

COSMIC EXPLORER FEASIBILITY STUDY

MAY 2026



SMITHGROUP

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Preface

The Cosmic Explorer (CE) Feasibility Study summarizes the results of a programming, planning and pre-conceptual design effort for the conventional facilities of CE Observatory. The Feasibility Study scope includes the following:

- Preliminary Space Program requirements
- Pre-Conceptual Systems criteria outlines for civil, architectural, structural, mechanical, plumbing, fire protection, electrical and lighting.
- Sustainability requirements and potential strategies.
- Pre-Conceptual code analysis
- Risk considerations and Risk register
- Cost Model
- Pre-Conceptual Visualization Video

The CE Feasibility Study report was prepared by architectural, engineering, and cost consultants with inputs from the following campus stakeholders: California State University Fullerton, Massachusetts Institute of Technology, and California Institute of Technology. This document is intended for use by CE team to include in their reporting and proposals to the National Science Foundation (NSF).

Acknowledgments

This feasibility study and video fly-around were led by SmithGroup and requested by the Cosmic Explorer Project (cosmicexplorer.org) with support from National Science Foundation and Nicholas and Lee Begovich and Dan Black and Family.

Contributors to this study included Cosmic Explorer Project members from Bard College, California Institute of Technology, California State University, Fullerton, Johns Hopkins University, Massachusetts Institute of Technology, Pennsylvania State University, Syracuse University, the University of Arizona, the University of Florida, the University of Minnesota, the University of Oregon, the University of Washington Bothell, and Université de Montréal, supported by National Science Foundation awards 2422892, 2409632, 2309064, 2308985, 2308986, 2308987, 2308988, 2308989, 2308990, 2309265, 2309266, 2309267, 2309268, 2309006, and 2309007.

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1 EXECUTIVE SUMMARY



1 EXECUTIVE SUMMARY

1.1 Introduction

Project Overview

Cosmic Explorer (CE) is a next generation U.S. gravitational wave observatory designed to extend sensitivity by approximately $10\times$ beyond current facilities, enabling routine detection of compact object mergers across the observable universe and transformative tests of fundamental physics. CE is planned as two L-shaped interferometric observatories in the continental United States, separated by at least 500 miles, with arm lengths of 40 km and 20 km. This Feasibility Study focuses on the 40km observatory and evaluates the conventional facilities, site planning, and infrastructure required to support at minimum of fifty years of scientific operations.

Purpose and Use of the Study

This site agnostic, preconceptual Feasibility Study supports CE's progression toward future NSF funding and site selection. It establishes baseline programmatic requirements, engineering criteria, planning frameworks, cost models, sustainability goals, and risk considerations using an idealized hypothetical site. The results define the minimum technical and facility requirements needed to evaluate candidate sites and inform subsequent conceptual design and budget refinement.

1.2 Facility Concept and Program

The CE 40km observatory is organized around two tightly integrated systems:

1. Beamline and Station Infrastructure

- Two orthogonal 40km Beam Tube Enclosures (BTEs) housing ultra high vacuum laser beam tubes.
- Distributed Corner, Mid, End, and Vacuum Valve Stations supporting interferometer optics, vacuum systems, and periodic maintenance.
- Facilities are designed to provide exceptional vibration isolation, thermal stability, precision alignment, and longterm structural durability, with protection against environmental and human generated hazards.

2. Main Campus

- Includes an Operations Support Building (OSB) for control rooms, laboratories, and technical shops; an Office Building (OB) for administration; and a Community and Education Building (CEB) supporting outreach and education.
- Campus design emphasizes operational efficiency, staff wellbeing, flexibility, and adaptability to future scientific upgrades.

The total program for the 40km observatory is approximately 2.78 million assignable square feet (ASF), or 4.63 million gross square feet (GSF), dominated by the beamline enclosures (See Figure 1). Program sizing and adjacencies are grounded in LIGO and LIGO India precedent and refined through interdisciplinary workshops with CE leadership and partner institutions.

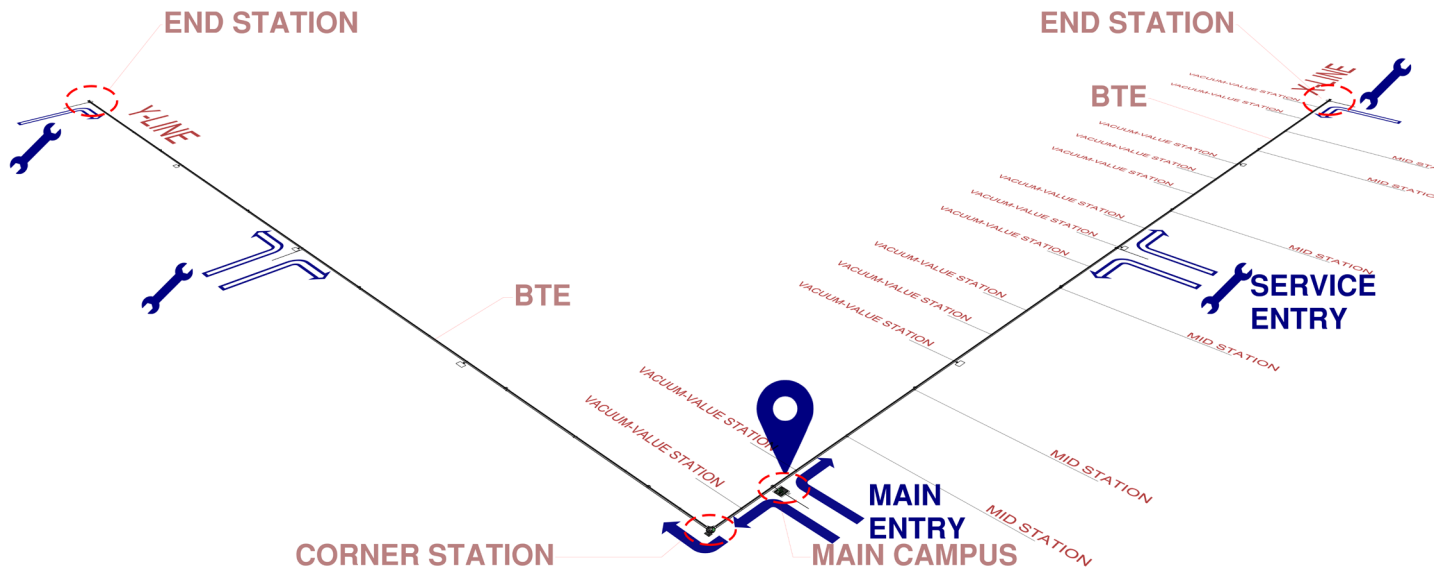


Figure 1 – Observatory Complex

1.3 Site Planning and Civil Feasibility

CE is conceived as permanent national scientific infrastructure, not as a single experiment. Site selection drivers identified in this study include:

- Availability of long, contiguous corridors to preserve straight beamlines over 40 km.
- Low ambient seismic and anthropogenic vibration environments.
- Favorable geologic and groundwater conditions to support longterm alignment stability.
- Compatibility with environmental protection, land use controls, and longterm buffers.

Representative civil engineering typologies—at grade construction, cuts and fills, bridges, and tunnels—were evaluated to support rough-order-of-magnitude cost estimation and risk screening. Results highlight the operational and lifecycle benefits of at grade and subsurface solutions for vibration control, durability, and reduced embodied carbon.

1.4 Engineering Systems and Reliability

Structural, mechanical, electrical, plumbing, and fire life safety systems are planned with redundancy, resilience, and low vibration as governing criteria. Designs assume decentralized, all electric systems compatible with remote operation, long service life, and future upgrades. Code and life safety strategies are feasibility level and will be finalized with Authorities Having Jurisdiction following site selection.

1.5 Sustainability and Stewardship

The project commits 1% of construction cost to sustainable design and targets ILFI Zero Carbon Certification, emphasizing all electric operation, onsite photovoltaics with battery storage, and reduction and offset of embodied carbon—particularly for concrete intensive beamline infrastructure. Additional frameworks (e.g., LEED and Envision) are identified to guide later design phases.

1.6 Conclusion and Next Steps

This Feasibility Study demonstrates that the CE 40km observatory is technically feasible, scalable, and aligned with NSF priorities for enduring national research infrastructure. The study provides a rigorous foundation for site selection, risk reduction, and advancement to conceptual design, positioning Cosmic Explorer for decades of discovery in gravitational-wave astronomy.

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2 PROJECT OVERVIEW



2 PROJECT OVERVIEW

2.1 Project Description, Goals and Mission Statement



Cosmic Explorer is a next-generation observatory—envisioned to begin operating in the U.S. in the mid-2030s—that will deepen and extend humanity’s gravitational-wave view of the cosmos while helping to train the next-generation of STEM leaders and to drive technical and educational innovations.

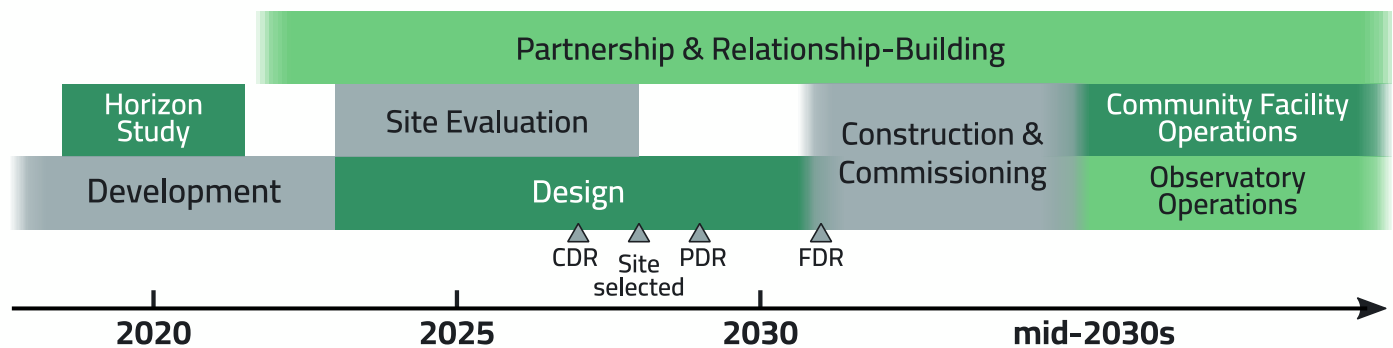
In 1916, Einstein predicted the existence of gravitational waves—stretching and squeezing of spacetime. These waves are produced in extreme astronomical events, such as the collision of black holes, and they travel through the universe at the speed of light, carrying information about the sources that created them. In 2016, the National Science Foundation (NSF)-funded Laser Interferometer Gravitational-Wave Observatory (LIGO) announced the observation of gravitational waves from merging black holes—leading to the 2017 Nobel Prize in Physics, awarded to LIGO’s founders. LIGO and its international partners have now observed hundreds of gravitational waves. Gravitational-wave astronomy has revolutionized humanity’s view of the universe, a revolution driven by observations that no other field can make.

Cosmic Explorer will build on the successful technology of LIGO—scaled up and enhanced—to enable discovery and drive technical innovation for decades to come. The NSF-funded [Cosmic Explorer Horizon Study](https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf)¹ presents a concept for Cosmic Explorer: one 25-mile-long observatory and one 12-mile-long observatory, both L-shaped (with footprints of 1800 and 900 acres) and at widely separated locations in the continental United States and a total estimated cost of \$1.6B (2021 USD). Major discoveries in astronomy and physics are driven by three related improvements: better sensitivity, higher precision, and opening new observational windows. Cosmic Explorer promises all three. Cosmic

1 <https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf>

Explorer will deliver an order-of-magnitude greater sensitivity than LIGO, extending our gravitational-wave vision to the edge of the observable universe, revealing the cosmic history of black holes and neutron stars, studying the universe’s densest material, and opening a wide discovery aperture to the novel and unknown².

The Cosmic Explorer Project is a team funded by the National Science Foundation to envision, design, and evaluate potential sites for Cosmic Explorer. Today (timeline), Cosmic Explorer is in its design and site evaluation stage. With sustained funding and no major delays, Cosmic Explorer will begin operating at NSF-selected sites in the mid-2030s. We envision that Cosmic Explorer will have a 50-year lifetime, after which it would follow an NSF-required divestment plan, likely returning the land to its natural state.



Economic and other impacts: Cosmic Explorer is an opportunity for tremendous investment in the United States’ scientific workforce and new educational and industrial partnerships needed to realize Cosmic Explorer’s vision. Cosmic Explorer will have positive economic and other impacts in the local regions near the observatory sites. A third-party assessment, “Economic and Qualitative Impacts of Cosmic Explorer”, was conducted in 2025 by Economic and Planning Services Inc. (available [here](#)³). This study found, for example, that the 40km Cosmic Explorer’s economic impact will include \$1.2B construction costs, half spent within the local economy, supporting contractors, labor, and materials suppliers; \$70 million per year ongoing local economic output associated with CE operations, 70% of which are associated with employee compensation including an operations staff of 200 people. The report also highlighted how Cosmic Explorer will advance science and higher education; grow community partnerships with local schools, organizations, and governments; expand community science education by developing hands-on learning centers to attract roughly 10,000 students annually; drive technological innovation that will impact other high-tech fields; and building a skilled workforce pipeline through jobs, internships, and collaboration.

The Cosmic Explorer Project is currently carrying out detector design and site identification and evaluation studies. This feasibility study contributes directly to both of those efforts. The National Science Foundation will select the sites for Cosmic Explorer. The Cosmic Explorer Project’s role is to vet locations as thoroughly as possible and to report what it learns to the NSF. We have conducted initial national studies revealing dozens of promising locations in the US for hosting a CE observatory. These are locations where CE can achieve its science goals within appropriate cost boundaries; attract, support and retain its workforce; and work synergistically with community goals and values.



This document was adapted from Cosmic Explorer Document CE-L2600002.

2 <https://arxiv.org/abs/2306.13745>.

3 https://dcc.cosmicexplorer.org/public/0163/T2500006/004/EPS_Cosmic_Explorer_Report.pdf

2.2 Feasibility Study Description

To support the Cosmic Explorer (CE) project's next phase towards future funding and support from the U.S. National Science Foundation (NSF), and to provide guidance to future site selection and facility planning, this Feasibility Study presents series of programming, campus planning, pre-conceptual engineering, and visualization efforts for the conventional facilities of the CE project. This study is based on an idealized, hypothetical site and is intended to identify the essential facility requirements. These requirements establish technical criteria that will inform and support site selection activities and development of conceptual design in the subsequent phase.

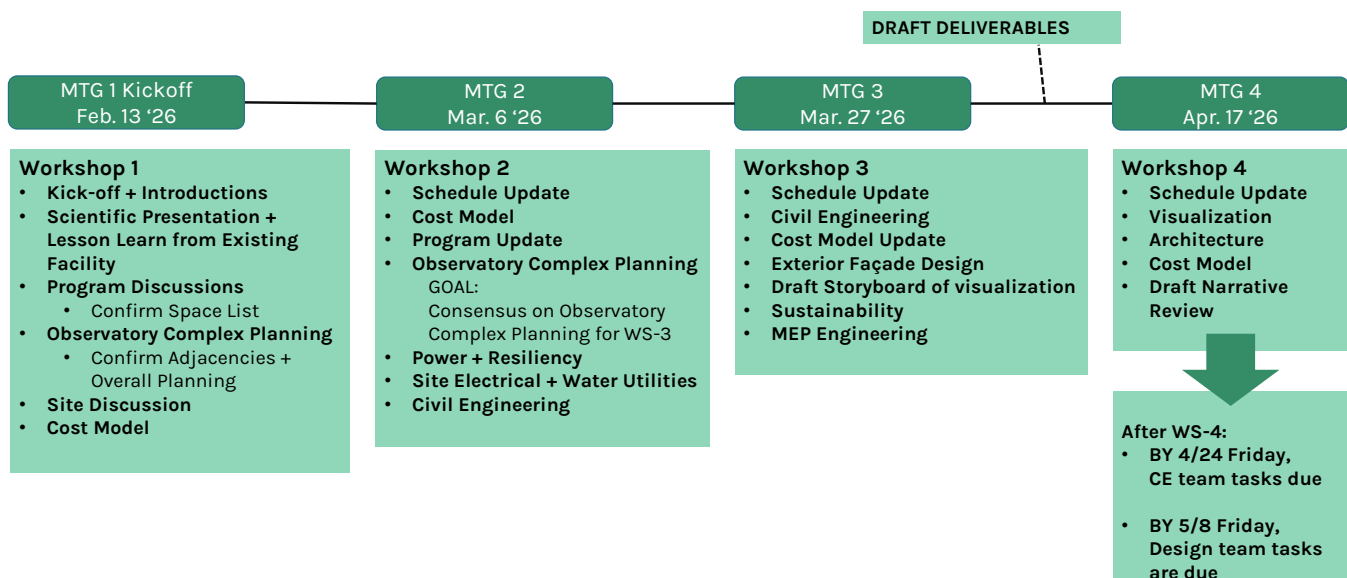
Feasibility Study Scope

The Feasibility Study scope includes the following:

- Preliminary Space Program requirements
- Pre-conceptual Design Strategies
- Pre-conceptual Systems Criteria Outline for Civil, Site Infrastructure, Architectural, Structural, Mechanical, Plumbing, Fire protection, Electrical and Lighting
- Sustainability requirements and potential strategies
- Pre-conceptual Code Analysis and considerations
- Cost model and limitations
- Risk considerations in individual Systems Criteria and Site-driven Risk Register
- Visualization of the CE project in site-agnostic environment in a form of video and renderings

Feasibility Study Process

The CE project requirements were developed through a series of collaborative workshops involving CE leadership, California State University, Fullerton (CSUF), the Massachusetts Institute of Technology (MIT), and the California Institute of Technology (Caltech). These workshops addressed key elements of the project and supported alignment among all stakeholders. The feasibility study was conducted over a 15-week timeframe and included four virtual workshops that were facilitated to define and document critical criteria and considerations to inform future phases of the CE project. Workshop documentation is provided in the Appendix.



3 PROGRAM NARRATIVE



3 PROGRAM NARRATIVE

3.1 Introduction

BEAMLINE BUILDINGS AND MAIN CAMPUS PLANNING

The mission of the Cosmic Explorer Observatory is to detect gravitational waves from across the universe. The architectural design must support this mission while accommodating research and operational needs. The observatory comprises two primary components: the Beamline Buildings and the Main Campus.

The Beamline Buildings consist of facility clusters that house the primary laser beams along each Beam Tube Enclosure (BTE). These enclosures form two nominally 25-mile-long arms extending at 90 degrees from the Corner Station (CS). The Beamline Buildings must be robust and resilient, protecting the beamline vacuum system from environmental factors and external threats such as vandalism and stray gunfire. Programmatically, these facilities are predominantly high-bay experimental halls with overhead cranes, providing long, column-free spans. Supporting spaces include pump rooms, electronics shops, cleanrooms, and mechanical rooms. Additional program details are provided in the Appendix.

