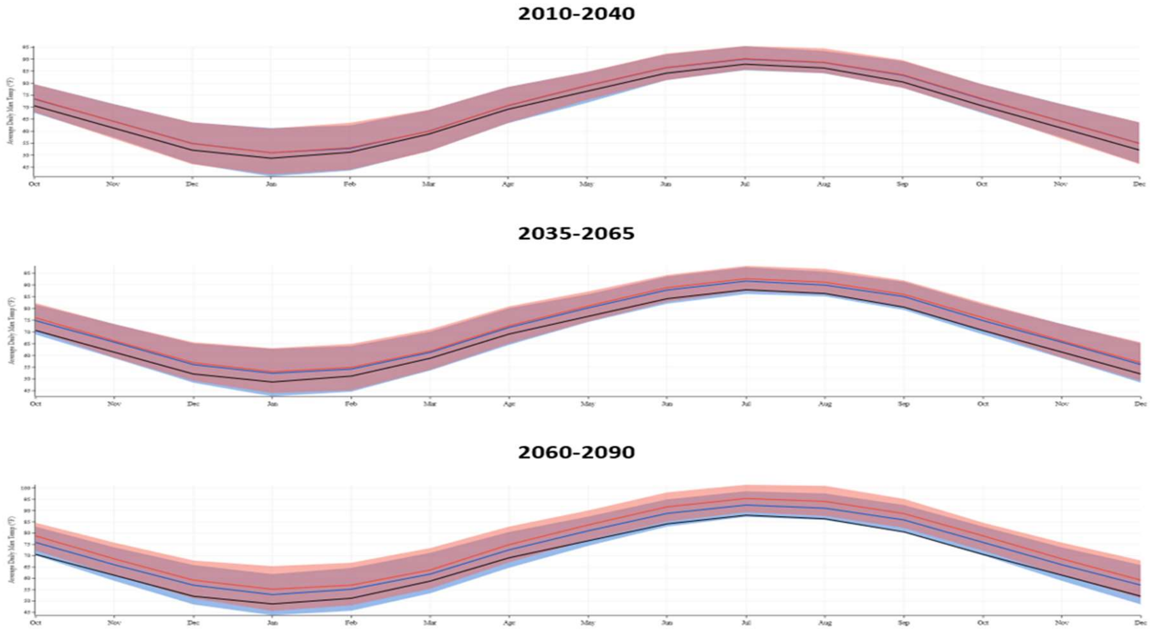


Figure 2: Projection for Monthly Average Maximum Daily Temperature for Newport News, VA

The number of heat days (>90°F) are projected to increase throughout the 21st century from the 1961-1990 observed average of 28 days per year to 70 (RCP 4.5) to 110 days (RCP 8.5) per year by 2090, with the degree of difference between RCP scenarios increasing from 2050 onward. The number of cold days (minimum temperature < 32°F) are projected to decrease from the 1961-1990 observed average of 55 days per year to 18 (RCP 8.5) to 33 days (RCP 4.5) per year by 2090. Consequently, there are projected to be more cooling degree days and fewer heating degree days compared to 1961-1990 (Figure 3).