The Main Campus includes the Community Education Building (CEB), Office Building (OB), and Office Support Building (OSB). The primary objective of the Main Campus is to provide a welcoming public interface and a restorative environment for Cosmic Explorer staff. These facilities should embody a transparent, engaging, and state-of-the-art character, fostering collaboration across research disciplines and supporting unconventional, transdisciplinary work. To achieve this, a modular planning approach is proposed, balancing adaptability with scalability to accommodate future growth. The use of repetitive planning modules also supports efficient engineering system design, simplifying long-term maintenance and future renovations.

BUILDING MODULE SIZE

Beamline Buildings are sized using the LIGO–India facilities as the initial basis of design, further refined through a series of workshops with the Cosmic Explorer team conducted during this Feasibility Study. Where programmatically feasible outside the primary Experimental Halls, a planning module width of 11'-0" to 12'-6" is recommended, depending on office and laboratory space typology. These dimensions are consistent with current research laboratory standards and provide adequate aisle clearances, safe working conditions, efficient circulation for carts and equipment movement, and compliance with applicable accessibility and life-safety requirements, including ADA provisions.

An Overall Space Summary and a Detailed Space List have been prepared and are presented on the following pages. The Space Program is organized around the primary functional components identified above, including associated parking capacities. Given the project's complexity, non-assignable mechanical, electrical, and plumbing (MEP) spaces are also incorporated into the Space Program and will be further refined and validated in subsequent project phases.

3.2 Definitions

The space list uses the following terms or categories to describe the space requirements:

- Net or Assignable Area (ASF). The area of each room, workstation and/or space, as measured from interior wall to interior wall. No circulation space to or from the room such as corridors and stairs is included (but circulation within the room is included).

- **Building Gross Area (GSF).** The total area of the building, including all primary circulation routes, shared vertical circulation, exterior walls and all mechanical and electrical support spaces and chases. The building efficiency used for the CE ranges from 75% to 60% depending on the space type. The assumed building efficiency is listed with the detailed portion of the space program.

3.3 Space Program Summary

The total building gross area for the CE Observatory (40-km) is anticipated to be 2,780,673 assignable square feet as shown below:

Table 3.3.1 - Space Program Summary

(N) COSMIC EXPLORER RESEARCH FACILITY		Program Summary from Sec. 4~6 (ASF)
BEAMLINE BUILDINGS:		
1.0	CORNER STATION COMPLEX (CS)	121,725
2.0	END STATION COMPLEX (ES)	52,400
3.0	MID STATION COMPLEX (MS)	80,400
4.0	BEAM TUBE ENCLOSURES (BTE)	2,428,000
5.0	VACUUM VALVE STATION (VS)	39,000
MAIN CAMPUS BUILDINGS:		
6.0	OPERATION SUPPORT BLDG (OSB)	19,050
7.0	COMMUNITY/EDU BLDG (CEB)	15,568
8.0	OFFICE BLDG (OB)	24,530
Total ASF		2,780,673
Building Efficiency Gross Sq. Foot ***		1,853,782
Total GSF		4,634,454

ASF = Assignable Square Feet

*** Building Efficiency = Mechanical, toilets, circulation, walls, structure, etc.

60%

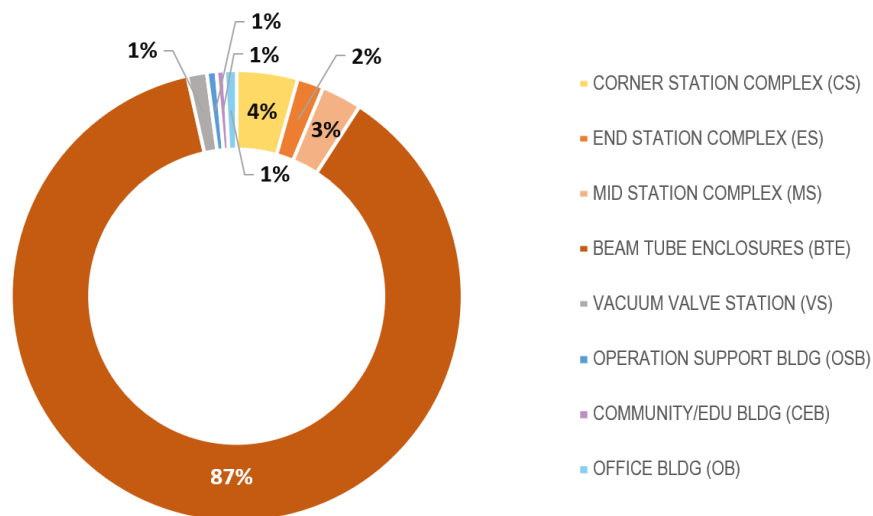
GSF = Gross Square Feet

The following Figure 3.3.1 represents a graphic depiction of the CE Observatory Space Program components and its proportions as compared to one another. Each program is color-coded by the programmatic components listed in the Space Program Table 3.3.1. Detailed breakdown of each components are listed on the subsequent section 3.4.

Figure 3.3.1 - Graphic Program – Assignable Areas

COSMIC EXPLORER RESEARCH FACILITY

ASSIGNABLE SPACE SUMMARY BY BLDG TYPE



3.4 Space Program

LABORATORY DESIGN

The research spaces for Cosmic Explorer are being designed to have systems and equipment that make up some unique lab types particularly in the Specialty Suites. Listed below are Beamline Buildings – Corner Station Complex (CS); Staging, Prep, & Storage (SPS); Machine, Electrical & Vacuum Shop (MEV); Mid Station Complex (MS); End Station Complex (ES); Beam Tube Enclosures (BTE). In addition, listed below are Main Campus Buildings – Operation Support Building (OSB); Community & Education Building (CEB); and Office Building (OB).

*See Space Program for proposed ASF of space types listed below.

**Reference engineering section for lab infrastructure & utility requirements.

BEAMLINE BUILDINGS:

- Corner Station Complex (CS):
 - Corner Station Experimental Hall
 - Staging, Prep, & Storage (SPS)
 - Machine, Electrical & Vacuum Shop (MEV)
- End Station Complex (ES):
 - Vacuum Equipment Area (VEA) & Equipment Room
 - End Station Support Building (ESB)
- Mid Station Complex (MS):
 - Vacuum Equipment Area (VEA) & Equipment Room
- Beam Tube Enclosures (BTE)
- Vacuum Valve Stations (VS)

MAIN CAMPUS BUILDINGS:

- Operation Support Building (OSB)
- Community & Education Building (CEB)
- Office Building (OB)

CORNER STATION COMPLEX (CS):

Located at the intersections of 25mi beamlines, Corner Station Complex is the heart of Cosmic Explorer Observatory facilities. Combining research visions and reference/experience from existing facilities including LIGO Hartford and LIGO India facilities, Corner Station Complex (CS) will consist of the following buildings:

- Corner Station Experimental Hall
- Staging, Prep & Storage (SPS)
- Machine, Electrical & Vacuum Shop (MEV)
- Substation & Chiller Yard (SCY)
- Pump Room & Water Tank Building (PRB)

Corner Station Experimental Hall – Corner Station (CS) will have layout heavily influenced by LIGO India combined with future research vision unique to the Cosmic Explorer Observatory. Given the vibration sensitivities of experiment/equipment including from ground tilt caused by dynamic wind force, wind-mitigating design including but not limited to aerodynamic or buried design that minimizes building height should be explored. The Experimental Hall will have program layout based on Figure 3.4.1 below, to accommodate various vacuum equipment and research spaces including Class 10,000 ISO7 Clean Room:

- **Laser Vacuum Experiment Area (LVEA):** LVEA will house precision interferometer and other detector components. Experimental Area is to have dimensions approximately 390ft x 390ft per below reference sketch, with 10t rated crane with hook height of 14m AFF. Vacuum equipment will be housed mainly within the triangular footprint, with additional axillary spaces along Beamline axis. Furthermore, LVEA will have basement floor that aligns to the centerline of the beamline with 15ft ceiling height and 50ft width below.
- **Class 10,000 ISO 7 Clean Room:** used for assembly of detectors and components requiring clean room environments provided via air exchanges through HEPA filters. Experimental components flow through Staging, Prep, Storage (SPS), therefore would require close proximity to each other.

See below Figure 3.4.1 for conceptual planning sketch from CE FACILITY ARCHITECTURAL REQUIREMENTS CE-T2500017.

Figure 3.4.1 – CS Space Layout Diagram from CE-T2500017 Document:

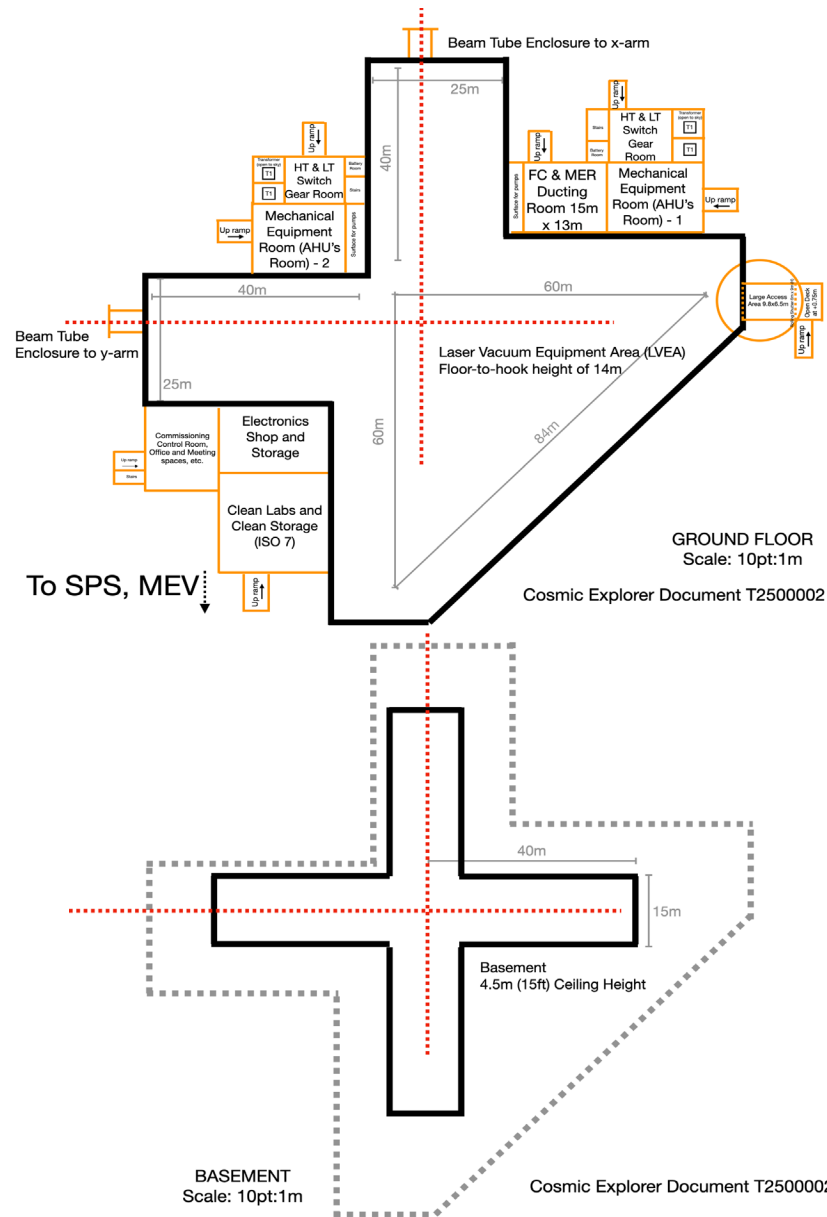


Figure 15: Sketch of the Central Station VEA Building. *Top:* Ground floor plans, based on the LIGO India Corner Station (figure 14) and the CE technical layout. *Bottom:* Basement plans. <https://dcc.cosmicexplorer.org/T2500002>

Staging, Prep, & Storage (SPS) – Located approximately 100ft away from Experimental Hall, SPS will house (2) main functions:

- **Staging & Prep:** Spaces dedicated to staging, cleaning, and bake operation, as well as optics lab and shipping/receiving area. SPS will house 10t rated crane with hook height of 7.5m AFF. In order to facilitate seamless transport of various experimental components, SPS to have finished floor level that is aligned with LVEA of CS.
- **Storage:** Clean storage space for various components and tools critical to operational support.

Machine, Electrical & Vacuum Shop (MEV) – Located adjacent to SPS (and approximately 100ft from CS as result), Machine, Electrical, and Vacuum Shop Building (MEV) will house an electronic shop, machine shop, and

vacuum hardware shop for testing and maintenance of detector components. MEV will also house/store instruments, electronics, tools, and other equipment/hardware that does not require cleanroom environment. As with SPS, final finished floor level of MEV to align with LVEA of CS.

Figure 3.4.2 – Referenced LIGO India SPS & MEV Plan:

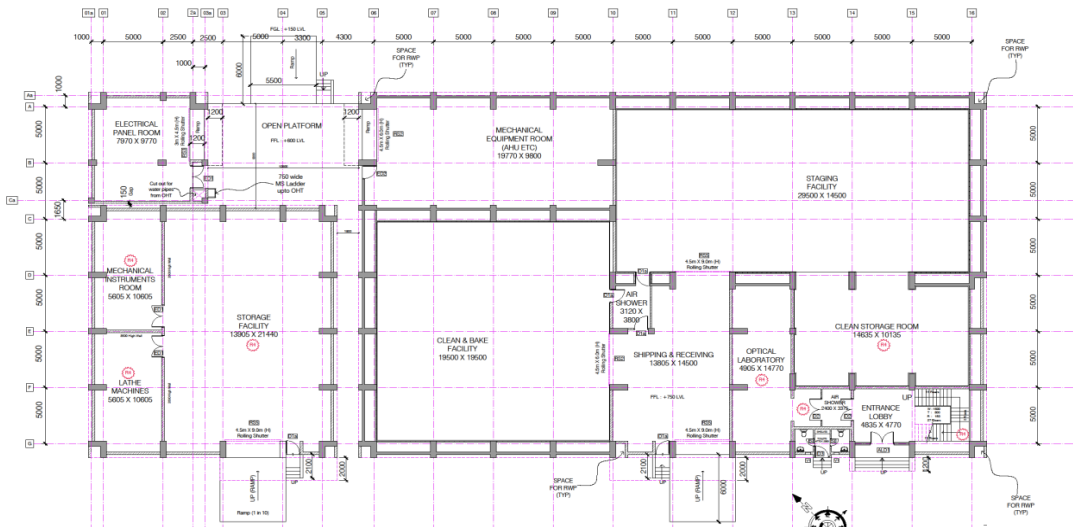


Figure 16: SCBS plan from LIGO India design, similar to SPS for CE (for reference only). Dimensions are in mm.

END STATION COMPLEX (ES):

Located at ends of each Beamline axis, End Station Complex (ES) are modeled after LIGO India facility, composed of the following buildings:

- Vacuum Experiment Area (VEA)
- End Station Support Building (ESB)
- Substation & Chiller Yard (SCY)
- Pump Room & Water Tank Building (PRB)

Vacuum Experiment Area (VEA) – similar to CS, ES will house equipment with high vibration sensitivities including to vibration from ground tilt caused by dynamic wind force. Therefore, wind-mitigating design including but not limited to aerodynamic or buried design that minimizes building height should be explored. In addition to vibration mitigation, VEA should minimize noise and electromagnetic interference. Similar to CS, VEA will also include basement level that runs the entire length of VEA aligned to the centerline of beamline, with ceiling height of 15ft. VEA will also house a crane with 10t rating and crane hook of 14m AFF.

End Station Support Building (ESB) – for smooth onsite operations and to support personnel, End Station Complex will also include an End Station Support Building (ESB). ESB will house small control room, office/workstations, electronic shops, optics labs, as well infrastructure/spaces to facilitate locate monitoring, data analysis and maintenance/operational activities coordination.

Figure 3.4.3 – Referenced LIGO India End Station plan:

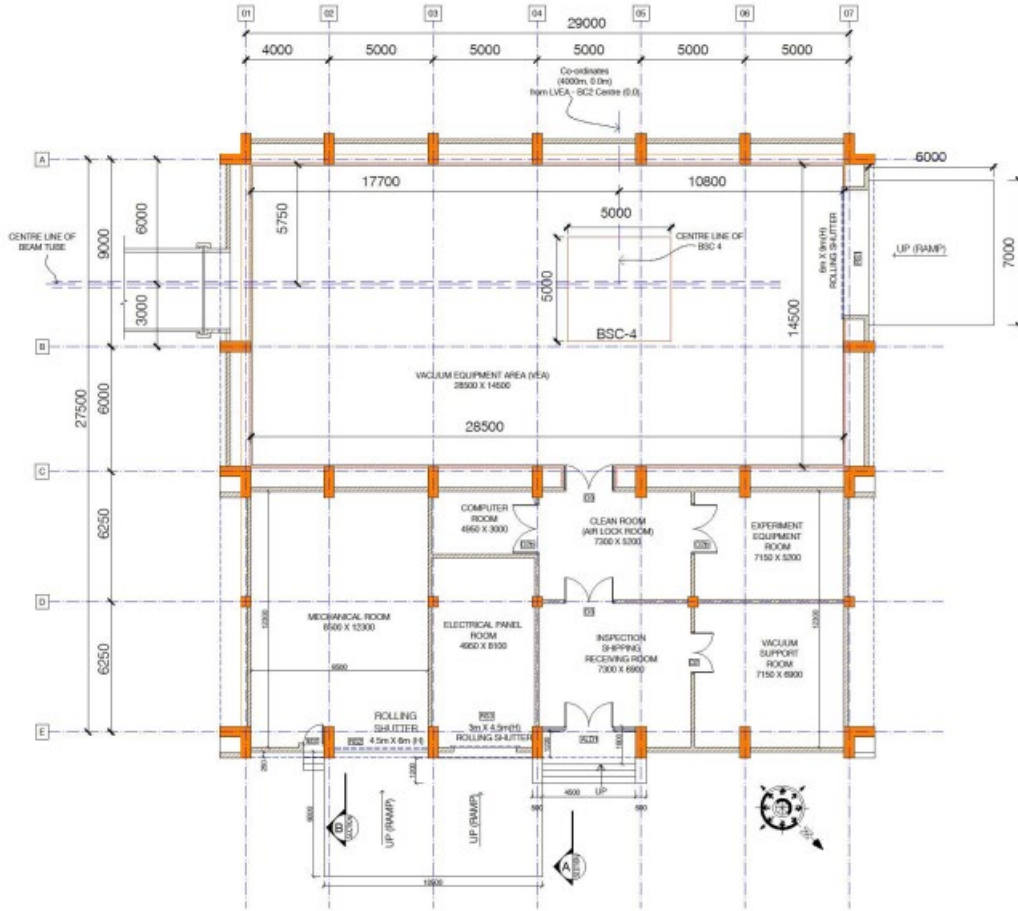


Figure 9: Layout plan of LIGO India End Station VEA building (for reference only). Dimensions are in mm. Note that this is a mirror image of the building in figure 8, since one is for the X-arm and the other for the Y-arm (i.e., EX vs. EY complex). The Cosmic Explorer VEA experimental hall will be somewhat wider (30m rather than 15m).