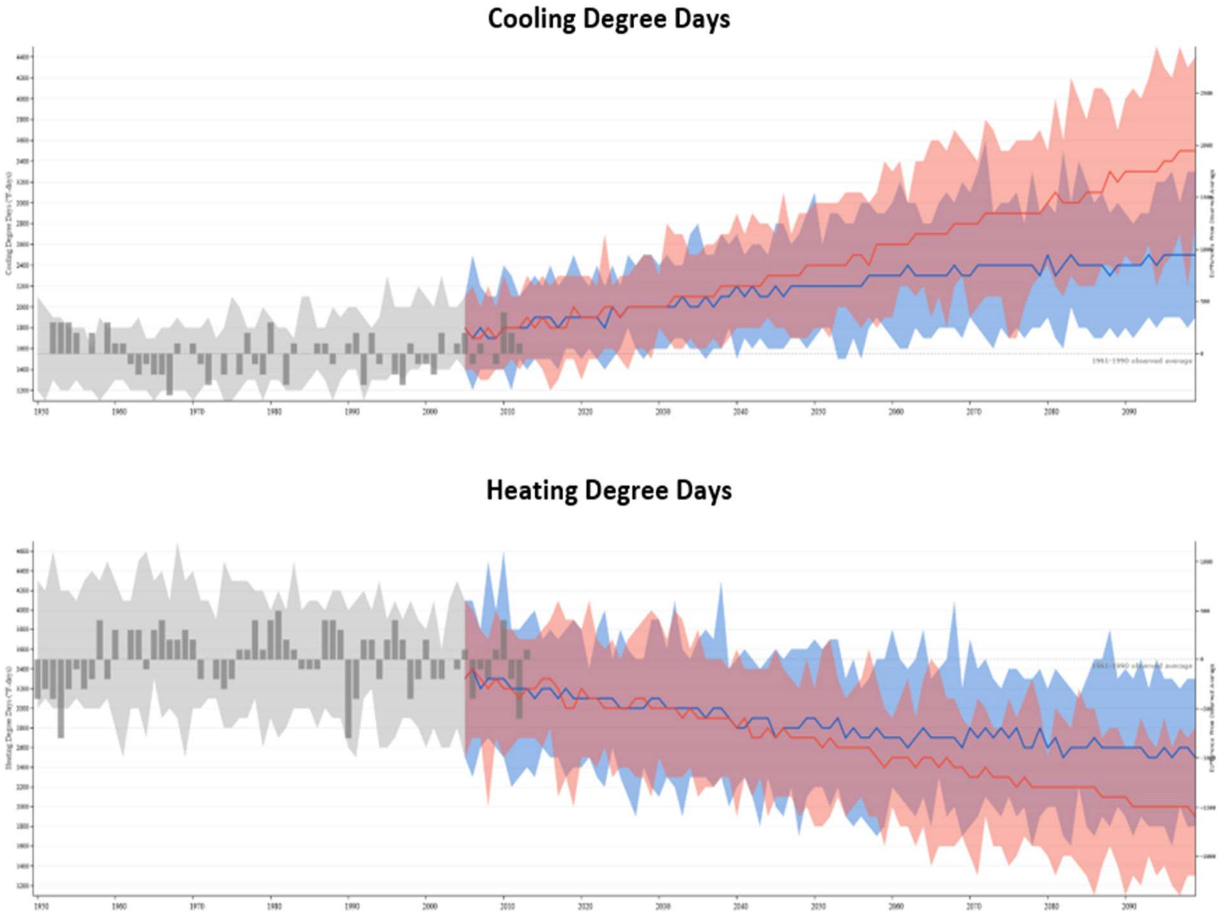


Figure 3: Projection for Annual Cooling and Heating Degree Days for Newport News, VA

With increased temperatures, TJNAF anticipates it is more likely that mission-critical equipment, water and wastewater systems, and site buildings will be at risk. Higher temperatures have the potential to impact cooling capabilities that protect both equipment and occupants. With a small percentage of TJNAF's workforce performing tasks outdoors, increasing temperatures also threaten the health, safety, and productivity of employees. There could also be compounding effects; for example, TJNAF relies on millions of gallons of potable water per year for cooling from one supplier. If temperatures increase, TJNAF will need to increase cooling capacity, which will require additional potable water consumption. If temperatures remain elevated for more than two days, known as a heat wave, and result in a drought, the public utility could curtail water usage which would put laboratory operations at risk.

Increasing temperatures have several related impacts to the NCA Southeast Region where TJNAF is located. While storm severity has been linked to a warmer climate, thunderstorms and the related climate hazards, such as lightning and strong winds, occur over short time periods and in smaller areas that make the trends difficult to detect and, consequently, the projections more difficult to develop. Therefore, while there is a strong confidence in temperature projections, there is low to medium confidence in the increasing frequency of lightning and strong wind. Due to the lack of trend data available, TJNAF relied on historical and current events to understand the vulnerability and impact of lightning and strong wind on asset and infrastructure systems. In 2021, TJNAF experienced 21 accelerator operation disruptions due to lightning events. With a high level of confidence in the projected temperature increases and the potential for increased storm severity, TJNAF projects that lightning events will continue to impact accelerator operations without additional adaptive measures.

TJNAF also relied on the projections for extreme rainfall events, which are projected with a high level of confidence, to derive assumptions about projected lightning frequency. Historically, TJNAF has experienced heavy rainfall events as thunderstorms. These storm events have required adaptive measures when heavy rainfall occurs over a short period of time. TJNAF focused on projections for increasing precipitation in two different scenarios: annually and monthly. For each scenario, there is a projected increase in rainfall for both RCP 4.5 and 8.5. In Figure 4, the annual precipitation increases from the 1961-1990 observed average of 46.78 inches per year to 49.81-52.63 inches per year by 2090 depending on the greenhouse gas concentration pathway. By 2050, annual precipitation is projected to increase by 2.8 (RCP 4.5) to 3.0 (RCP 8.5) inches per year.