MID STATION COMPLEX (MS):

Functionally similar to ES, Mid Station Complex (MS) are located at kilometer marks 5, 8, 16, 24, 32 and 35 and will contain:

- Vacuum Experiment Area (VEA)
- Substation & Chiller Yard (SCY)

Similar to CS and ES, MS will house equipment with high vibration sensitivities (such as large chambers that contain suspended baffles), including sensitivity to vibration from ground tilt caused by dynamic wind force – therefore wind-mitigating design including but not limited to aerodynamic or buried design that minimizes building height should be explored. While its functionality and design are similar to ES, MS will not contain personnel/support building, and MS VEA will contain 10t crane with hook height of 9m AFF.

BEAM TUBE ENCLOSURES (BTE):

Based on LIGO design, beamline vacuum system known as Beam Tube that allows propagation of laser beam along full length of each 40km arm will be housed within the Beam Tube Enclosure (BTE). Because the laser beam requires straight lines, significant terrain modification which also address curvature of Earth will be required. BTE will require sufficient clear space to accommodate 48 inch beam tube, its support structure, and personnel access for inspection; and constructed for protection of equipment that makes up beamline vacuum system itself from environmental and artificial threats. See below figure 3.4.4 for BTE cross-section from LIGO.

Figure 3.4.4 – Referenced LIGO BTE Cross Sections:

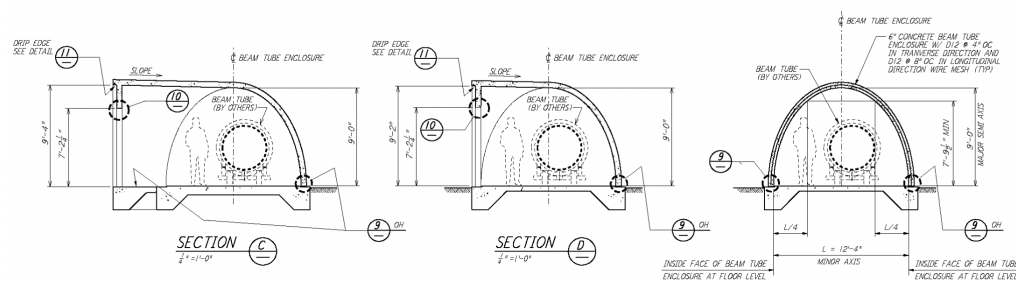
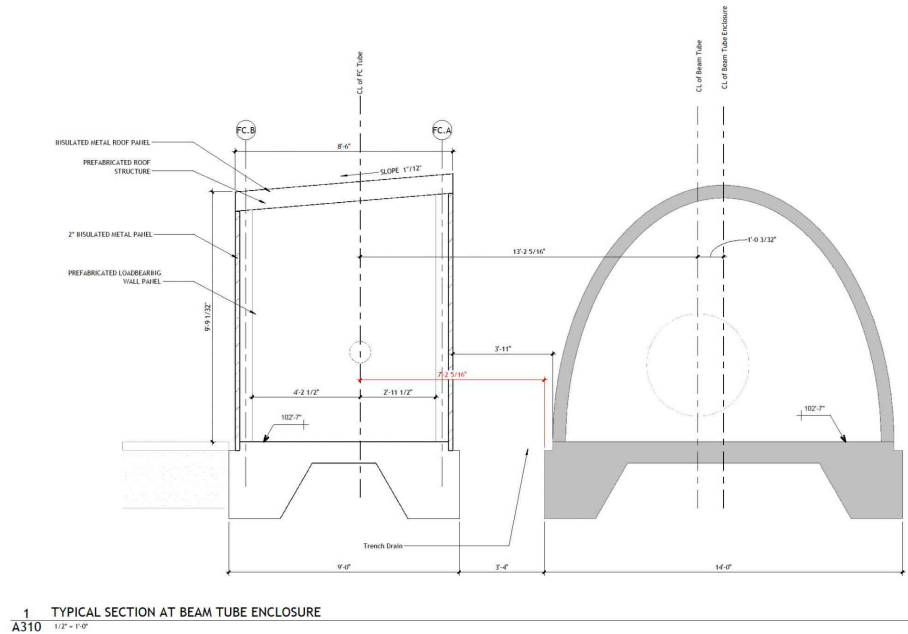


Figure 6: Top Right: LIGO Beam Tube Enclosure drawing. Top Left: Alternate LIGO enclosure. Bottom: Sections of the LIGO Beam Tube Enclosure showing beam tube and support structure (for reference only)

Beam Tube Enclosure (BTE) shall accommodate both beam tube installation and personnel access along the full 40km length of each arm. A minimum interior width of 10 ft is required, with at least 6 ft of this width providing a minimum interior height of 9 ft. Access to BTE shall be provided at beam tube pump ports at approximately 820ft intervals. Each access point shall include a doubledoor entry with minimum clearances of 9 ft (H) × 9 ft (W) × 15 ft (L). BTE structure shall support a 48inch diameter beam tube with an estimated linear weight of 254 lb/ft, including support systems. Longterm structural stability shall limit displacement to less than 5 mm over a 50-year service life and shall withstand normal temperature variations and wind loading to minimize noise and contamination. Sitespecific vibration criteria (e.g., VCE, NIST, or equivalent) shall be evaluated following site selection. BTE shall include protection against vandalism and firearms, with applicable ballistic standards (e.g., NIJ, DoD) determined based on site conditions.

VACUUM VALVE STATIONS (VS):

Located along the beamlines at kilometers marker 1, 3, 10, 12, 14, 18, 20, 22, 26, 28, 30, 37 and 39, Vacuum Valve Stations (VS) will house various vacuum equipment such as pumps and large gate valves. For equipment access and maintenance, VS will require roll-up door as well as crane with hook height of 9m above finish floor (AFF).

Figure 3.4.5 – Referenced LIGO India Vacuum Valve Station plan:

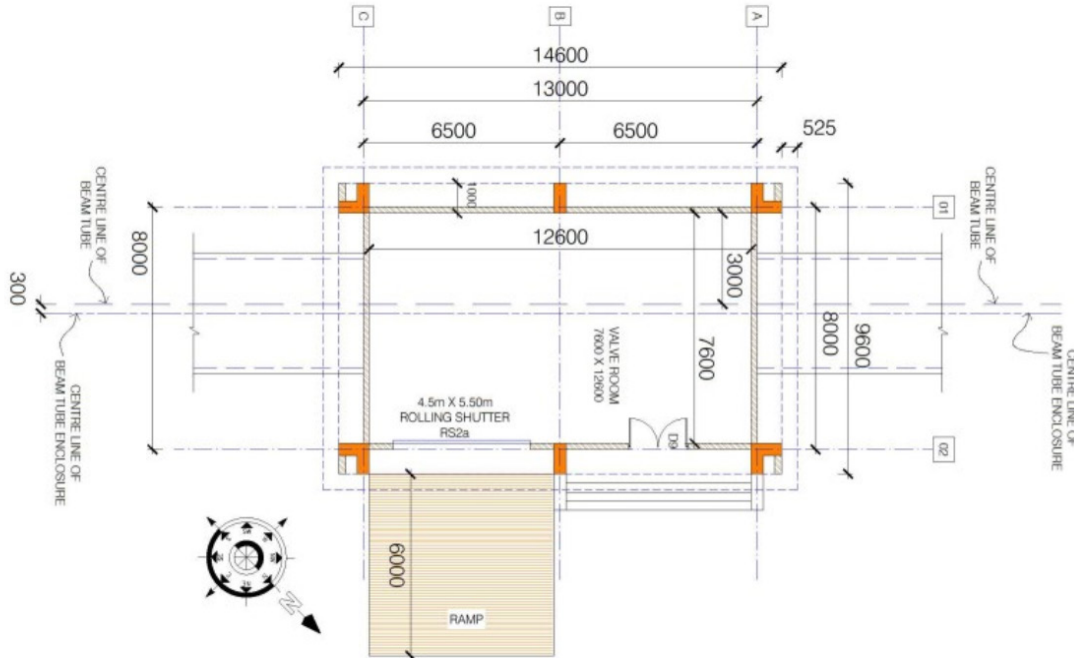


Figure 12: Example Vacuum Valve building layout from LIGO India (for reference only). Dimensions are in mm.

OPERATION SUPPORT BUILDING (OSB):

Located at the heart of Main Campus Building and near main service entry, Operations Support Building (OSB) serves as CE Observatory's operational, administrative, and technical activities hub. OSB will house critical functions including:

- **Control Room:** Serving as operational center with ergonomic office environment for the Operations Team.
- **Technical Spaces & Laboratories:** Requires high ceiling height (25ft AFF) for precision assembly & maintenance of detector hardware including:
 - Electronic Shop
 - Machine Shop
 - General Workshop
 - Clean Labs
 - Optics Lab
 - Electronic Testing & Maintenance Lab
 - Vacuum Preparation Lab
 - Data Storage
- **Office / Administration:** Designated for support staff and scientific visitors to ensure functionality and comfort, including conference rooms, private and modular open office spaces, entry lounge and amenities such as pantry.

- **Storage:** Serves as both active and long-term storage solutions to accommodate components, equipment and materials.

OSB will centralize functions currently distributed across LIGO Corner Stations to create cohesive research spaces that will streamline operations, encourage collaboration across the research disciplines, and long-term missions at CE Observatory.

Figure 3.4.6 – Referenced LIGO India OSB Plan:

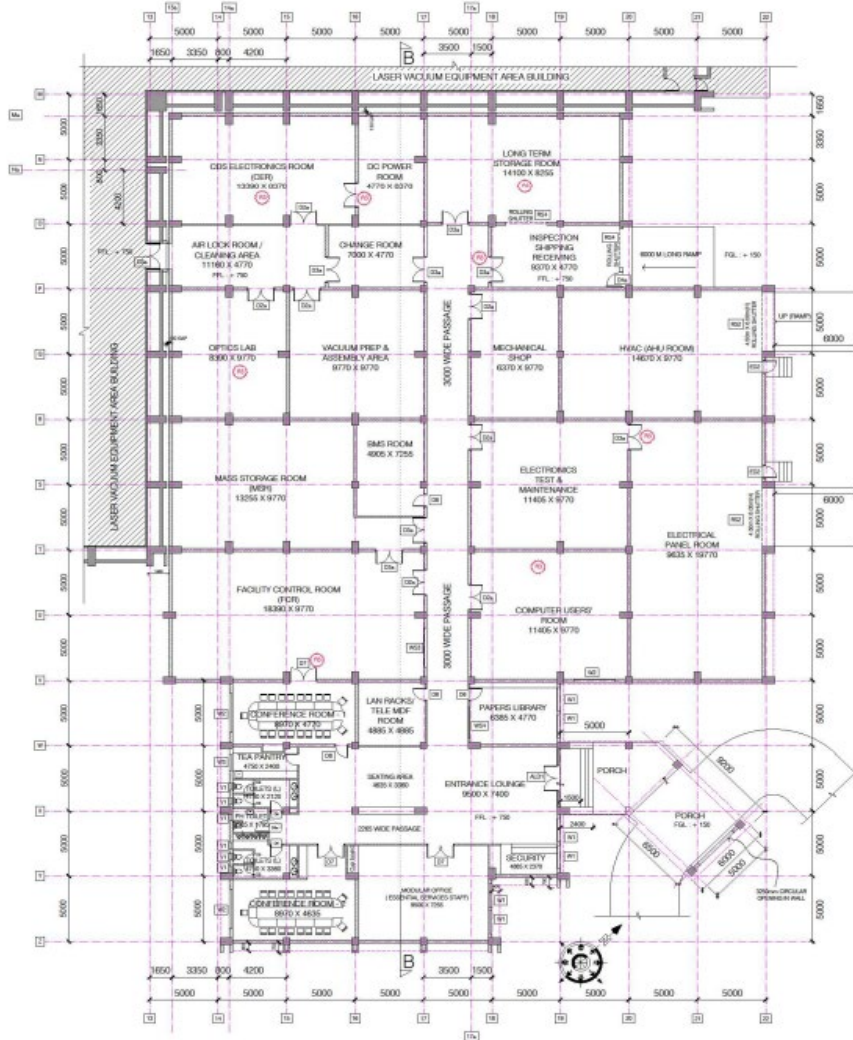


Figure 17: OSB plan from LIGO India design (for reference only). Dimensions are in mm.

COMMUNITY & EDUCATION BUILDING (CEB):

Community engagement and education are core components of CE Observatory mission, similar to the role of the LIGO Exploration Center (LExC). Community Education Building (CEB) on the Main Campus will serve as the flagship facility for these activities. Depending on the final site location, CEB is expected to include:

- 200-seat capacity Auditorium
- Three (3) Classrooms
- Exhibition Hall and Offices

Aforementioned spaces will provide opportunities for hosting various visitors ranging from K-12 students and community visitors to wider scientific visitors from home and abroad.

OFFICE BUILDING (OB):

Located near the main service entry and adjacent to the Community Education Building (CEB), the Office Building (OB) will serve as the administrative headquarters during CE Observatory construction and subsequently transition to the primary administrative facility supporting ongoing Observatory operations.

The OB design will incorporate wellness oriented features that enhance natural daylighting and ventilation, such as an open-air courtyard. Interior spaces will support administrative and project functions and include a mix of private offices for senior staff and discipline leads, open office areas, conference rooms, and shared amenities including a cafeteria, pantry and sample display area.

4 SITE AND SITE WIDE PLANNING



4 SITE AND SITE WIDE PLANNING

4.1 SITE PLANNING CONSIDERATIONS

The Cosmic Explorer site wide planning study proposes a long-term framework for a national scientific observatory complex designed to support gravitational-wave discovery for at least 50 years after construction is complete. The planning study incorporates current programmatic needs while ensuring the ability to remain operationally resilient, environmentally responsible, and harmonize with its regional context.

At its core, this planning exercise treats Cosmic Explorer not as a single experimental installation, but as a permanent scientific infrastructure, one that must be sited and organized to support multiple generations of research, continuous operation, and public stewardship over many decades.

The site wide plan assumes that there will be a selection of geographically expansive sites capable of accommodating two approximately 40-kilometer (25 mile) interferometer beam tunnel enclosures (BTE) arranged at, ideally, 90-degrees to each other. Key planning criteria include:

- Sufficient contiguous land or control easements to preserve clear BTE corridors.
- Regional geological stability and low ambient seismic disturbance.
- Ability to mitigate an inevitable but inconsistent wind induced vibrations.
- Ability to address the actual curvature of the Earth's surface and how to maintain a level and consistent beam line.
- Minimal conflicts with existing development, transportation corridors, and local communities.
- Compatibility with environmental protection goals and land-use regulations.

The planning boundary incorporates not only current facility needs but would consider long-term buffer zones to protect the observatory from encroachment, vibration, electromagnetic interference, and other incompatible influences.

4.2 SITE PLANNING CRITERIA

Building Zones

The site is organized into clearly defined planning zones, each with distinct operational and access requirements, refer to Figure 4.1.1 illustrating these zones:

- **Beam Tunnel Enclosure (BTE)**
Linear corridors reserved for vacuum laser beam tubes, protected through setbacks, easements, and vegetation management. These corridors define the fundamental geometry of the observatory. The BTE serves as a protective enclosure against the natural elements as well as man-made factors to include projectiles, vehicular accidents, and vandalism.
- **Corner Station**
Located at the intersection of the interferometer arms, this zone accommodates the central experimental facilities, control rooms, cleanrooms, and support spaces. Buildings are clustered to minimize infrastructure runs, improve operational efficiency, and reduce environmental footprint. Due to precision optical components, very rigorous environmental controls are required, for example, setback distances for vibration mitigation, architectural consideration to reduce wind induced interference, etc. Staffing is expected to be minimal during observation periods.

- **Main Campus**
Located 2 kilometers from the Corner Station is the central activity hub during observational periods. This area also functions as the Observatory Complex's main point of entry and the interface with the external community. Additional training and teaching opportunities to be undertaken here to establish future generations of scientists and engineers. Main Campus will house the Community Education Building, an Operations Support Building, an Office Building, and various infrastructure support buildings. Deliveries, staff, and visitors will transit through this area prior to accessing the main observatory complex.
- **End Station Zones**
Compact campus nodes at the terminus of each BTE arm, housing precision interferometer equipment, mechanical systems, and maintenance access. These zones are planned for limited staffing. The End Stations need to adhere to the same stringent environmental controls as the Corner Station.
- **Support and Utility Zones**
Areas designated for power systems, cooling, maintenance yards, storage, and future infrastructure expansion, sited to minimize noise and vibration transmission. Additional BTE support facilities like the Vacuum Valve Stations, situated at designated mile-markers will also need to be accommodated to maintain and compartmentalize the ultra-high vacuum state of the beam tubes.

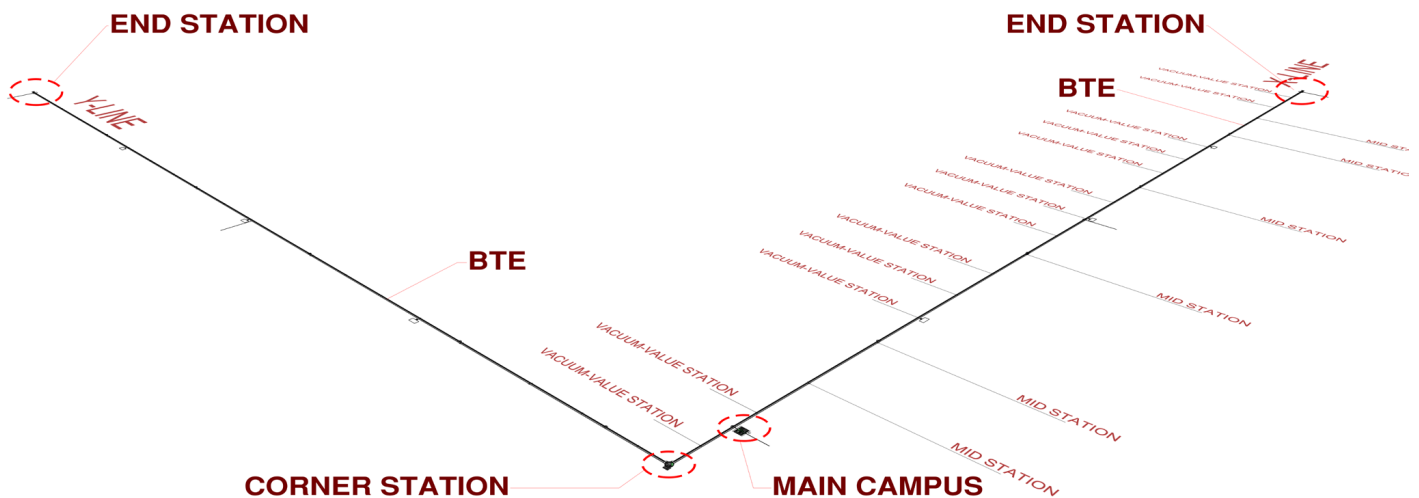


Figure 4.1.1 Site Planning Criteria

Site Access Considerations

The Master Plan establishes a hierarchy of access routes:

- Service roads along the BTE arms for inspection and maintenance. These could be unpaved roadways.
- A system of paved roads to provide vehicular access between Corner, Main, and End Station campuses.
- A dedicated paved fire-life safety access route to service the entire Observatory Complex.
- An amenity landscaped walking and / or bike path to connect the Main Campus and Corner Stations with each other for both staff and visitors.