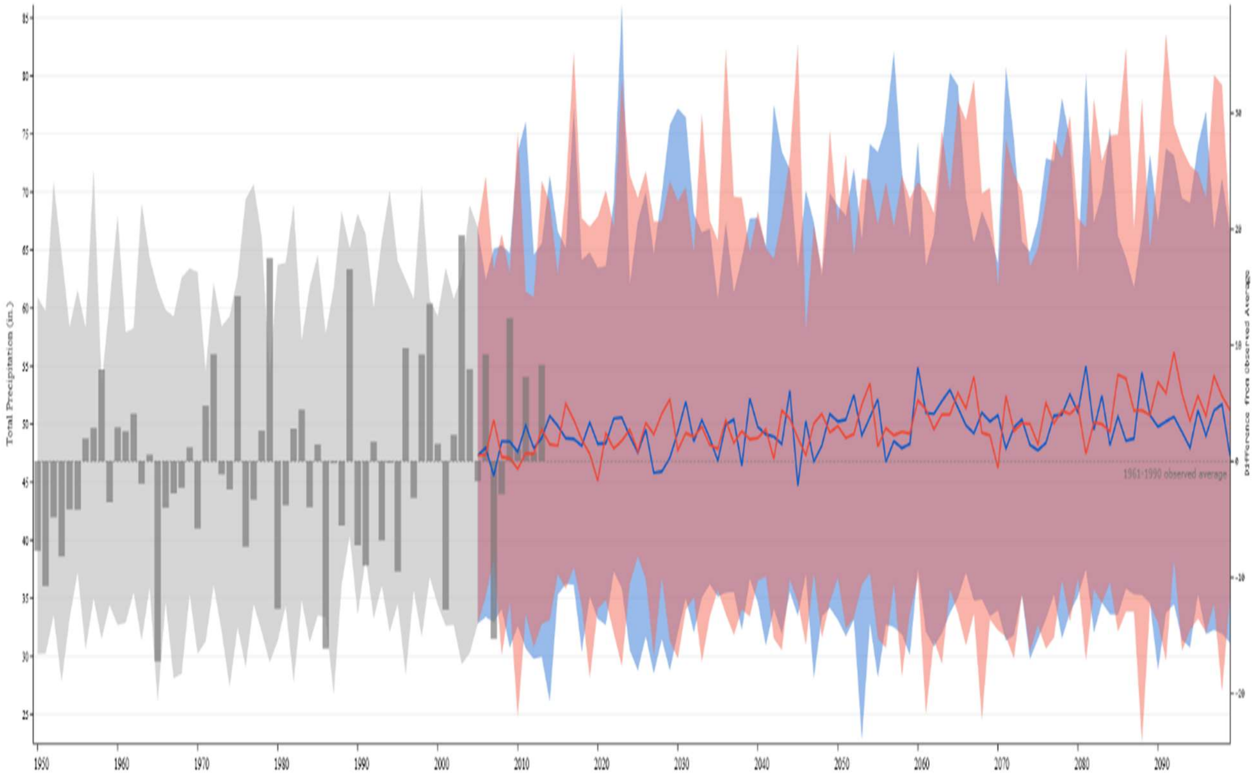
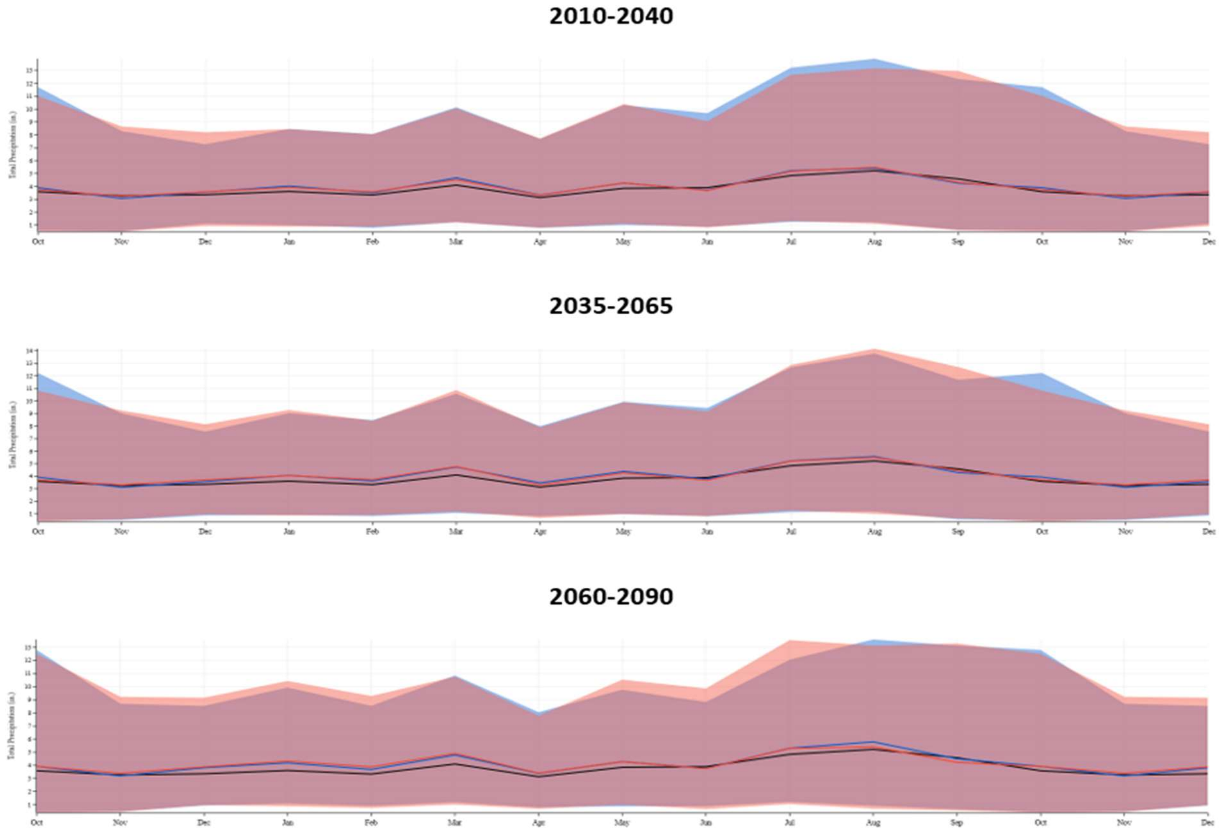