Due to the overall dimensions of the Observatory Complex, additional vehicular access points are to be considered to supplement the Main Campus' point of entry. The End Stations will be provided with their own controlled access gates. At least one more controlled gated access to be situated midway along the BTE length. More control gates can be considered as needed.

Roads and crossings need to be planned to avoid vibration to the detector systems and to minimize intersection with the BTE arms, refer to section 5.2 for details. An overpass and/or underpass system ought to be considered where intersections cannot be avoided. Again, due to the length of the BTE, wildlife migratory patterns, if any, need to be identified, and animal crossings points must be accommodated to avoid wildlife disruption.

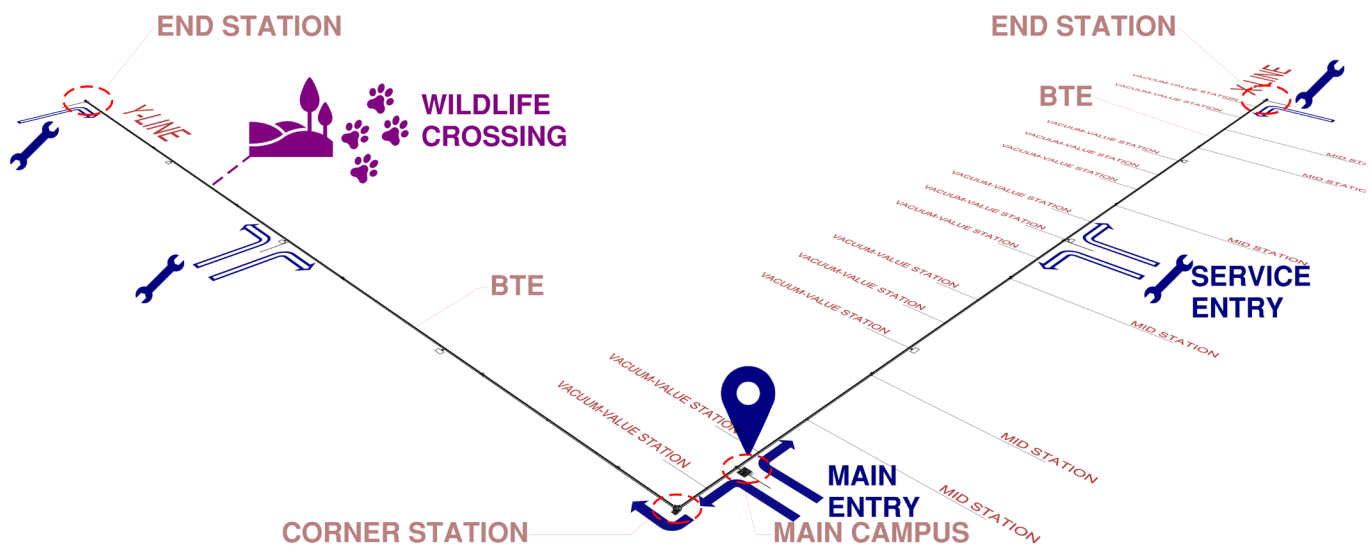


Figure 4.1.2 Site Planning Criteria

Wildlife Crossing and Mitigation Considerations

Referencing from Federal Highway Administration (FHWA), wildlife crossing at major highway infrastructure is derived from the type of specie(s) that requires to be accommodated by the recommended approaches, which may include Landscape bridges, Wildlife overpass, Multi-use overpass, Viaduct, Underpasses suitable for animal sizes, and so on. For example, Wildlife overpass of 130 to 165 feet wide that can accommodate most wildlife species may be employed for budgeting purposes; once prospect site is more defined and can narrow down the wildlife specie(s), this can potentially be reduce to more targeted solution such as Multi-use overpass. Other effective measures may entail fencing and gating as part of wildlife mitigation plan. Please refer to Appendix A.6 for detailed guidances from FHWA.

Site Utility Planning

Utility systems are planned as campus-scale networks, not ad hoc connections. These include:

- Redundant power distribution with capacity for future observatory upgrades.
- On-site renewable power generation. Due to the vibration sensitivity, windmills are omitted from consideration. Photovoltaic fields and their associated infrastructure are ideal.
- High-reliability communications infrastructure supporting remote operations and scientific teams.
- Modular mechanical and cooling systems designed for expansion.
- Stormwater and drainage systems to be integrated with landscape design and designed to drain water away from the BTE and attendant support equipment.

Utilities are consolidated into corridors and lined along the BTE where feasible to reduce land disturbance and simplify maintenance access. Please reference section 5.3 for details.

Site Wide Planning as Guiding Principle

The Site Wide Planning study integrates environmental stewardship as a guiding principle:

- Preservation of natural landforms and sensitive habitats. These are to be avoided if possible.
- Landscape buffers and building massing to reduce environmental visual impact or blend into the natural context.
- Low-impact drainage and erosion control strategies.
- Energy-efficient site systems with potential for renewable integration.
- Any excess on-site renewable energy should be considered as a shared resource with the local communities.

The Cosmic Explorer Site Wide Plan study establishes a framework that helps organize land use, infrastructure, and facilities around the immutable geometry of the interferometer beam lines. The plan ensures that Cosmic Explorer can evolve scientifically while maintaining its operational resilience. The complex would tread lightly and respectfully upon the land, its habitats and communities. This study provides criteria to help the observation team choose the best location for their scientific endeavors and thereby provide the foundation for decades of discovery, stewardship, and innovation.

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5^{.1} PROJECT SYSTEMS INTRODUCTION



5^{.1} PROJECT SYSTEMS INTRODUCTION

5.1 Introduction

This section establishes baseline guidelines and technical criteria to support site-selection considerations and the architectural design of the Cosmic Explorer (CE) Observatory conventional facilities in future project phases. These system criteria are limited in scope and are intended to support conceptual visualization and provide input to the project cost model based on site-agnostic assumptions and showing the wide range of environmental design parameter depending on potential project sites that were assumed for the purpose of this report.

The content is organized by major building systems, including civil engineering, site infrastructure, architectural, structural, mechanical, plumbing, fire protection, fire alarm, electrical, and lighting systems.

During subsequent design phases, the CE project team is expected to reevaluate and refine these systems based on the conditions, infrastructure, and technologies available at the selected site(s). Detailed and fully engineered architectural and systems designs for the CE Observatory will be developed as part of those later phases.

5^{.2} CIVIL ENGINEERING AND SITE DEVELOPMENT



5.2 CIVIL ENGINEERING AND SITE DEVELOPMENT

5.2.1 Overview

Civil engineering and site development for the Cosmic Explorer (CE) facility will be governed by the fundamental geometric requirements of the observatory, particularly the need to maintain long, straight beamline alignments over distances of up to 40 km. The feasibility-study approach is intentionally site-agnostic and pre-conceptual in nature, aimed at identifying representative civil engineering typologies, construction approaches, and rough order-of-magnitude (ROM) quantities rather than site-specific solutions.

Major civil scope elements include earthworks along the beamline corridors supporting the beam-tube enclosure (BTE) structure and associated access infrastructure, BTE crossings for vehicles and animals, campus site development at the Corner, Mid, and End Stations, associated roadway and stormwater infrastructure, and localized use of bridges or tunnels where required by topography to support the BTE. This section also addresses environmental constraints and access considerations. Civil utilities and related infrastructure are described in Section 5.3 of this report. Details regarding the BTE structure are provided in Section 5.5 of this report.

This section has been prepared by Arup engineers specializing in civil engineering and earthworks, geotechnical engineering, bridge engineering, and tunnel engineering, and aims to provide ROM quantities of site-specific construction conditions for the purpose of cost-estimation exercises performed by Cumming. This section does not provide explicit recommendations for final design.

5.2.2 Construction Typologies

The following construction typologies for BTE support were considered for applicability to CE based on experience with long linear infrastructure projects and are reflected in Figure 5.2.1 below:

- | | |
|----------------------|---|
| 1. Elevated Viaduct | 6. U-wall with support of excavation (SOE) |
| 2. MSE Wall | 7. Open Cut Trench |
| 3. Embankment / Fill | 8. Cut and Cover Tunnel |
| 4. At-Grade | 9. Bored or Mined Tunnel |
| 5. Emersed | |

Construction typology factors include length of application, height and depth of application, footprint limitations, and geotechnical limitations. In the absence of site-specific factors, the construction typologies in boldface font in the list above were selected for use in quantity estimation for the costing exercise. We understand that the primary construction types supporting the BTE at the LIGO Hanford and Livingston sites are earthen embankments and open-cut trenches, as indicated in Figure 5.2.1; this knowledge also guided our selection process herein. Earthwork solutions for cut/fill (Open-Cut Trench and Embankment) were selected over walled cut/fill solutions (U-Wall with support of excavation [SOE] and MSE [Mechanically-Stabilized Earth] Wall) for the following reasons:

1. Potential sites are remote, limiting access to and increasing mobilization costs for specialty contractors, equipment, and crews required for these structure types.
2. Walled cut/fill solutions reduce footprint, which is useful in confined and urban settings but generally unnecessary where a larger earthwork footprint is acceptable.
3. Precedent at the LIGO sites.

However, where footprint is constrained at a specific site, the other typologies may still be feasible, although they were not included in this study. Similarly, tunnels are included in the costing exercise presented in Section 5.3, but the estimate does not differentiate between bored tunnels and mined tunnels using the Sequential Excavation Method (SEM), which should be evaluated further during site-specific design at a later stage of this project.

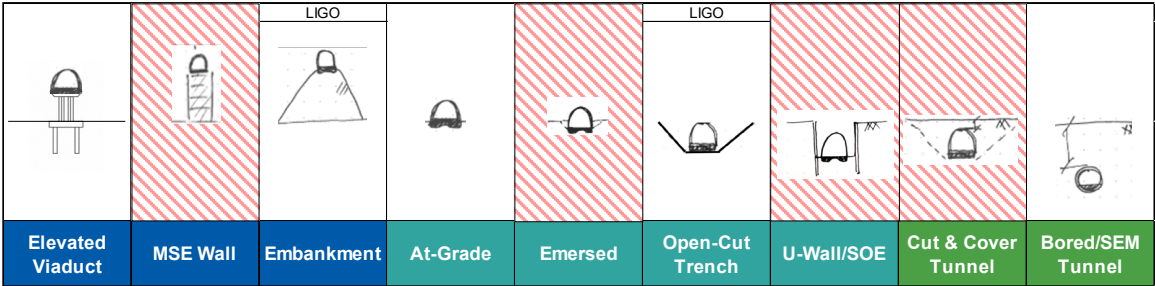


Figure 5.2.1 Construction typologies considered during feasibility review. Red hatched typologies were not considered for CE costing exercise. Two primary typologies used in the existing Laser Interferometer Gravitational-Wave Observatory (LIGO) sites are indicated.

After evaluating the applicability of the various typologies, the following were determined to have merit for further consideration and costing for this feasibility-level study considering constructability, maintenance, and access requirements to the BTE. To facilitate costing, assumptions are made regarding vertical delineations for each construction typology and listed as Table 5.1. These assumptions are based on engineering judgement and relevant precedents and are strictly not based on project- or site-specific analysis.

5.2.3 Civil Engineering & Earthworks

Civil and geotechnical coordination is required to establish preliminary site grading parameters, earthwork quantities, and stormwater management approaches. Topography, ground conditions, and groundwater levels influence both the grading feasibility and long-term performance related to drainage reliability and erosion control.

While the present study is site-agnostic, the use of an indicative topographic profile illustrates the estimated proportion of earthworks and special structures required to achieve the BTE alignment which fits a Euclidian flat plane in 3D space. Figure 5.2.2 below illustrates the various site conditions along a theoretical BTE alignment. This profile is conceptual and not intended to illustrate exact proportions used for the feasibility study or cost estimate.

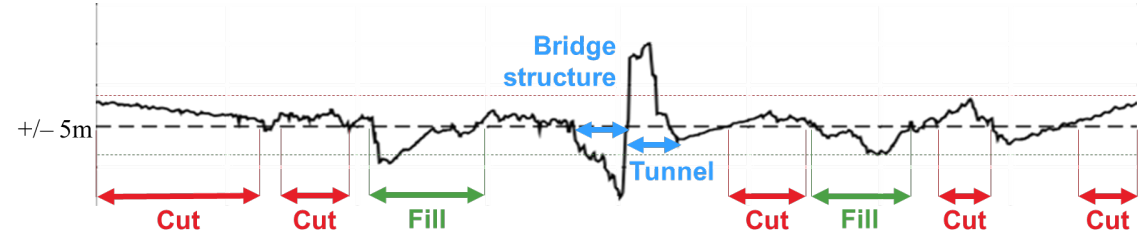


Figure 5.2.2 Indicative BTE profile mapped against a theoretical topographic site profile as an example of length, magnitude, and transitions of civil earthworks and special structures.

The CE science team provided a statistical average of 26 long-listed sites under consideration for potential 40-km CE sites (Datrier et al., 2025), resulting from a National Suitability Analysis performed in a similar study (Bristol et al. 2025). The statistical averages match the five construction typologies used to approximate earthwork and civil construction needs and may be thought of as a representative set of values accounting for real-world ground variability and Earth curvature effects over long distances. The nominal distribution of percentages of lengths of each

typology representative of the averaged CE site over 40 km are included in Table 5.1. These assumed values were used for ROM costing only and are expected to be refined with the provision of site-specific data. Cutoff depths/elevations (when one construction type transitions to another) are based on experience from long linear infrastructure projects, although we recommend performing a future assessment to confirm the appropriate cutoffs based on site selection and construction cost in the next phase of the project. The cutoffs delineating each construction typology feed into the calculations in the following subsections of this report.

Table 5.1 Summary of Construction typologies along full CE alignment for BTE

Civil Engineering Construction Typology Percent		Fraction of lineament		BTE alignment ¹ elevation compared to existing grade
		Percent of Typology	Length [km] ²	
Earthworks	At-grade	23%	9.2	within $\pm 5'$
	Cut	37%	14.8	5-20' below
	Fill	22%	8.8	5-20' above
Special Structures	Bridge/Viaduct	11%	4.4	> 20' feet above
	Tunnel	7%	2.8	> 20' below

Note 1: Elevation values in feet with respect to BTE invert elevation.

Note 2: Computed with respect to a 40-km single arm of the CE array.

It is assumed that in CE alignment sections where earthworks are performed, at-grade sections will not require import or export of earth materials, fill sections will require import of earth materials to the site, and cut sections will require export of earth materials off-site. It is recommended that the Corner Station and End Station are constructed at-grade, or as close to at-grade as possible, to minimize disturbance and vibrations to more sensitive portions of the CE scientific apparatus.

A Note on a Bowl-Shaped Site

Since the Earth is not flat, it is understood that a bowl-shaped site with respect to Earth-surface topography is desirable. Such a concave-up curvature would counteract the convex-up curvature of the Earth, thereby potentially minimizing the amount of earthwork and grading required to achieve a CE alignment most parallel to the target BTE alignment. Arup did not perform such analyses, but in Figure 5.2.3 we present an illustrative example provided by the CE science team presenting this fitting analysis. For the bowl-shaped site, the earthwork volume (cut or fill) is $\sim 4\text{M m}^3$, while for the flat site, that volume is 19M m^3 (Joshua Smith, 3/25/2026, written communication). The difference between the CE arm profile (dashed line) and the topographic elevation profile (solid line) and the arm profile relates to the amount of earthwork needed at that location.

Natural bowl-shaped sites correspond to geographic and tectonic basins which are often characterized by relatively deep sediments at the center of the basin, which thin out towards the mountains or hills bounding the edges of the basins; potential fault-bounded basin edges; and variable groundwater depths.

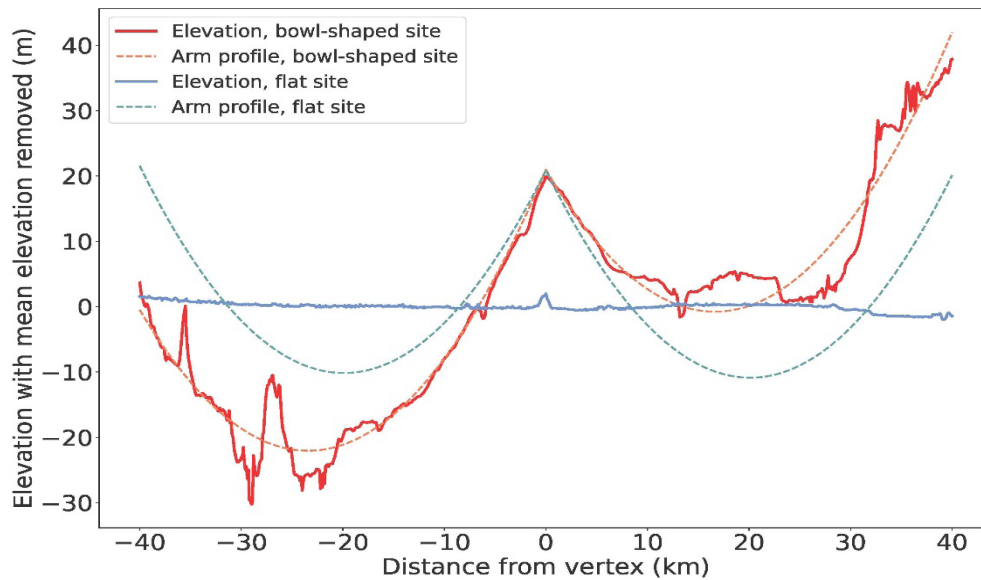


Figure 5.2.3 Elevation and CE arm profiles (dashed lines) with mean elevation removed for two locations, one in a flat-in-elevation site, and one in a bowl-shaped valley. (Source: Joshua Smith, 3/25/2026, written communication.)