Figure 4: Projection for Annual Precipitation in Newport News, VA

While annual precipitation is projected to increase slightly, monthly projections for increased precipitation provided more information about potential risks. In Figure 5, the monthly projections show increases in precipitation in summer months (June, July, and August). Historically, TJNAF has experienced flash flooding events due to heavy rainfall in these months resulting in damages and lost work hours. Despite current adaptive measures, TJNAF still experiences flash flooding events particularly during these months. TJNAF examined projected precipitation increases for August since the most recent extreme precipitation event occurred in August 2012. Within the next two decades, precipitation in August is projected to increase from the 1950-2013 observed average of 5.22 inches to 5.41-5.48 inches depending on RCP 4.5 or 8.5, respectively. By August 2090, precipitation is expected to increase from 5.22 inches to 5.41-5.79 inches depending on RCP 8.5 or 4.5, respectively. Projected precipitation increases would continue to impact TJNAF without implementing additional resilience solutions.


2010-2040

2035-2065

2060-2090

Figure 5: Projections for Monthly Total Precipitation for Newport News, VA

Vulnerability/Site Adaptive Capacity

TJNAF identified highly vulnerable assets utilizing the Risk Assessment Tool. By examining historical and current events and relying on TJNAF asset and infrastructure systems experts, the VARP planning team was able to catalog existing adaptive measures and rate each measures ability to reduce the impact of climate hazards. Using this approach, the VARP planning team applied a vulnerability level to each asset and infrastructure system. TJNAF determined there are 4 asset and infrastructure systems that are the most vulnerable with adaptive measures likely to fail in the event of a climate hazard. The asset and infrastructure systems are described below:

- **Mission-critical equipment:**
    - The Continuous Electron Beam Accelerator Facility (CEBAF) accelerator and the peripheral process support equipment needed to operate the accelerator are all considered mission-critical. Adaptive measures currently in place include redundant

electrical substations with a tie feeder to support critical loads such as cryogenic operations in order to mitigate a helium loss event similar to what occurred in 2003 during Hurricane Isabel, a looped configuration on the accelerator site electrical distribution system, and limited emergency generation to support life safety needs. No adaptive measures exist, however, to maintain cryogenic operations in the event of an electrical disruption affecting both electrical substations which is a key vulnerability. External dependencies on helium and liquid nitrogen deliveries persist, but TJNAF currently has adaptive measures in place on the liquid nitrogen deliveries with the ability to obtain this resource from three different locations as well as an emergency supply available from a nearby NASA Langley facility. There is currently no alternative source identified for helium and there are added concerns due to the recent decision by General Services Administration (GSA) to auction the Federal Helium Reserve (FHR).

  - The data center located in the CEBAF Center building is also considered mission-critical and adaptive measures currently in place include a redundant electrical feed, emergency generation for critical loads, provisions for a rental chiller to be quickly installed during disruptions of chilled water from the central utility plant, and a backup HVAC system capable of supporting core computing needs. No adaptive measures exist, however, to fully support both core computing and high performance computing in the event of an electrical disruption affecting both electrical substations which is a key vulnerability. Also, the time and logistics involved in renting a temporary chiller as opposed to having a redundant source of chilled water readily available is considered an additional vulnerability.

- **Energy generation and distribution systems:** Electrical service from Dominion Energy comes to the site from two different offsite electrical yards. The Warwick Blvd location feeds the 33MVA and 40MVA substations located on the accelerator site and the Rock Landing location feeds the 22MVA substation located on the campus portion of the site. While this redundancy in itself could be considered an adaptive measure, an onsite tie feeder connecting the 22MVA substation and the 40MVA substation as well as a looped configuration on the accelerator site electrical distribution system are examples of additional adaptive measures which have already been implemented. Spares are also maintained to support smaller unit substation distribution transformers located across the complex. A key vulnerability still exists, however, in the lack of capacity of the 22MVA substation and 17MVA tie feeder to fully support accelerator operations.
- **Site buildings:** Buildings used for functions such as office, laboratory/research, fabrication, warehouse, etc. typically have few, if any, adaptive measures in place. A few key facilities such as the Test Lab and Technology and Engineering Development Facility have emergency generation capabilities which are only sized to support the most critical loads.
- **Water and wastewater systems:** Potable water, sanitary sewer, and storm water management all have few, if any, adaptive measures in place. Critical loads related to process cooling benefit from the adaptive measures previously described above for energy generation and distribution systems as well as mission-critical equipment. A key vulnerability is the current lack of any redundant or alternate source of water to support process cooling needs.

Characterize Vulnerabilities with a Risk Matrix (VARP Step 6)

The following risk matrix in Table 3 helps to visualize the impacts of climate hazards on critical assets and infrastructure:

Table 3. TJNAF VARP Risk Matrix using the Risk Assessment Tool. This matrix uses output from Tab 6b which displays risk results by asset or infrastructure type.

		Hazards				
Asset and Infrastructure System Type	**Number of Assets**	**Precipitation**	**Hurricane**	**Strong Wind**	**Lightning**	**Heat Wave**
Specialized or mission-critical equipment (lasers, high performance computers, particle accelerators, etc.)	**6**	7.8	7.7	5.9	8.2	8.4
Water and Wastewater Systems	**4**	None	6.5	5.3	5.3	8.1
Site Buildings (may be broken down by type, those with critical functions, office buildings, etc.)	**6**	4.0	6.2	5.9	7.8	7.8
IT and Telecommunication Systems	**1**	None	3.5	4.0	4.0	4.0
Energy Generation and Distribution Systems	**1**	None	7.3	7.5	7.8	6.5
Transportation and Fleet Infrastructure	**1**	5.5	5.0	None	None	5.5
Site Workforce (outdoor workers, researchers, office staff, etc.)	**1**	4.0	3.5	4.0	4.0	4.0
Supply Chains for Critical Material	**1**	6.5	6.0	None	None	4.0

TJNAF utilized the Risk Assessment Tool to identify asset and infrastructure types with the highest risk. After completing previous steps to determine asset and infrastructure criticality, site vulnerability, and climate hazard impact, TJNAF confirmed that for each hazard the asset and infrastructure systems most commonly affected by projected climate change are mission-critical equipment, site buildings, energy generation and distribution systems, and water and wastewater systems. TJNAF's Continuous Electron Beam Accelerator, associated service buildings, cryogenic plants, and laboratory buildings routinely reached a high- or medium-risk level for all climate hazards. These assets are highly critical to TJNAF's ability to meet DOE objectives, and due to the limitations of current adaptive measures, they are the most likely to be impacted by projected climate changes.

TJNAF's energy generation and distribution system was identified as the second most at risk asset and infrastructure system with a high-level risk in each climate hazard category related to storm frequency and strength, such as hurricane, strong wind, and lightning. Although there are current adaptive measures in place to provide emergency energy generation and redundancy, power outages have historically and currently resulted in an impact to operations and work hours. With climate change models projecting an increase in storm strength and frequency at TJNAF, the energy generation and distribution system is projected to experience more outage events without additional adaptive measures. Power outages due to storm related climate hazards place a high secondary risk on site buildings. While critical electrical load redundancy and emergency power generation exists for mission-critical equipment, there is no adaptive measure providing additional energy generation and distribution for all site buildings.

Mission-critical equipment, site buildings, and water and wastewater all scored high risk against the climate hazard heat wave. TJNAF's accelerator relies heavily on potable water for cooling, more specifically low conductivity water (LCW), which is critical for accelerator operations. Evaporative cooling tower are designed to operate with an ambient temperature of 78°F. Any projected increases in temperature for an extended period of time poses a risk to the equipment and accelerator operations due to impacts to specific LCW temperature. Additionally, there is a secondary high-level risk to TJNAF's potable water system. TJNAF relies on a local municipally owned potable water provider. If heat waves increase in strength and frequency and result in drought conditions, the utility provider could institute water curtailment requirements that pose a risk to TJNAF operations.

TJNAF has previously implemented a water reuse system to supplement cooling needs. However, there are currently no other alternative water sources able to support cooling requirements at TJNAF. Projected heat waves and increasing temperatures also pose a high risk to site buildings and their heating, ventilation, and air conditioning (HVAC) systems. Due to heat generated from mission-critical equipment, several service buildings already have difficulty managing heat loads and require supplemental cooling in the summer months. If temperatures increase for longer periods of time, these systems are likely to fail due to heat stress. Additionally, if temperatures increase as projected, site buildings will need to be resized for large HVAC systems that can withstand additional heat loads to maintain equipment and occupant cooling requirements.