5.2.4 Considerations for Ground Conditions

Geotechnical engineering considerations are fundamental to site selection for the Cosmic Explorer, particularly due to the facility’s sensitivity to ground vibrations, deformation, and long-term stability. These factors influence alignment feasibility, construction methodology, lifecycle performance, and cost.

At the feasibility stage, subsurface and geotechnical conditions have not been characterized and are assumed to vary significantly among and within potential sites. Planning assumptions implicitly contemplate sites with generally competent near-surface materials suitable for conventional construction techniques. Variations in ground conditions represent a key source of uncertainty to be addressed during future investigations and conceptual design.

To narrow down sites, ground conditions considered to be “red flags” and avoided are:

- significant fault crossings,
- areas prone to landslides,
- karstic terrain with sinkhole potential, and
- regions of widespread subsidence due to groundwater or other fluid extraction.

While such ground conditions can be mitigated, their presence on a broad scale may render maintenance costs to retain a level BTE infeasible or impractical.

Regional Geology and Subsurface Profile

The ideal site is underlain by laterally continuous and competent geologic formations that support predictable excavation behavior and long-term stability. Frequent transitions between soft soils and hard rock, or highly variable stratigraphy, introduce uncertainty in excavation method selection and increase the risk of differential settlement and alignment control challenges. For most of the construction typologies, depth to competent rock is a primary consideration among candidate corridors; although in basin environments, such bedrock depth may vary significantly across the site profile.

Ground Motions, Seismicity, and Vibration Environment

Baseline ambient ground vibration, including natural microseisms and anthropogenic noise, is a first-order screening criterion. Seasonal variability, such as increased microseismic activity driven by winter ocean storms, must be evaluated in addition to average conditions to fully characterize site performance potential.

Regional seismicity and site-specific response conditions shall also be considered, including ground-motion amplification due to soft sediments; fault proximity potentially resulting in strong shaking levels, pulse-like ground motions, and long-duration ground motions; and long-term ground deformation mechanisms. These factors inform both feasibility and high-level mitigation concepts.

Refer to Section 5.5.3 for further discussion of ambient vibration considerations.

Hydrogeology and Groundwater Management

Hydrogeologic conditions influence both constructability and long-term operational stability. Viable sites must support continuous alignments without unacceptable groundwater inflow, aquifer drawdown, or environmental impact. Sites characterized by high groundwater pressures, variable aquifers, or groundwater-dependent ecosystems generally introduce increased construction risk and long-term operational complexity.

Early hydrogeologic modeling and piezometric monitoring are recommended to confirm corridor viability and support realistic assumptions in the cost and feasibility models.

Settlement and Deformation Risk

In soft ground or geotechnically sensitive environments, predicted surface settlement and deformation can constrain excavation / tunnel depth, excavation methodology, and alignment selection. Site suitability depends on the ability to limit volume loss and ground movements to within tolerances compatible with third-party infrastructure and environmental constraints using established construction controls.

Integration with Cost and Procurement

Geotechnical input informs the development of site-specific parameters and high-level mitigation concepts used in mature cost models. This includes narrative input addressing geotechnical criteria, review of the cost estimate, and contribution to the overall feasibility assessment to ensure that subsurface risks are appropriately characterized and reflected.

When the CE site has been selected and procurement documents are being generated, a Geotechnical Baseline Report (GBR) is recommended to serve as a contract document that establishes a binding, agreed-upon interpretation of anticipated subsurface conditions to fairly allocate risk between owners and contractors, thereby minimizing disputes regarding differing site conditions claims.

5.2.5 Civil Engineering Site Work

Roadways

Conceptual layouts for site access, internal roadways, and parking must consider constructability, accessibility requirements, maintenance needs, and emergency vehicle access. Favorable sites allow multiple access points, including portals, ramps, or shafts, enabling parallel construction activities and reducing schedule risk over long corridors.

Surface circulation must also be evaluated with respect to right-of-way constraints, crossings of existing infrastructure, and interface with local transportation networks. The ability to manage these interfaces using standard civil engineering solutions and without disproportionate cost or risk represents an important site-selection factor.

Roadway infrastructure is required to support construction, operations, and maintenance activities across the CE site. For feasibility-level assumptions, circulation and access roadways were assumed to be two-lane flexible pavements with a 26-ft paved width. A representative pavement section includes asphalt concrete surface and binder courses over aggregate base and subbase layers.

Maintenance roadways adjacent to the BTE were assumed to be gravel surfaced, also with a nominal 26-ft width, supported by granular base layers. These assumptions are intended to represent typical rural or remote site roadway construction and support ROM cost estimation only.

Road design and construction criteria would reference applicable codes, industry standards, and national and international best-practice guidance for the chosen site.

Stormwater Management

Stormwater strategies must balance regulatory compliance with protection of sensitive hydrogeologic systems and minimization of construction-induced impacts. Sites that allow gravity-driven drainage systems with predictable runoff behavior are generally preferred over those requiring extensive pumping or control structures.

Stormwater management assumptions were simplified accordingly. For each campus area, one retention basin was assumed, with a nominal depth of approximately 6 ft and a plan area equivalent to roughly 12% of the impervious surface created by buildings and parking. Paved roadways were assumed to drain via superelevation to continuous gravel swales running longitudinally along the roadway alignment. Gravel maintenance roads were assumed to infiltrate runoff without the need for additional stormwater controls.

Final stormwater strategies would be highly dependent on site-specific and jurisdiction-appropriate hydrology, regulatory requirements, and environmental constraints.

5.2.6 Bridges and Elevated Structures

Bridges are anticipated where beamlines or access roads cross existing corridors or terrain constraints. Quantities were approximated using standardized highway bridge typologies from the Arizona Department of Transportation (<https://azdot.gov/sites/default/files/2025-08/BDG-Sections-Archived-2025.pdf>) and the Federal Highway Administration (FHWA) Bridge Replacement Cost Database (<https://www.fhwa.dot.gov/bridge/nbi/sd.cfm>) to support ROM costing. The proportion of alignment requiring bridges remains subject to refinement after selection of a site or general region. Arizona DOT was selected for this exercise as it is assumed that general climate and geological conditions in the state of Arizona would be indicative for a potential candidate for a western U.S.-based 40-km CE site. Bridge and viaduct design and construction criteria would reference applicable codes, industry standards, and national and international best-practice guidance for the chosen site.

A conceptual diagram for a bridge deck including the BTE and access roads is provided in Figure 5.2.4. The quantities in this section encompass only the support structure, not the BTE; for details on the BTE structure itself, see Section 5.5. Table 5.2 below summarizes approximate amounts of concrete required for a 100-ft portion of bridge deck, resulting in approximately 630 cubic yards for the statistically representative profile described in Section 5.3; these quantities were used for the cost estimation exercise.

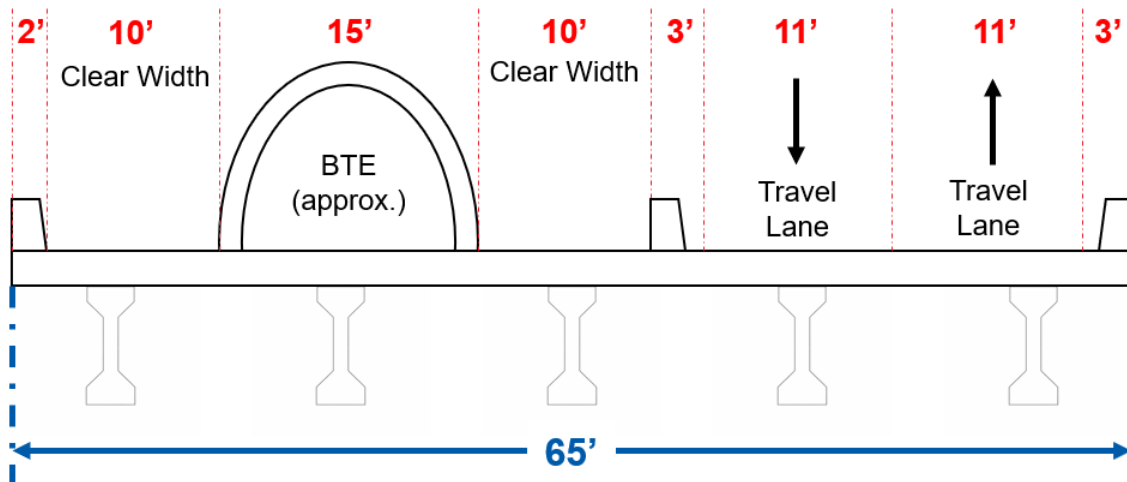


Figure 5.2.4 Indicative bridge deck section depicting BTE, travel lanes connected to roads, and approximate widths.

Table 5.2 Indicative bridge deck section depicting BTE, travel lanes connected to roads, and approximate widths.

Bridge Component	Approx. Volume Concrete per 100-ft Span (yd ³)
Deck	180
Superstructure	130
Pier columns	70
Pier cap + footing	250
Total	630 yd³ / 100-ft span

A list of assumptions pertinent to the above calculations are as follows:

- Deck width: 65 ft
- Span length: 100 ft on-center
- Average column height: 35 ft
- Typical overpass: multi-span, concrete superstructure, concrete piers
- Cast-in-place concrete deck on concrete girders or box
- One pier line per span; two columns per pier
- Typical Arizona DOT / AASHTO proportions (conceptual level)

Further refinement of the cross-section to optimize the design and reduce cost by reducing the bridge deck width, combining access roads, and/or re-routing them at grade could be studied in the next phase.

5.2.7 Tunneling

Select locations may require tunneling where surface construction is impractical. Tunnel design considerations integrate geological, geotechnical, and civil engineering factors to determine whether candidate sites support robust, continuous, and economically viable underground construction over long distances.

Tunnel Construction Method Feasibility

Site selection must support at least one continuous and well-understood tunneling method, such as Sequential Excavation Method (SEM) or Tunnel Boring Machines (TBMs). Ground conditions that require frequent changes in excavation approach, extensive ground treatment, or highly customized support systems reduce the attractiveness of a tunnel corridor typology and increase cost and schedule uncertainty.

For the purposes of the CE study, we can draw on the following precedents such as:

- the Long-Baseline Neutrino Facility (LBNF) in South Dakota,
- the SLAC National Accelerator Laboratory in Palo Alto, California, and
- the Large Hadron Collider at the CERN facility in Switzerland.

for relevant feasibility-level tunneling options. These included mined tunnels for short sections (less than approximately one mile [1.6 km]) in competent rock with shotcrete or cast-in-place linings and TBM bored tunnels with precast segmental lining systems or cast-in-place linings for longer segments. The current cost model does not include tunnels longer than one mile, so only the use of SEM mined tunnels has been included in this study.

Tunneling or cut-and-cover options carry the added benefit of allowing at-grade on-land overcrossing for wildlife, which would be impossible with U-box open channels and could be more practical than building wildlife land-bridge crossings at regular intervals.

Alignment Constraints and Tolerances

Horizontal and vertical alignment limitations must be evaluated in relation to excavation methodology, ground conditions, and achievable construction tolerances. These constraints are critical for long and straight facilities, where cumulative deviations can significantly affect system performance.

Alignment depth, tunnel diameter, lining stiffness, and construction tolerances must all support long-term control of deformation and differential movement. Even slow, time-dependent ground deformation or lining creep can require ongoing realignment or active compensation methods within the BTE system. As a result, sites with geological conditions that naturally limit creep, settlement, and stress redistribution are strongly preferred.

Codes, Standards, and Best Practices

Tunnel design and construction criteria reference applicable codes, industry standards, and national and international best-practice guidance. These references establish baseline expectations for design loads, durability, groundwater control, and construction tolerances, and provide a consistent framework across candidate sites.

Safety concepts are assumed to be performance-based and aligned with low-occupancy operational models, which are generally limited to periodic, controlled entry for maintenance workers and scientists. Such factors include considerations for tunnel ventilation, life safety ingress and egress points, confined-space entry portals, and limited climate-control elements for temperature and humidity. For example, CERN tunnels do not follow rail or road tunnel codes (e.g., NFPA 130 / 502). Instead, they use a bespoke, performancebased safety concept that is fundamentally different from publicoccupancy tunnels. The life safety strategy at CERN is heavily influenced by:

- Low occupancy during operation
- Controlled access (trained personnel only)
- Strict operational procedures
- Compartmentalization and ventilation control
- Refugeinplace strategies
- Fire compartment lengths typically ~400 m
- Alcoves / safety features used for refuge and intervention
- Major access points (shafts, caverns) spaced at hundreds of meters up to approximately 1km.

Tunnel Lining, Loads, and Durability

Typical tunnel lining systems, such as cast-in-place concrete, precast segmental linings, or shotcrete / composite systems, are evaluated based on ground conditions, groundwater ingress tolerances, and durability requirements. Structural design considers common dead and live loads, including ground loads, groundwater pressures, seismic effects, and long-term deformation.

Groundwater Ingress and Long-Term Environment

Allowable groundwater ingress levels are established based on tunnel end use and operational requirements. It is assumed that the BTE will have strict ingress limitations and the lining will be designed to facilitate mitigation of groundwater ingress, if observed.

Excessive reliance on dewatering, ground freezing, or emergency tool-box measures during construction is viewed as an indicator of elevated site risk, increased unit costs, and potentially challenging long-term groundwater ingress issues. Preferred sites support manageable long-term drainage strategies.

5.2.8 Sustainability

Across the CE civil engineering and site development scope, sustainability considerations focus on minimizing land disturbance over long linear corridors, reducing embodied carbon in earthworks, construction, and build structures, and limiting long-term environmental and operational impacts. Key strategies include balancing cut and fill where feasible, minimizing trucking onto or offsite of earth fill, reusing stripped topsoil onsite for landscaping or other purposes, selecting civil typologies that reduce material quantities (e.g., limiting bridges and tunnels to continuous locations), using carbon-neutral concrete mix for structural or non-structural applications, and favoring durable, low-maintenance solutions that support the facility's anticipated long service life. Stormwater approaches emphasize infiltration and localized retention to preserve natural hydrology, while reduced surface disruption through selective use of tunneling can mitigate habitat fragmentation, visual impacts, and future land-use conflicts. At the feasibility stage, these measures are qualitative and indicative, with site-specific sustainability performance to be refined as candidate sites and design solutions are further developed.

5.2.9 References

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5^{.3} SITE INFRASTRUCTURE



5^{.3} SITE INFRASTRUCTURE

5.3.1 Domestic Water & Sanitary Sewer Infrastructure

Facility domestic water system is limited in scope and is intended to support basic occupant needs, select mechanical systems, and life safety requirements. Domestic water use is confined to restroom fixtures serving building personnel, water connections serving mechanical equipment in the electrical substation and chiller yard areas, and the facility's fire protection systems. The facility does not utilize domestic water for manufacturing processes, equipment washdown, food service, irrigation, or other production-related uses.

Overall domestic water demand is low and predictable when compared to typical industrial facilities with process or high-volume mechanical water requirements.

Figure 5.3.1 below depicts all buildings, their distance to the Corner Station (CS) in kilometers, domestic water supplies, and sewage types on the X-Arm. Only the X-Arm is shown as the Y-Arm is the same.

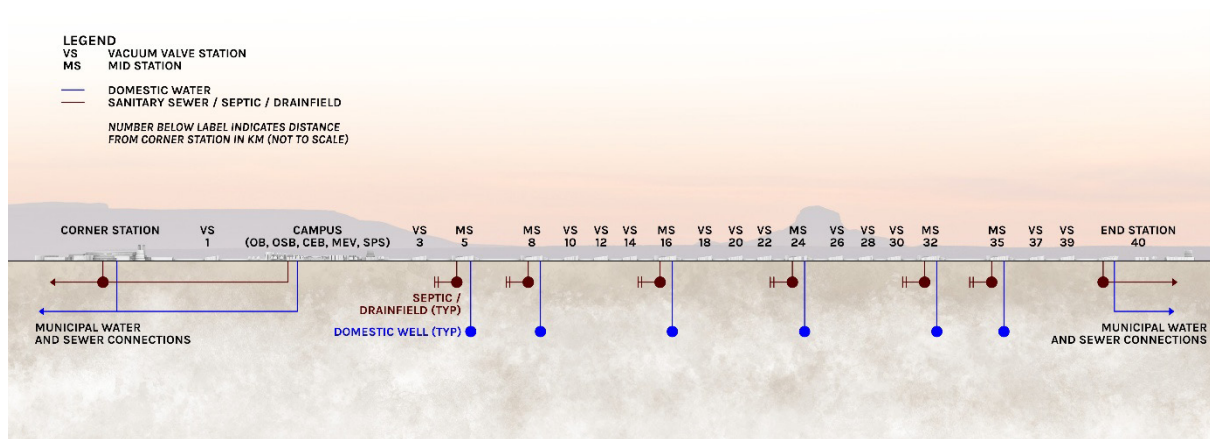


Figure 5.3.1 Domestic and Sanitary Layout

Domestic Water Supply and Distribution

Potable water is supplied to the facility via a municipal water service connection, if available. However, if a municipal connection is unavailable, the domestic water supply will be provided by a series of potable water wells.

The domestic water distribution system serves:

- Restroom fixture groups in occupied areas
- Selected mechanical equipment in the substation and chiller yards
- Fire protection systems

Restroom Water Usage

Domestic water consumption for occupant use is limited to restroom fixtures. Restroom water use is directly tied to staffing levels, shift schedules, and occupancy patterns. The facility does not include showers, locker rooms, or continuously operating fixtures. As a result, water use is intermittent and generally peaks during shift changes and normal operating hours.

Mechanical System Water Usage

In addition to restroom usage, limited domestic water connections are provided to support mechanical systems serving the electrical substation and chiller yard areas. These uses are ancillary to core operations and may include:

- Equipment make-up water
- Intermittent cooling system support
- Equipment maintenance or service connections

Based on the scale of the loads, air-cooled chillers are anticipated, which consume no water during normal operation. Mechanical water use is non-continuous and low volume, with demand typically driven by periodic maintenance, seasonal startup, or abnormal operating conditions rather than sustained operation. These systems do not represent a significant or ongoing domestic water load.

Fire Protection Water Demand

The fire protection system, consisting of fire sprinkler piping and associated components, is supplied from the domestic water service or a dedicated fire service connection. Fire protection water use is event-driven only and does not contribute to routine domestic water consumption.

Water usage is limited to testing, inspection, and maintenance activities under normal conditions, with full flow demands occurring only during emergency events.

Sanitary Sewer System – Low Volume Septic and Drainfield System Overview

The facility's sanitary sewer system is a low-volume, on-site wastewater treatment system designed to serve a limited number of restroom facilities along the beam path. Restroom facilities are planned at the corner station (CS) mid-station (MS), end station (ES) facilities. These facilities are low occupancy and the individual systems serving these buildings are designed for low loads. The system consists of septic tanks and associated drainfields that provide wastewater treatment and disposal for occupant use only. These facilities do not generate sanitary flows from kitchens, showers, process equipment, laboratories, or industrial operations. Due to the limited scope of use and low fixture count, sanitary wastewater generation is minimal, intermittent, and directly correlated to building occupancy.

System Description

Sanitary waste from restroom fixtures, including water closets, urinals, and lavatories, is conveyed through a gravity-fed sanitary piping network to one or more septic tanks. The septic tanks provide primary treatment by separating solids and allowing partial biological breakdown of organic material prior to discharge to the soil absorption system. Effluent from the septic tanks is distributed to subsurface drainfields, where final treatment and disposal occur through soil filtration and natural biological processes. The system is designed in accordance with applicable local and state health department requirements for small-capacity, on-site wastewater systems.

Septic Tank Condition and Operations

The septic tanks are appropriately sized for the limited number of fixtures and occupants served. Under normal operating conditions, tanks function effectively as primary treatment units with minimal operational complexity. Maintenance requirements primarily consist of periodic inspection and scheduled pumping to remove accumulated solids.

The drainfield systems provide subsurface effluent disposal through controlled infiltration into surrounding soils. Given the low wastewater volumes and intermittent use, the drainfields will operate reliably and reduce the risk of surfacing effluent, soil saturation, or system failure.

Reliability and Risk Considerations

Due to the simplicity of the system and the limited wastewater load, the sanitary sewer infrastructure presents low operational risk. Potential risks are primarily associated with deferred maintenance, such as inadequate septic tank pumping or unmonitored drainfield performance over time.

The system's reliance on soil conditions and biological processes underscores the importance of protecting the drainfield from vehicle traffic, surface water intrusion, or changes in land use that could impair infiltration performance.

Capacity and Future Considerations

The septic and drainfield systems are sized for current restroom usage. Any future increases in occupant load, fixture count, or building program changes would require re-evaluation of system capacity and regulatory compliance.

5.3.2 Electrical Infrastructure

Power to site is specified in “CE Facility Architectural Requirements (CE-T2500017)” document as 13kV buried power lines. The design for each station is based on this distribution voltage with a transformer at each station.

Figure 5.3.2 below depicts all buildings, their distance to the Corner Station (CS) in kilometers, underground power routing, and underground communication routing on the X-Arm. Only the X-Arm is shown as the Y-Arm is the same.

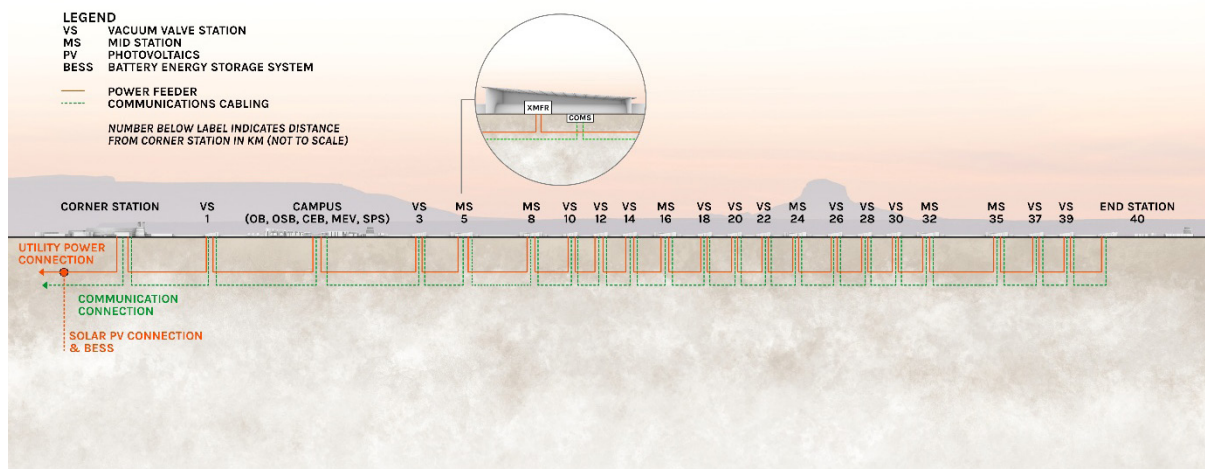


Figure 5.3.2 Electrical Layout

This layout includes underground distribution at distribution voltage and communications to each building with a step-down transformer at each building. The upper bubble shows a magnified detail of a step-down transformer and communications pull box next to building MS5, and this section view applies to all buildings along the length of the arm.

Communication between each building is anticipated to be needed for communication between process equipment and is included to ensure appropriate labor and materials are accounted for.

MV System

The architecture requirements document mentioned supply power as 13kV. Typical distribution voltage levels available throughout the United States include 12.47kV, 13.2kV, 13.8kV, 25kV and 34.5kV. All distribution voltage levels are acceptable for this site's power demand and footprint and all are also acceptable when including photovoltaics (dependent on power output), as described in Section 6 Sustainable Design Principles. Though 15kV class voltages (12.47kV, 13.2kV, and 13.8kV) can provide adequate power throughout site, significantly larger power cables are required to minimize voltage drop. 34.5kV distribution is the preferred distribution level as this reduces cables sizes, which will minimize parallel feeders, parallel conduits, make cable pulling easier, reduce quantity of cable splices and pull points.

Due to this project's unknown final location, an assumption is made that the site's utility source is located at the Corner Station. Since the majority of the site's load is at or near the Corner Station, the overall project's cabling cost is lowest, as significant loads drop off closest to the Corner Station. Once the site has a finalized location, a study will be required to understand available utility distribution voltages throughout and near the site's footprint. This will help optimize power distribution and minimize costs associated with voltage drop. It is also worth noting that the most prevalent distribution voltage throughout the US is 15kV class and the probability of intersecting multiple existing 15kV power lines across the site's footprint is high.

Site Power Distribution

Underground

Underground buried distribution is specified as the basis for power distribution throughout site. Underground cables provide the highest reliability but require proper design to maintain this reliability. Also, coordination with AHJ is required to ensure installation types are acceptable.

Underground installation can be either direct bury or installation in duct bank. In either installation type, proper burial depth is required. Direct bury requires proper cable selection, trenching, backfill material, concrete cap (typically colored red), and warning tape. Road crossing should be completed using concrete encased duct bank. Duct bank is also a viable option using concrete encased conduit system. Trenching is performed, conduits and manholes are installed, and concrete is poured, encasing duct conduits. This provides the highest level of mechanical protection, though it comes at a higher cost as it is more labor intensive and requires more materials. In-ground or above-grade pull points also must be designed to accommodate cable pulling and cable splicing. Another viable option is directional drilling. This involves using a direction drilling machine and a continuous conduit to route cabling. This traverses from entrance to exit points over a wide range of depths, allowing high mechanical protection at its lowest depth but lower mechanical protection near its entrance and exit points. Directional drilling is the least cost option, dependent on soil types and underground conditions.

Cost model range contains high variability due to potential soil conditions that could be encountered and site's proximity to required concrete materials.

Above Grade

Above grade installation is an alternative to underground installation. Above grade can be the least cost installation type, dependent on proximity to existing utility provider infrastructure. Due to the size of this project, it is very likely this site will cross existing 15kV or 35kV class utility distribution power, which can be used to provide power at the crossing location(s) and distributed throughout site. Above grade power is routed on poles and is more susceptible to weather conditions and inherently less resilient than underground cable distribution.

Transformers

Transformers are required at each separate building throughout site. The transformer will step-down distribution voltage to building utilization voltage, which will be 480/277V, 208/120V, or 240/120V, depending on the building's needs. Each transformer will be part of a loop-fed design, which allows termination of both the incoming and outgoing medium-voltage power cables on the transformer's primary terminals. The outgoing power cable from this transformer will route to the next building and terminate on its transformer, continuing this process to the last building and providing power to the site. The transformer's primary voltage must align with the utility voltage provided for the project and should also contain multiple taps to correct voltage differences that can be seen along the project's footprint.

Utility Power/Power Generation

Utility Power

In general, distribution throughout site from the utility provider will be the least-cost option for providing power to this campus and the provider can offer a complete engineered solution, complete with installation and inclusive of each building transformer. Dependent on the location, the site may intersect existing distribution lines, allowing for easier installation. Where possible, utility power should be considered as the basis for site power.

Baseload Generation

Non-renewable baseload generation should only be considered where utility power is not available. This type of generation requires either a connection to existing natural gas lines or a constant supply of diesel fuel. In the case of diesel fuel, day tanks and bulk storage tanks would be required to ensure uninterrupted power.

Renewable, photovoltaic (PV) baseload generation coupled with a battery energy storage system (BESS) can be a viable option to supply most the site's power needs. This PV system would be sized roughly 12MW to power site and provide power to the BESS, which will be utilized when solar power does not meet demand. A connection to the utility power grid is still required as PV is an intermittent power source. A large PV system can be implemented without the use of BESS if grid interconnectivity is available to provide excess power to the local community. When PV cannot meet the demand of the campus, the utility would provide the required power. Where permitted, the utility may have net billing/inflow-outflow arrangements where excess power sent to the grid is sold and proceeds are deducted from the electricity bill. Financially, however, outflow rates are typically far less than inflow rates. PV site should be located close to the Corner Station to reduce costs associated with power cabling.

The project team should consider weighing scope of work of PV and BESS solutions with prospect or selected project site as these solutions are highly dependent on-site location and a deep evaluation is required to appropriately size PV and BESS solutions.

Backup Generation

Backup generators are required at Corner Station (CS) and Office Building (OB) to provide services in a utility loss-of-power event. Backup generators in remote locations are typically diesel generators; however, BESS can be a viable alternative. Though exact backup time is not specified in the Architectural Requirements document, diesel generators commonly come with fuel storage capacity to support 24 hours of run times; therefore, BESS is recommended to support full load for 24 hours. Clarification was provided that vibration from diesel generators on the Corner Station is not a concern, as backup generation will be used to maintain vacuum in the Beam Tube Enclosure and sensitive instrumentation does not require backup power. Diesel generation the least cost option; however, BESS is preferred as this helps meet sustainability goals.

The Corner Station is shown to have 1500kW demand and the Office Building requires 600kW. For 24-hours of backup time, and considering maximum BESS discharge of 50%, the required sizes are 72MWh BESS for the CS and 29MWh for the OB.

CS: The Corner Station is shown to have 1500kW demand. For this effort, 24-hours of backup is used and for BESS, a 50% depth of discharge is anticipated. This yields a BESS of 72MWh and a footprint of roughly 55,000 sqft. By comparison, a 1500kW diesel generator requires roughly 600 sqft.

OB: The Office Building is shown to have 600kW demand. For this effort, 24-hours of backup is used and for BESS, a 50% depth of discharge is anticipated. This yields a BESS of 29MWh and a footprint of roughly 23,000 sqft. By comparison, a 600kW diesel generator requires roughly 600 sqft.

Diesel generation does require refueling and has high emissions but with refueling can provide unlimited backup time, while BESS is finite. It is also worth noting, BESS is typically designed in 2-hour increments, with 2-hour and 4-hour being the most common sizes. The basis for the CS and OB is 24-hour. If BESS is desired, and desired backup time differs, the total storage size, cost, and footprint can be scaled linearly for a high-level estimate.

Communications

Hard wired communication between all buildings on site is anticipated for process equipment monitoring, alarming, and telemetry. Fiber optics is assumed to be the mode of transmission via fiber optic cable routing through underground duct bank, alongside power cables, but in a separate conduit. If poles are used to route power, fiber optic cabling can be installed on poles, lashed to a messenger wire.

5.3.3 Sustainability

See Section 6, Sustainable Design Principles.

5.3.4 Risks

Electrical infrastructure risks are related to reliability and resilience of the chosen path, equipment availability, schedule, cost variability, land availability for PV, and operational risks.

Equipment Lead Time

Electrical equipment lead times should not be a concern, as related to overall project timing. However, PV and BESS for full site baseload generation can be a multi-year project. Also, there is a small chance distribution level utility power is not within a reasonable distance to site. This will require a deeper evaluation and comparison of bringing utility power to site vs baseload generation for the selected site(s).

Power Generation

Utility power is considered the best option for site but if it isn't available, baseload generation must be considered. To support the site's power needs, diesel generation, reciprocating natural gas engines, natural gas fuel cell, or PV with BESS should be considered. It is likely that where distribution level utility power is not available, natural gas supply is also not available. For this, diesel generators with day tanks and bulk storage tanks are necessary.

Baseload PV with BESS in islanding scenario is also a risk as the systems can be designed using averages and worst-case scenarios; however, under sizing is still a possibility due to variability in solar conditions. This could cause an outage. To resolve this, grossly oversizing would be required. Land availability is also a risk as PV requires a large area and additional space beyond the project's minimal area may be required.

Cost Variability

High level cost estimates provide current estimated equipment pricing scaled to a particular year; however, equipment prices can be vastly different at the time of purchasing due to market conditions at that time. A deeper evaluation is required to support a tighter estimate during detailed design.

Operations

As power infrastructure equipment and complexity increases, operational requirements also increase. Required personnel become more difficult to find and corrective and preventative maintenance becomes costlier. Site location also can also make it more difficult to find qualified personnel.

5^{.4} ARCHITECTURE



5^{.4} ARCHITECTURE

5.4.1 Concept

Architectural concept for Cosmic Explorer (CE) is generated through the convergence of two formative forces, the scientific inquiry it enables and the environmental dynamics, particularly wind, that act upon the complex. These forces operate as primary ordering systems, informing the project's massing strategy, façade articulation, and material language. Rather than being site specific determinants, they function as universal architectural drivers, capable of being reinterpreted through local climatic conditions, regional constraints, and cultural contexts to produce a responsive yet coherent architectural expression.

5.4.2 Massing

To mitigate wind induced reverberation impacting sensitive scientific instrumentation, the massing of primary research buildings is conceived through tapered and curvilinear geometries that deflect and dissipate localized wind forces. These forms operate aerodynamically, allowing air currents to pass smoothly over and around the structures rather than accumulate against their façades. Analogous to the shaping of a race car body for optimized airflow, the architectural volumes are formally calibrated to minimize resistance and environmental disturbance.

Support buildings housing fewer sensitive functions adopt a more restrained formal strategy, relying on streamlined tapered forms that maintain visual and conceptual continuity with adjacent structures while accommodating functional efficiencies. Larger building volumes are perceptually scaled using inset wall planes and framed portals that articulate entry sequences and introduce depth and hierarchy to the façade. In select conditions, shading canopies extend between discrete building elements, reinforcing spatial connectivity, improving environmental comfort for users, and further modulating the apparent scale of the overall massing.

Figure 5.4.2 Corner Station



5.4.3 Articulation and Materials

The façades of the Cosmic Explorer buildings are articulated through a striated wall language that conceptually derives from the linear intensity and precision of the laser systems housed within the primary facility. This patterning operates as a formal abstraction of the scientific processes within, translating internal function into external expression. Horizontal striations extend along the façades of the main research buildings, reinforcing their longitudinal emphasis, while vertical striations are deployed on support buildings to establish a complementary yet differentiated architectural rhythm. These articulations introduce calibrated breaks in the massing, accommodating window systems and recessed reveals that generate shadow lines, modulate scale, and selectively frame visual connections along the exterior.

Figure 5.4.3 Wall Systems



On buildings containing sensitive scientific equipment, wall geometries are tapered, curved, or subtly sculpted in elevation to perform as aerodynamic surfaces that redirect wind forces and reduce environmental disturbance. In this way, façade form becomes an active mediator between environmental conditions and architectural performance rather than a purely representational surface.

Figure 5.4.4 Support Buildings



The exterior wall assemblies are conceived as high performance rainscreen systems supported by steel framing, enabling a thermally efficient and durable building envelope. Cladding is envisioned as a modular system composed of metal panels, glass fiber–reinforced concrete (GFRC), precast concrete elements or similar systems, allowing for precision fabrication offsite and efficient onsite assembly. High-performance insulated glazing units, integrated within window and curtain wall systems, introduce controlled daylight and outward visibility in regularly occupied spaces, balancing openness with environmental control. The façade color palette draws from subdued, natural tones informed by the surrounding landscape, situating the architecture within its regional context and producing an intentionally restrained visual presence that minimizes disruption to the broader population.

Figure 5.4.5 Wall Systems



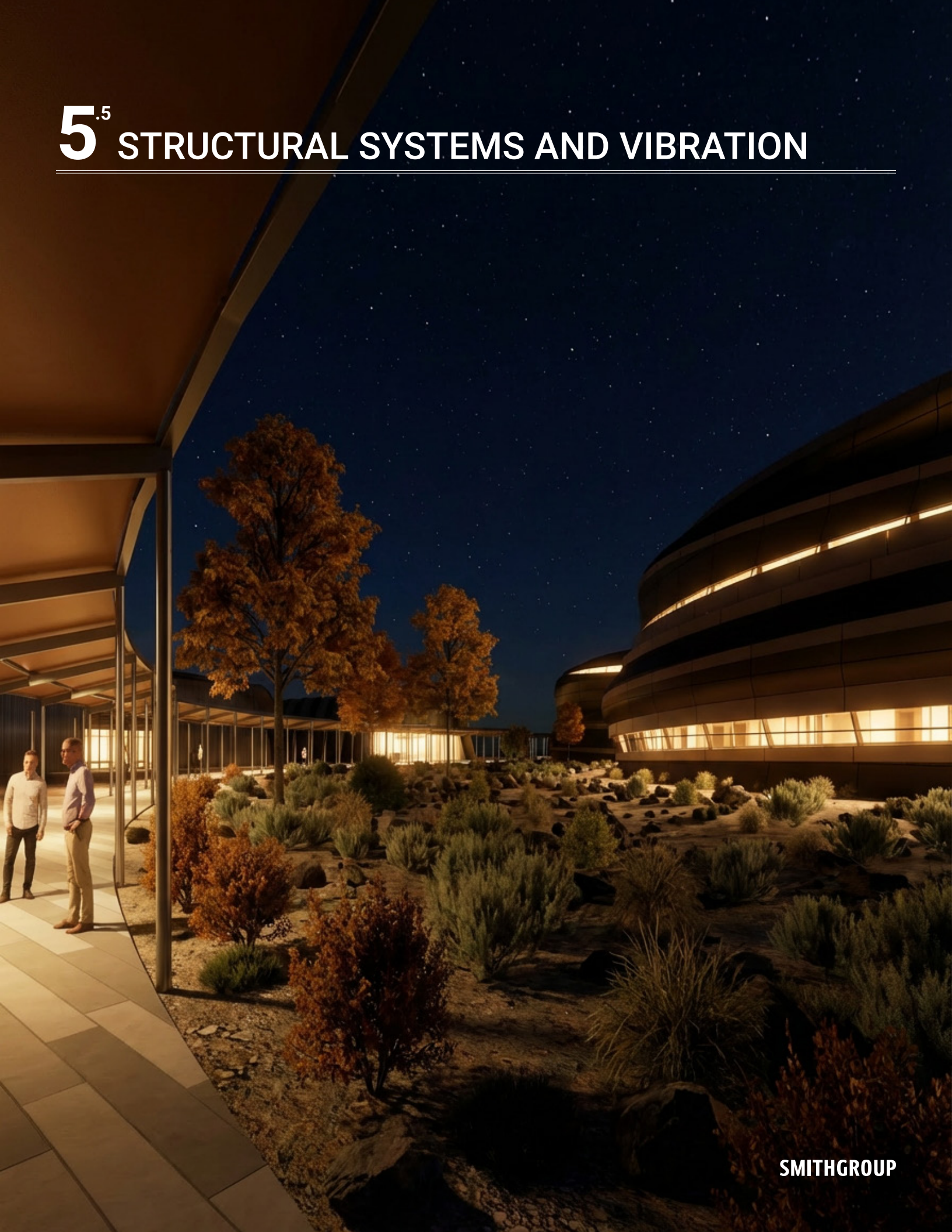
5.4.4 Sustainability

See Section 6, Sustainable Design Principles.