Identify and Develop Resilience Solutions

TJNAF identified resilience planning gaps utilizing the Risk Assessment Tool. By focusing on climate hazards that affect the Laboratory rather than the locality as a whole, TJNAF identified areas of high- and medium-risk and commonalities across asset and infrastructure system types. TJNAF determined there are 5 resilience planning gaps that currently exist and should be addressed with resilience solutions. The resilience planning gaps are described below:

- **Resilience Planning Gap 1: Lack of Adaptative Capacity to Precipitation**: Permanent site infrastructure lacks protection against flash flooding from precipitation events. This has resulted in a high risk to mission-critical equipment and a medium risk to site buildings and should be addressed by resilience solutions to reduce lost work hours and cost of repairing infrastructure after flooding events.
- **Resilience Planning Gap 2: Lack of Adaptive Capacity to Hurricanes:** Permanent site infrastructure has limited protection against hurricanes. This has resulted in a high risk to multiple assets and infrastructure types and should be addressed by resilience solutions to reduce lost work hours and impact to mission-critical equipment.
- **Resilience Planning Gap 3: Lack of Adaptive Capacity to Lightning:** Permanent site infrastructure has limited protection against lightning events. This has resulted in a high risk to mission-critical equipment, site buildings, and energy generation and distribution systems and should be addressed by resilience solutions to reduce impact to operations.
- **Resilience Planning Gap 4: Lack of Adaptive Capacity to Heat Wave:** Permanent site infrastructure has limited protection against heat wave events. This has resulted in a high risk to mission-critical equipment, site buildings, and water and wastewater systems and should be addressed by resilience solutions to reduce impact to operations and lost work hours.
- **Resilience Planning Gap 5: Lack of Adaptive Capacity to Strong Wind:** Permanent site infrastructure has limited protection against strong wind events. While site buildings are engineered to withstand strong winds, there is a high risk to energy generation and distribution systems due to a lack of adaptive measures and high infrastructure criticality. This should be addressed by resilience solutions to reduce impact to operations and mission-critical equipment and to reduce lost work hours.

The VARP planning team was able to optimize time and research by relying on existing data. Using the interview method in Step 1, TJNAF's site planning and sustainability program staff avoided making assumptions about what resilience solutions would be most effective in limiting climate hazard impact to mission-critical equipment, site buildings, and energy generation and distribution systems. By relying on expert knowledge, the VARP planning team was able to collect existing feasibility, cost, and timeline data on several resilience solutions that were already identified, confirmed, planned, or funded. Several resilience solutions were already a part of the 10-Year Campus Master Plan to improve infrastructure and reduce impact of current climate hazards. These projects were previously evaluated for additional site, DOE, and community benefits and impacts and were already identified on TJNAF's Annual Lab Plan infrastructure investment table. The VARP planning team focused on solutions that could potentially accomplish both DOE sustainability and resiliency goals to optimize funds to the greatest extent practicable and to benefit the site, DOE, and the local community.

Summary of Identified Resilience Solutions (VARP Step 7)

The following table provides a summary of identified resilience solutions, which describes of the specific assets and infrastructure systems affected by each solution, and if/how the solution addresses the specific hazard:

Table 4: TJNAF Resilience Solutions Table

Solution	**Description**	**Critical Asset Type(s)**	**Hazard(s)**	**Expected Effectiveness**	**Feasibility** *(Easy, Moderate, Difficult)*	**Cost & Funding Type**	**Community Impact**	**Environ-mental Impact**	**Recommended Approach**
Increase stormwater pond capacity	Increase conveyance capacity and construct additional retention and/or detention basins	Mission-Critical Equipment Site Buildings	Precipitation Hurricanes	Highly Effective – Will zero out impact of increased precipitation to on-site assets; Moving from high risk to low risk	Moderate	$2.3M GPP	Beneficial - Local stormwater management system is undersized and routinely overflows. Increasing capacity allows for slow release to system.	Beneficial impact on site ecology	Proceed to Step 8
Replace flood monitoring system in south ditch	Replace water level sensor for flood monitoring system	Mission-Critical Equipment Site Buildings	Precipitation Hurricanes	Effective – Alerts staff to rising water levels to allow implementation of adaptive measures and reduce impact of hazards on assets	Easy	$20K Indirect	None anticipated as entirely on-site solution	Repair of existing infrastructure resulting in minimal environmental impact	Proceed to Step 8

Solution	Description	Critical Asset Type(s)	Hazard(s)	Expected Effectiveness	Feasibility *(Easy, Moderate, Difficult)*	Cost & Funding Type	Community Impact	Environ-mental Impact	Recommended Approach
Upgrade flood doors for Experimental Halls	Modify or replace flood doors installed on Experimental Hall truck ramps to improve performance	Mission-Critical Equipment Site Buildings	Precipitation Hurricanes	Highly Effective – Current adaptive measures do not function as designed; Reduces impact and vulnerability, thus moving from high risk to medium risk	Easy	$300K Indirect	None anticipated as entirely on-site solution	Repair of existing infrastructure resulting in minimal environmental impact	Proceed to Step 8
Repair groundwater removal system	Remove buildup of material in drainage system pathways from Experimental Hall floor to the Counting House basement groundwater removal pumps	Mission-Critical Equipment Site Buildings	Precipitation Hurricanes	Highly Effective – Current adaptive measures are not operating as designed; Reduces impact and vulnerability, thus moving from high risk to low risk	Moderate	$150K	None anticipated as entirely on-site solution	Repair of existing infrastructure resulting in minimal environmental impact	Proceed to Step 8
Upgrade existing central utility plant	Replace aged chillers, increase system cooling capacity, and provide N+1 redundancy	Mission-Critical Equipment Site Buildings	Heat Wave	Highly Effective – Reduces impact and vulnerability by increasing system cooling capacity and providing redundancy, thus moving from high risk to medium risk	Moderate	$4.2M GPP	None anticipated as entirely on-site solution	Normal environmental impact from new site infrastructure projects	Proceed to Step 8