5.4.5 Risks

Availability of regional building materials and local skilled labor forces may impact the cost and feasibility of the architectural systems described above.

5^{.5} STRUCTURAL SYSTEMS AND VIBRATION



SMITHGROUP

5^{.5} STRUCTURAL SYSTEMS AND VIBRATION

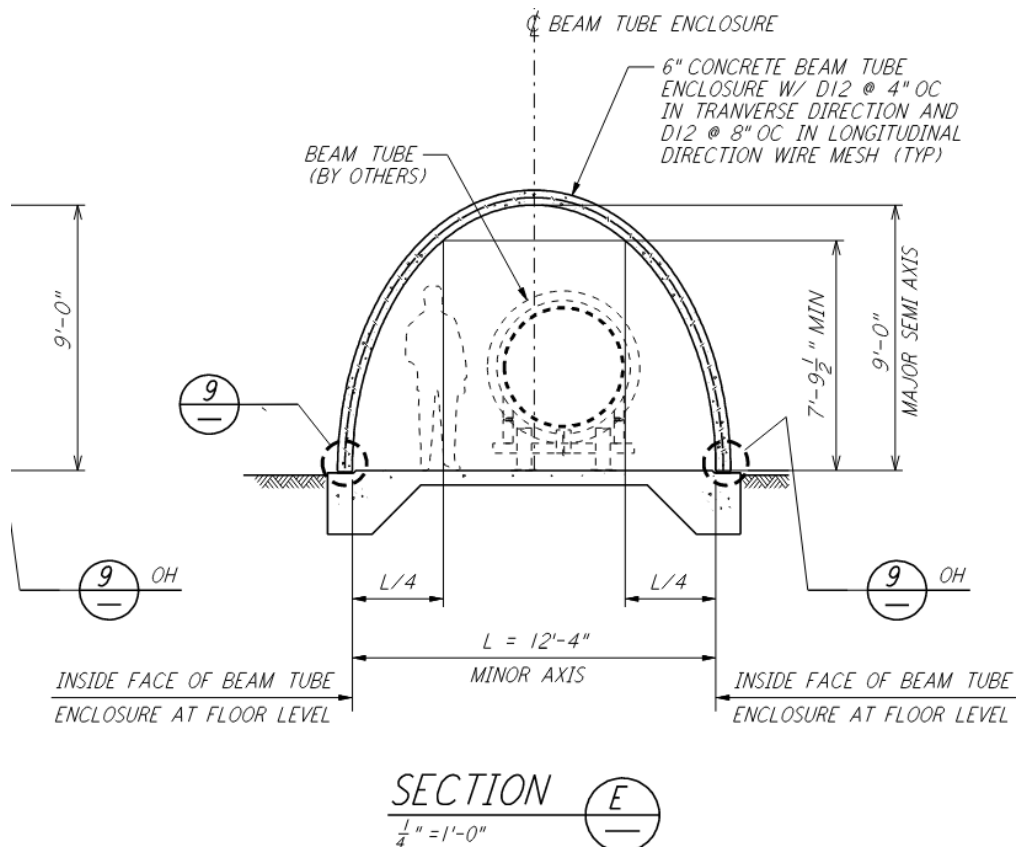
5.5.1 Overview

The Cosmic Explorer structures are comprised of three major components:

- Two 25-mile Beam Tube Enclosures (BTE) that house approximately one-meter steel beam tube that creates a vacuum environment for the laser beam line. The beam line terminates at mirrors which are suspended on pendulum support to protect from natural seismic rumblings which can interfere with the precision readings of the interferometer. Spaced along the beam line there are access ports and vacuum pumps which maintain the beam line environment.
- Corner Station and End Station complex that houses the laser, interferometer detectors and other support equipment.
- Low-rise research, offices, community center, and support buildings

5.5.2 Structural Systems

The Hanford LIGO facility, constructed in 1996, provides the best example of pre-cast concrete construction for the beam line tunnel (BTE) and support facilities (Mid Stations and Vacuum Valve Stations) as shown below. The structure features a thin shell precast concrete tunnel enclosure, cast in 10-foot-long segments which sits on a cast-in-place concrete base. Access tunnels and pump stations that are arrayed periodically along the length of the tunnels are also made of precast concrete shells, similar to how the tunnels are constructed.

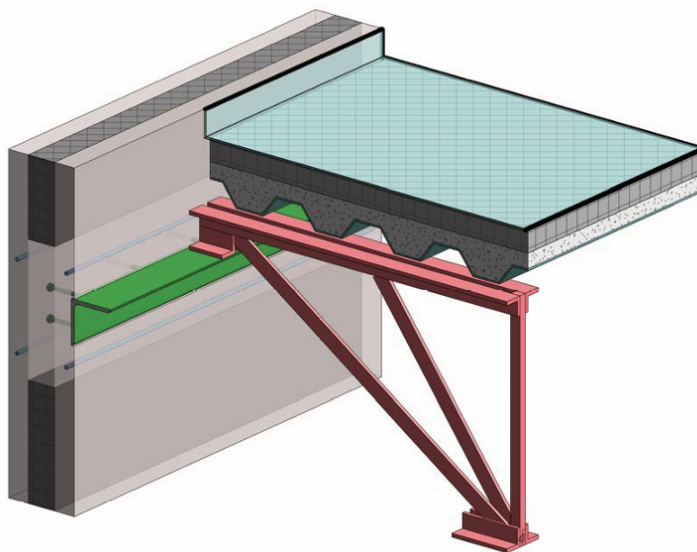


Precast concrete construction has significant advantages over other types of construction which include:

- High precision construction tolerances
- Extreme durability against environmental impacts including firearms
- Thermal mass which reduces fluctuations in tunnel temperature
- Excellent waterproofing to provide a dry environment for the steel tube line
- Access to competitive marketplace of suppliers not limited to the local of the facility
- Contribute to shorter construction schedules in the field as compared to stick-built system
- Ability to flexibly adapt to buried and overhead construction requirements to maintain a consistent beam line across the 25mile facility.

A comparable structural system for the low-rise central facilities and support buildings—offering many of the benefits of a precast tunnel system—is insulated precast architectural panels. These precast concrete panels function as load-bearing structure and insulated building envelopes, providing a practical and cost-effective solution for large-scale projects across a range of environments. The panels are typically cast in three layers:

- Exterior is 3inch precast concrete and can have a wide variety of finishes, colors, textures and architectural expression.
- Next layer is 3inch of insulation that provides a thermal break
- Final layer is 6inch of structural concrete that is load bearing for gravity and an extremely stiff structural system for wind and seismic loadings
- Interior surfaces are normally finished in the field with a shallow metal stud framing/gyp that improves sound performance and allows for electrical and plumbing utilities to run along the wall concealed.
- Excellent fire protection, which may be important in locals subject to wildfire fire hazards.
- Interior structure for the floors/roof system can be long span metal trusses or wide steel beams supported on steel columns. A concrete topping for the roof system is highly recommended to provide in-plane and out-of-plane support for the panels:



5.5.3 Vibrations

The laser system is most susceptible to external vibrations on the mirrors located at the terminus of each of the tunnels. These mirrors are protected against seismic earth rumblings by pendulums that tune out the vibrations in the range of instrument perception. However, even the best of systems can be overcome by ambient vibrations which maybe natural or man-made. Therefore, it is highly recommended that extended environmental studies be performed to investigate the range of ambient ground vibrations. Furthermore, there should also be zoning restrictions in place to prevent future construction adjacent to the mirror stations that would create adverse vibrations, such as freeway and train track right of ways.

Ambient ground vibration is a primary site-selection risk for the Cosmic Explorer due to the extreme sensitivity of the long laser interferometry system to low-frequency ground motion. Of particular concern is vibration in the approximately 0.1–1 Hz range, where natural microseisms, earth tides, and distant anthropogenic sources can induce differential motion along the baseline, affecting laser alignment, stability, and operational noise performance.

Candidate sites must be evaluated based on both baseline vibration levels and temporal variability, including seasonal increases in microseismic energy driven by ocean storms and weather systems. Short-duration measurements are insufficient; sites that appear acceptable under average conditions may still pose unacceptable operational risk during peak ambient vibration periods. Geological setting is a key determinant, with laterally continuous, competent rock formations generally providing more predictable vibration propagation and lower amplification than shallow, unconsolidated, or highly layered soils.

These vibration considerations directly inform siting and civil engineering decisions, particularly the preference for subsurface alignments over surface or elevated corridors. While surface facilities may offer lower initial capital cost, they are more exposed to wind, traffic-induced vibrations, temperature cycling, and future land-use changes. Subsurface siting, at appropriate depth, provides improved thermal inertia and mechanical shielding, reducing broadband ambient vibration, and improving long-term laser stability once lifecycle performance is considered.

Vibration risk also influences constructability and access strategies. Sites that require extensive ground treatment, aggressive groundwater control, or frequent changes in excavation method tend to exhibit less predictable vibration behavior and higher residual risk. In contrast, sites that support continuous construction using standard methods allow tighter control of construction-induced vibration and reduce uncertainty during both construction and operation.

From a site-selection perspective, the most favorable candidates are those where:

- Ambient vibration spectra already approach operational performance requirements or can be mitigated using well-established, passive design measures.
- Subsurface civil and tunnel configurations can be optimized to isolate the laser system from external vibration sources.
- Long-term ground and structural stability enables precise performance over decades, minimizing reliance on extensive active vibration control.

Long-span bridge structures, which are too flexible to control vibrations, can be avoided.

5.5.4 Sustainability

It is recommended that NRMCA Industry Wide LCA Project Report – V3.2 dated July 2022 be used to create the Global Warming Potential limits (GWP) on concrete mix designs for a more sustainable project. This document provides limits to the GWP for sustainable concrete mix design by regions that cover the entire continental United States. Reference Appendix for additional information.

5^{.6} MECHANICAL SYSTEMS



5^{.6} MECHANICAL SYSTEMS

5.6.1 Basis of Design

Heating, Ventilation, and Air Conditioning (HVAC) systems for the Cosmic Explorer Facility are governed by the need to provide exceptionally stable, low-vibration, and contamination-controlled environments for precision scientific instrumentation. These requirements coexist with a project mandate for site-agnostic, scalable, and durable solutions suitable for multiple potential locations within the continental United States.

The HVAC Basis of Design is informed by existing LIGO observatories (Hanford and Livingston), adaptations developed for LIGO-India, and expanded requirements associated with the increased scale, distributed geometry, and longer design life of Cosmic Explorer.

Codes, Standards, and Guidance

Final HVAC designs shall comply with all codes and regulations applicable at the selected site. For feasibility-level planning, the following nationally recognized standards are assumed:

- ASHRAE 55 – Thermal Environmental Conditions for Human Occupancy
- ASHRAE 62.1 – Ventilation for Acceptable Indoor Air Quality
- ASHRAE 90.1 – Energy Standard for Buildings Except Low-Rise Residential
- International Mechanical Code (IMC)
- International Energy Conservation Code (IECC)

Where conflicts arise between prescriptive code requirements and scientific performance needs (e.g., vibration, air change rates, humidity stability), performance-based solutions are anticipated.

Design Life and Reliability

All HVAC systems and major components shall be selected for a 50-year facility design life, with an emphasis on:

- Long-term maintainability
- Redundancy for critical spaces
- Ease of component replacement without disrupting scientific operations

5.6.2 Operating Modes and HVAC Implications

HVAC systems must support several distinct operating modes over the facility lifecycle:

Nominal Operation: Continuous scientific observation with minimal onsite staffing at beamline stations; stable and tightly controlled environmental conditions in VEAs.

Major Equipment Installation: Elevated occupancy, higher internal heat gains, and temporarily relaxed particulate or temperature criteria in select technical spaces.

Minor Equipment Installation: Short duration activities requiring flexible zoning and scheduling without wholesale system reset.

Systems are therefore designed with zoning, turndown capability, and operational flexibility as primary criteria.

5.6.3 Climate Zone and Site Considerations

The Cosmic Explorer project is siteagnostic at this stage, with candidate sites spanning multiple ASHRAE climate zones. Feasibility analysis has examined representative conditions including:

- Hot dry climates (e.g., Mineral Wells AP, TX)
- Cold and mixed climates (e.g., Havre CityCounty AP, MT)

HVAC strategies respond to climate variability by emphasizing:

- Condensation control over absolute temperature conditioning in lightly occupied spaces
- Robust humidification strategies in cold climates for cleanrooms and optical labs
- Economizer operation in dry or mild climates where compatible with cleanliness and vibration constraints

The extreme length of the beamlines (20 km and 40 km arms) inherently favors distributed mechanical systems rather than centralized plants.

Figure 5.6.1 ASHRAE Climate Zone map

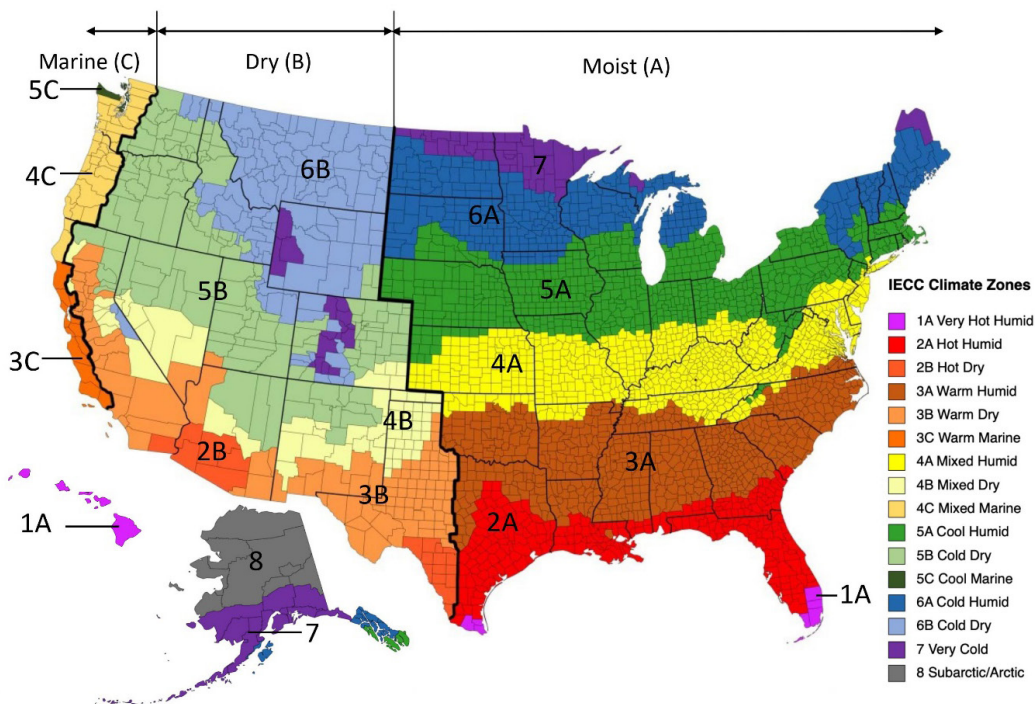
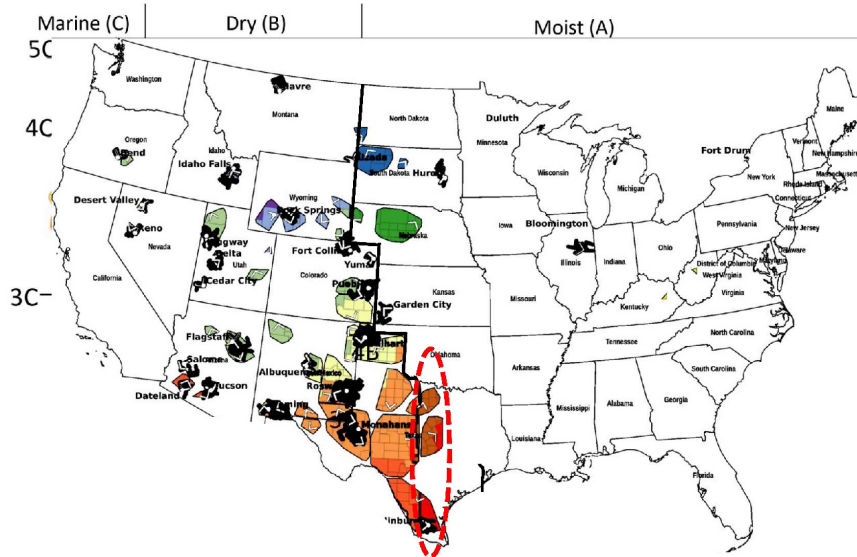


Figure 5.6.2 Proposed CE sites overlay with ASHRAE Climate Zone map indicating proposed sites located in zones 2A and 3A

ASHRAE CLIMATE ZONES



5.6.4 Environmental Design Criteria

Environmental criteria are differentiated by building type and function.

Vacuum Equipment Areas (VEAs)

VEAs are located at Corner Stations, End Stations, and Mid Stations and house the most vibration and contamination-sensitive equipment.

Design Criteria:

- Temperature: $68 \pm 1^\circ\text{F}$
- Relative Humidity: $55 \pm 5\% \text{ RH}$
- Cleanliness: ISO Class 8 (with ISO Class 7 in select clean and bake functions)
- Occupancy Category: Laboratory

VEA HVAC systems employ high-recirculation air handling with terminal HEPA filtration to maintain particulate control while minimizing outside air loads and pressure instability. Supply air velocities, duct construction, and diffuser selection are coordinated with vibration performance objectives.