Solution	Description	Critical Asset Type(s)	Hazard(s)	Expected Effectiveness	Feasibility *(Easy, Moderate, Difficult)*	Cost & Funding Type	Community Impact	Environ-mental Impact	Recommended Approach
Install additional central utility plant	Install additional central utility plant to reduce load on existing plant and provide redundancy	Mission-Critical Equipment Site Buildings	Heat Wave	Effective – Reduces impact and vulnerability by providing redundancy and increasing system capacity, thus moving from medium risk to low risk	Moderate	$10M SLI-GPP	None anticipated as entirely on-site solution	Would require breaking new ground, resulting in higher environmental impact	Proceed to Step 8
Upgrade helium capture systems	Upgrade helium capture systems and install additional tanks to increase on-site storage capacity	Mission-Critical Equipment Supply Chains	Hurricane	Effective – Preserves critical Helium supply and reduces vulnerability on mission critical equipment and supply chain	Difficult	T.B.D, currently performing site evaluation to determine costs;	None anticipated as entirely on-site solution	Would require breaking new ground, resulting in higher environmental impact	Do not proceed due to cost ineffectiveness and space limitations
Install on-site Nitrogen generation plant	Construct and operate a new nitrogen generation plant	Mission-Critical Equipment Supply Chains	Hurricane	Effective – Minimizes impact to supply chain and deliveries of a mission critical cryogenic gas	Difficult	T.B.D, currently performing site evaluation to determine costs;	None anticipated as entirely on-site solution	Would require breaking new ground, resulting in higher environmental impact; Increase energy usage and greenhouse gas emissions on-site	Do not proceed due to cost ineffectiveness

Solution	Description	Critical Asset Type(s)	Hazard(s)	Expected Effectiveness	Feasibility *(Easy, Moderate, Difficult)*	Cost & Funding Type	Community Impact	Environ-mental Impact	Recommended Approach
Reuse stormwater in evaporative cooling towers	Pump and treat stormwater from off-site and on-site ponds for reuse in evaporative cooling towers	Mission-Critical Equipment Site Buildings	Heat Wave	Effective – Reduces vulnerability of dependence on singular potable water supplier; Moving from high risk to medium risk	Moderate	$4.2M SLI-GPP	Would require obtaining an easement to access off-site water source; Would require a minimal amount of land disturbance to install infrastructure	Beneficial – Reuses non-potable water for systems that would normally deplete potable water resources, especially in periods of drought caused by heat wave	Proceed to Step 8
Install additional substation	Construct new 33MVA substation and 17MVA tie feeder	Energy Generation and Distribution Systems	Hurricane Lightning Strong Wind	Effective – Reduces impact and vulnerability by providing redundancy and increasing system capacity, thus moving from high risk to medium risk	Moderate	$1.5M GPP	None anticipated as entirely on-site solution	Normal environmental impact from new site infrastructure projects; Uses existing cleared land to avoid additional land disturbance	Proceed to Step 8

Solution	Description	Critical Asset Type(s)	Hazard(s)	Expected Effectiveness	Feasibility *(Easy, Moderate, Difficult)*	Cost & Funding Type	Community Impact	Environ-mental Impact	Recommended Approach
Install on-site photovoltaic array with battery storage	Construct 3MW photovoltaic array with battery storage	Energy Generation and Distribution Systems	Hurricane Lightning Strong Wind	Highly Effective – Reduces dependence on electricity service provider, reduces impact of electricity outage on critical infrastructure, and allows site to participate in demand response activities	Moderate	T.B.D, currently performing site evaluation to determine costs;	None anticipated as entirely on-site solution	Beneficial – Decreases dependence on carbon pollution electricity types	Proceed to Step 8
Install emergency generators	Install (3) new 3MW generators for campus and (3) new 6MW generators for accelerator site	Energy Generation and Distribution Systems	Hurricane Lightning Strong Wind	Effective – Provides 3 days of additional power to maintain critical load, reducing impact on assets and risk to operations	Moderate	$13.5M SLI-GPP	None anticipated as entirely on-site solution	Normal environmental impact from new site infrastructure projects; potentially higher Greenhouse Gas emissions due to fuel type needed for power requirements	Proceed to Step 8

Solution	**Description**	**Critical Asset Type(s)**	**Hazard(s)**	**Expected Effectiveness**	**Feasibility** *(Easy, Moderate, Difficult)*	**Cost & Funding Type**	**Community Impact**	**Environ-mental Impact**	**Recommended Approach**
Increase cooling capacity for linear accelerator service buildings	Provide (80) tons of additional cooling capacity in the north and south linear accelerator service buildings	Mission-Critical Equipment Site Buildings	Heat Wave	Highly Effective – Assures temperature set points can be met during all design conditions, including a 15% load increase in future years	Easy	$1.4M GPP	None anticipated as entirely on-site solution	Normal environmental impact from new site infrastructure projects	Proceed to Step 8
Repair Accelerator grounding loop	Verify condition of existing lightning protection systems and the site accelerator ground loop and make all needed repairs	Mission-Critical Equipment Site Buildings	Lightning	Highly Effective – Currently experiencing electronic failure due to failed adaptive measure, new adaptive measure will reduce impact and vulnerability	Easy	Phase 1: $110k Phase 2: T.B.D - cost based on Phase 1 findings; Indirect	None anticipated as entirely on-site solution	Normal environmental impact from new site infrastructure projects	Proceed to Step 8
Duplicate or move essential business services to the cloud	Duplicate or move essential business services to the cloud	IT and Telecommunications Systems	Hurricane Strong Wind Heat Wave Lightning	Highly Effective – Preserves business service availability in the event of power loss to the existing data center	Easy	$1-2M per year; Indirect	None anticipated as entirely cloud based solution	None anticipated as entirely cloud based solution	Proceed to Step 8

Summary of Resilience Solutions to be Tracked in SSP Dashboard (VARP Step 8)

Resilience solutions being tracked in the SSP dashboard were prioritized by considering the following factors:

- Number and magnitude of key vulnerabilities mitigated
- Mission and operational impacts avoided or mitigated
- Costs and benefits of resilience investments
- Co-benefits of greenhouse gas (GHG) emission reductions
- Enhanced sustainability
- Effects on energy efficiency

Cost-effective resilience solutions were assigned a priority rank of “High”, “Medium”, or “Low” based on the number of operational impacts avoided or the potential to significantly mitigate key vulnerabilities. A summary of all resilience solutions whose implementation status will be tracked n the SSP Dashboard is found in Table 5 below:

Table 5: TJNAF Resilience Portfolio Summary Table

Solution	**Priority Rank** (High, Medium, Low)	**Timing** (Include planned start and end dates as data allows; at min include FY information)	**Funding Mechanism** *(See above for categories)*	**Implementation Status** *(See above for categories)*
Increase stormwater pond capacity	High	Planned start in FY 31 and complete in FY 33	Direct – GPP	Confirmed
Upgrade flood doors for Experimental Halls	Medium	Planned start in FY 24 and complete in FY 26	Indirect – M&R	Identified
Replace flood monitoring system in south ditch	Low	Planned start in FY 23 and complete in FY 23	Indirect – M&R	Identified
Upgrade existing central utility plant	High	Planned start in FY 24 and complete in FY 26	Performance Contract – UESC	Planned
Install additional central utility plant	Medium	Planned start in FY 26 and complete in FY 28	Direct – SLI-GPP	Identified
Reuse stormwater in evaporative cooling towers	High	Planned start in FY 23 and complete in FY 25	Direct – SLI-GPP	Funded
Install additional substation	Medium	Planned start in FY 24 and complete in FY 26	Direct – GPP	Identified
Install on-site PV array with battery storage	High	Planned start in FY 24 and complete in FY 26	Performance Contract – UESC	Identified
Increase cooling capacity for linear accelerator service buildings	High	Planned start in FY 24 and complete in FY 26	Direct - GPP	Confirmed

Solution	**Priority Rank** (High, Medium, Low)	**Timing** (Include planned start and end dates as data allows; at min include FY information)	**Funding Mechanism** *(See above for categories)*	**Implementation Status** *(See above for categories)*
Repair accelerator grounding loop	Medium	Planned start in FY 22 and complete in FY 25	Indirect – M&R	Identified
Duplicate or move essential business services to the cloud	Medium	Planned start in FY 25 and complete in FY 28	Indirect – Overhead	Identified

Resilience Planning (VARP Step 9)

For a summary of how findings and actions described in this document will be adapted in response to new information, new funding, new technologies, or new policies, see Table 6 below:

Table 6: TJNAF Monitoring, Evaluation, and Review Plan Summary

Component	**Description**
Monitoring	Resilience solutions indicated will be incorporated into existing processes for Annual Work Plan (AWP) and Annual Lab Plan (ALP) development. Data for these plans is often reviewed quarterly with site organizations, and status is officially documented annually.
Evaluation	Key performance indicators or specific objectives will be identified for each resilience solution. Impact to energy costs, climate, and/or resilience will be included as measurable factors to determine effectiveness. Additionally, climate hazard events are cataloged using an internal system and effectiveness of resilience solutions will be evaluated during and immediately following each event to determine impact to assets and infrastructure systems.
Reassess	A complete VARP document will be reviewed and produced every four years with the status of resilience solutions being tracked and updated on a quarterly basis. If new climate data, technologies, or funding opportunities are revealed or if a climate hazard event occurs resulting in a negative impact to assets or infrastructure systems, the VARP planning team will reconvene and investigate next steps and identify additional adaptive measures to reduce impact and vulnerability during future events.