Cleanrooms and Humidified Spaces (CS, SPS, ES)

Cleanrooms supporting optical preparation, staging, bake operations, and clean storage are provided primarily within the Corner Station and SPS buildings, with limited clean functions in End Station Support spaces.

Design Criteria:

- ISO Class: ISO 7 / ISO 8
- Temperature: $68 \pm 1^\circ\text{F}$
- Relative Humidity: $55 \pm 5\% \text{ RH}$

These criteria trigger requirements for tightly sealed building envelopes, vaporimpermeable interior finishes, and dedicated humidification systems. HVAC systems serving humidified zones are isolated from nonhumidified areas to mitigate condensation risk.

Shops, Equipment Rooms, and Support Spaces

Machine shops, electronics shops, storage, and general support spaces are designed for equipment protection rather than precision environmental control.

Typical Criteria:

- Temperature: 65–80°F
- Relative Humidity: <50% RH, non-condensing

Ventilation rates are determined based on occupancy classification, internal loads, and hazard classifications. Hazardous exhaust systems are provided where chemical use or particulate generation occurs.

Beam Tube Enclosure (BTE)

The Beam Tube Enclosure spans the full arm length and is not actively conditioned for temperature.

Design Objective:

- Maintain a non-condensing environment
- Maximum interior relative humidity <70% RH

Primary strategies is induced airflow with fans and ventilation openings at intervals to generate air movement through the tunnel length and prevent moisture accumulation.

Vacuum Valve Stations (VS)

Vacuum Valve Stations may require intermediate control between VEAs and the BTE via air volume separation.

Design Criteria:

- Temperature: $73 \pm 10^\circ\text{F}$
- Maintain a non-condensing environment
- Maximum interior relative humidity <70% RH

Airtight construction is required to maintain conditions with modest conditioning systems.

Corner Station Complex HVAC

The Corner Station Complex represents the most environmentally intensive portion of the Cosmic Explorer facility, combining Vacuum Equipment Areas (VEAs), cleanrooms, laboratories, control rooms, support spaces, and administrative areas within a single integrated campus.

HVAC systems serving the Corner Station are designed to accommodate:

- Multiple ISO 7 and ISO 8 cleanrooms with active humidification
- Large VEAs with the strictest temperature, humidity, and vibration requirements
- 24/7 occupied control rooms and operations spaces

Systems are zoned by cleanliness and humidity requirement, with humidified clean and VEA zones fully segregated from non-humidified offices, shops, and warehouses. Dedicated air handling units with high recirculation rates and terminal HEPA filtration are provided for VEAs and cleanrooms. General spaces are served by lower-intensity systems with broader thermal setpoints.

Mechanical equipment serving the Corner Station is physically separated from VEAs through the use of Substation and Chiller Yard (SCY) buildings located a minimum of 100–330 ft away to control structure borne vibration.

EQUIPMENT CATEGORY	TYPICAL SIZING / CAPACITY	BASIS / NOTES
VEA / Cleanroom Air Handling Units	8–15 cfm/sf of clean or VEA area; 40,000–80,000 cfm per AHU	High recirculation systems supporting ISO 7–8 environments
Terminal HEPA Filters	1 terminal per 200–350 sf	Density varies by cleanroom class and airflow intensity
Humidification Systems	0.8–1.2 lb/hr per 1,000 sf	Electric or adiabatic; drives envelope vapor control requirements
Heating/Cooling Plant (Heat Pumps or Equivalent)	250–350 tons per 100,000 sf	Includes redundancy; serves VEAs, cleanrooms, and support areas
Office & Support Space HVAC Units	1 ton per 350–500 sf	Packaged or split systems with relaxed control tolerances

End Station Complex HVAC

End Station complexes house Vacuum Equipment Areas, support and assembly spaces, Vacuum Valve Stations, and limited personnel support areas. Compared to the Corner Station, End Stations have reduced cleanroom area but maintain equally stringent requirements within VEAs.

HVAC systems at End Stations are characterized by:

- Dedicated VEA air handling systems maintaining $68 \pm 1^\circ\text{F}$ and $55 \pm 5\%$ RH
- Modest humidification loads relative to the Corner Station
- Simplified zoning due to lower occupancy and reduced program diversity

Support spaces and equipment rooms are conditioned using standard airsource heat pump systems with expanded temperature tolerances. As with the Corner Station, major HVAC equipment is remotely located to minimize vibration transmission.

Mid Station Complex HVAC

Mid Stations are distributed along each beamline and primarily support beam tube access, monitoring, and localized vacuum equipment. These facilities have minimal occupancy and limited sensitive program elements.

HVAC design priorities at Mid Stations include:

- Maintaining a non-condensing environment for beam tube interfaces
- Providing modest conditioning to support equipment reliability
- Minimizing system complexity and maintenance burden

Active humidification is generally not required except where local VEA or valve station functions dictate. Systems are sized for reliability rather than precision environmental control.

Main Campus HVAC

The Main Campus includes administrative offices, operations centers, laboratories, storage, and general support spaces. While not as environmentally sensitive as beamline facilities, the Main Campus supports continuous operations and extended staff occupancy.

HVAC systems serving the Main Campus:

- Meet standard ASHRAE comfort criteria for occupied spaces
- Include dedicated systems for laboratories and equipment rooms
- Are optimized for energy efficiency, zoning flexibility, and maintainability

Unlike beamline stations, Main Campus systems offer greater opportunity for conventional energy efficiency measures, heat recovery, and operational scheduling aligned with occupancy patterns.

EQUIPMENT CATEGORY	TYPICAL SIZING / CAPACITY	BASIS / NOTES
Unit AHUs / Packaged Units	2–4 cfm/sf of conditioned area; 5,000–15,000 cfm per unit	Simple, reliable systems for low-occupancy facilities
Dehumidification (if required)	0.2–0.4 lb/hr per 1,000 sf	Climate-dependent; provided only where condensation risk exists
Heating/Cooling Capacity	40–70 tons per 100,000 sf	Sized for equipment reliability, not tight comfort control
Exhaust Fans	1–3 ACH	As required by equipment use and hazard classification

5.6.5 Mechanical System Architecture

Decentralized Mechanical Systems

Given the extreme distributed geometry of the Cosmic Explorer facility and the stringent vibration-control requirements associated with precision interferometry, HVAC systems are intentionally decentralized by building and complex. Each Corner Station, End Station, Mid Station, and Main Campus building group is served by its own dedicated mechanical systems rather than a single centralized plant.

This approach provides several critical benefits:

- Limits structure-borne vibration transmission to sensitive Vacuum Equipment Areas (VEAs)
- Enhances overall system resilience by avoiding single points of failure
- Supports phased construction, commissioning, and future expansion
- Simplifies longterm maintenance over the 50-year facility life

Major mechanical equipment—including heat pumps, chillers (if required), pumps, and electrical gear—is housed in Substation and Chiller Yard (SCY) buildings located approximately 100–330 ft from VEA structures, consistent with WS3 planning assumptions. Physical separation, inertia bases, spring isolators, and flexible connections are assumed for all rotating equipment.

Heating and Cooling Strategies

The baseline HVAC energy strategy for Cosmic Explorer is allelectric, reflecting longterm decarbonization goals and alignment with potential ILFI Zero Carbon certification. Feasibility-level system planning assumes the following:

- Airsource heat pumps as the primary means of heating and cooling at all complexes
- Electric resistance heating for supplemental capacity, trim heating, and contingency scenarios

System selection remains intentionally flexible to accommodate site-specific optimization during later design phases. Alternatives under consideration include:

- Ground-source heat pump systems where subsurface and landuse conditions are favorable
- Centralized heatpump plants with distributed hydronic loops within a complex
- Radiant floor heating systems in VEAs and cleanrooms to improve thermal stability and further reduce vibration and airflow-induced noise

Radiant systems are of particular interest for VEAs due to their potential to decouple thermal control from airflow, though their feasibility depends on integration with cleanliness and humidity requirements.

Air Distribution, Ventilation, and Filtration

Air distribution strategies are differentiated by space function:

- VEAs and cleanrooms utilize high-recirculation airhandling systems with terminal HEPA filtration to maintain ISO-classified environments while minimizing outside air loads and pressure instability.

- Support, office, and campus spaces are served by conventional variable-air-volume (VAV) or zoned constant-volume systems with broader thermal tolerances.

Minimum ventilation rates meet or exceed ASHRAE 62.1, with additional air change requirements driven by cleanliness classification, heat rejection, or hazard designation. High-efficiency filtration (minimum MERV13, with HEPA filters at terminals where required) is provided to protect both occupants and sensitive equipment.

Exhaust and relief systems are provided for laboratories, chemical handling areas, shops, and other hazardous spaces as dictated by code and hazard classification studies. Recirculation permissibility is evaluated on a space-by-space basis during later design phases.

Humidity Control and Zoning

Spaces requiring 55 ±5% RH (cleanrooms and VEAs) are served by dedicated or fully segregated airhandling systems to limit moisture migration and condensation risk. Humidification strategies may include electric steam or adiabatic systems, subject to water quality and reliability considerations.

Non-humidified spaces are isolated at both the system and envelope level. Airtight construction, continuous vapor barriers, and pressure-differential control are treated as integral components of the HVAC design.

Controls Integration

All HVAC systems are integrated into a centralized Building Automation System (BAS), providing:

- Continuous monitoring of temperature, humidity, pressure relationships, and equipment status
- Remote operation, alarming, and diagnostics for geographically isolated stations
- Control strategies prioritizing environmental stability over aggressive energy optimization

Given the scientific sensitivity of the facility, control algorithms emphasize steady-state stability, slow response tuning, and fault tolerance rather than following rapid load changes. The CE science team should develop a specification for air pressure fluctuations (i.e., infrasonic noise level).

5.6.6 Sustainability

The HVAC design strategies for Cosmic Explorer support longterm sustainability and decarbonization goals while recognizing the constraints imposed by scientific performance requirements.

Key sustainability principles include:

- All Electric HVAC Systems
 - Elimination of onsite fossil fuel combustion
 - Primary use of airsource heat pumps for heating and cooling
 - Alignment with future grid decarbonization and potential ILFI Zero Carbon objectives
- Energy Efficiency Within Scientific Constraints
 - High-recirculation airhandling systems for VEAs and cleanrooms to minimize outside air loads
 - Zoning and turndown capabilities to reduce energy use during low-occupancy or noncritical modes
 - Selective consideration of heat recovery where compatible with cleanliness, humidity, and vibration limits
- Compatibility with Site-Wide Energy Systems
 - Integration with onsite renewable energy generation and battery storage
 - Distributed plant configuration enabling phased upgrades and future micro-grid operation
- Water Use Awareness
 - Careful selection of humidification technologies based on site water availability, water quality, and maintenance burden

- Long-Term Adaptability
 - Conceptual system definitions that allow incorporation of future high-efficiency HVAC and control technologies over a 50-year facility life

5.6.7 Risks

HVAC-related risks at the feasibility stage reflect the scale, longevity, and environmental stability requirements of the Cosmic Explorer Facility.

Primary risks include:

- Climate and Site Uncertainty
 - Variability in heating, cooling, humidification, and dehumidification demands depending on final site selection
 - Uncertainty in economizer applicability and annual energy performance until climate is finalized
- Vibration and Acoustic Sensitivity
 - Potential for structure-borne and airflow-induced vibration to affect interferometer performance
 - Dependence on conservative equipment placement, isolation strategies, and airflow velocities
- Humidity Control and Condensation
 - Risk of envelope condensation and moisture migration in spaces maintaining $55 \pm 5\%$ RH
 - Requirement for tight coordination between architectural envelope design and HVAC systems
- Energy Intensity and Operational Cost
 - High energy demand driven by continuous operation and stringent environmental control
 - Sensitivity to longterm electricity pricing and grid reliability
- Technology Obsolescence
 - Risk of equipment obsolescence over a 50-year operational horizon
 - Need for modular systems, standardized components, and flexibility for future upgrades

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5^{.7} PLUMBING SYSTEMS



5^{.7} PLUMBING SYSTEMS

5.7 Overview

The Cosmic Explorer (CE) observatory is a large, distributed scientific campus extending up to 80 km in total length, composed of a main campus and multiple remote station complexes located along two interferometer arms. Plumbing systems must therefore support:

- A wide range of occupancies, from continuously occupied office and operations buildings to intermittently occupied technical stations
- Remote facilities lacking access to municipal utilities
- Long linear infrastructure runs
- Phased construction and longterm operations (50-year design life)

All plumbing systems shall be designed with a focus on reliability, maintainability, water conservation, and adaptability to arid or semi-arid environments, consistent with the precedent of existing LIGO facilities and the site utility strategies outlined in feasibility documentation.

5.7.1 Domestic Water Systems

5.7.1.1 Water Supply Basis of Design

Domestic water supply for the CE Facility shall be provided through a combination of municipal connections and on-site water systems depending on building type and location:

- Main Campus Buildings (OSB, OB, CEB): Assumed connection to a municipal potable water system where available
- Corner Station and End Stations: Municipal water preferred; otherwise on-site groundwater wells with treatment and storage
- Mid Stations and Vacuum Valve Stations: On-site groundwater wells or hauled water with localized storage

Where on-site water systems are required, the plumbing design shall include:

- Groundwater supply wells
- Filtration and disinfection systems suitable for potable use
- Above- or below-grade potable water storage tanks
- Distribution pumps sized for domestic demand and fire protection reserves

Water demand assumptions are occupancy-driven, consistent with the architectural requirements identifying primarily intermittent and low-occupancy use at beamline facilities.

5.7.1.2 Distribution Systems

Domestic water distribution systems shall be designed to serve:

- Plumbing fixtures and building support spaces
- Fire protection systems (where required by code)
- Limited process and equipment support (e.g., janitorial, cleaning, eyewash)

The following distribution principles apply:

- Looping of campus and station water mains where feasible to improve resiliency
- Isolation valves provided at each building and major branch

- Freeze protection based on local climate assumptions
- Pipe materials selected for durability, corrosion resistance, and constructability

At the feasibility level, distribution piping is assumed to consist of a combination of ductile iron, HDPE, copper, or approved plastic piping depending on size, burial depth, and exposure conditions.

5.7.2 Sanitary Waste and Vent Systems

5.7.2.1 Sanitary Wastewater Strategy

Sanitary wastewater systems shall be designed based on plumbing fixture load, building occupancy, and site utility availability:

- Main Campus Buildings: Gravity sanitary sewer connected to municipal systems where available
- Corner and End Stations: Municipal sewer where available; otherwise onsite wastewater treatment systems
- Mid Stations and Vacuum Valve Stations: Individual or clustered septic systems with drainfields

Feasibility documentation explicitly anticipates septic and drainfield systems at midstation locations due to their remote placement and low occupancy.

All onsite wastewater systems shall be designed to accommodate peak installation phase occupancies while remaining efficient during long periods of minimal use.

5.7.2.2 Venting Systems

Sanitary vent systems shall be designed in accordance with applicable plumbing codes once the AHJ is identified. Venting strategies shall:

- Maintain trap seal integrity
- Minimize roof penetrations in vibration sensitive buildings
- Be coordinated with architectural, structural, and mechanical systems

5.7.3 Laboratory and Specialty Utility Systems (Lab Gases, Vacuum, Compressed Air)

CE facilities include multiple program elements that are typically supported by laboratory utility piping and specialty services, including clean labs, an Optics Laboratory, Electronic Testing and Maintenance Labs, and a Vacuum Preparation Lab located within the Operations Support Building (OSB) program. In addition, the beamline station complexes (Corner, End, Mid, and Valve Stations) house vacuum infrastructure and vacuum equipment as part of the scientific vacuum system.

Accordingly, the plumbing discipline shall include feasibility level criteria and allowances for the following building utility systems where required to support these lab programs:

- Compressed air / instrument air (for lab tools, pneumatics, and maintenance activities)
- Laboratory vacuum (for bench equipment and small vacuum services distinct from the scientific beamline vacuum)
- Laboratory/process gases (e.g., inert gases for purging, testing, and laboratory work), if required by the final lab program

At this phase, gas types, quantities, pressures, or purity classes are not detailed; therefore, these systems are defined as parametric provisions to be confirmed during later design once detailed lab equipment lists and the scientific vacuum system interface requirements are finalized.

5.7.3.1 System Concepts and Design Criteria

Compressed Air / Instrument Air (Utility Air)

- Provide centralized compressed air (or localized packaged compressors where justified) serving lab and maintenance points of use in the OSB and other facilities that include shop/lab functions.
- Use oil free or coalescing filtration as required to protect sensitive lab equipment (final quality class to be confirmed).
- Provide isolation valves by zone and by lab area; route piping to minimize vibration and noise transfer into vibration sensitive spaces.
- Provide condensate management for compressors and distribution mains (drain points, traps, and/or automatic drains), coordinated with sanitary or dedicated condensate disposal strategy.

Laboratory Vacuum (House / Utility Vacuum)

- Where required by lab program, provide a utility vacuum system for bench-level equipment separate from the scientific beamline vacuum system.
- Conceptually, utility vacuum can be provided by:
- Central vacuum pumps located in a mechanical/service room with mufflers and vibration isolation, or
- Localized point-of-use vacuum pumps where centralization is not justified.
- Provide backflow/contamination prevention appropriate to lab use (final details to be confirmed).
- Provide vents/exhaust routing consistent with the architectural requirement to minimize adverse impacts to clean and sensitive spaces.

Laboratory / Process Gases

- Carry a program allowance for laboratory gases in the OSB lab areas (Optics, electronics testing, vacuum preparation) where such gases are typically required for purging, testing, and instrument support.
- At feasibility level, the preferred strategy is cylinder-based storage with manifolds and/or small bulk dewars where warranted, located in code-compliant, ventilated gas storage areas. Final selection depends on the confirmed gas list and consumption rates.
- Provide gas distribution via hard piping to designated labs only if required by the confirmed program; otherwise, plan for cylinder change-out and localized regulators.
- Incorporate safety provisions in design criteria (ventilation, leak detection/alarms where required, separation of incompatible gases, and emergency shutoff concepts) to be finalized with AHJ requirements and confirmed hazard classifications.

5.7.4 Building Specific Plumbing Systems

5.7.4.1 Main Campus Buildings

Operations Support Building (OSB)

The OSB has the highest sustained plumbing demand on campus and shall include:

- Code-compliant restrooms sized for approximately 20 full-time staff plus visitors
- Service sinks, janitorial closets, and laboratory support plumbing
- Emergency eyewash and safety fixtures where required

Systems shall be designed for frequent daily use, ease of maintenance, and adaptability to future program changes.

Office Building (OB)

The Office Building shall include:

- Office-grade restroom facilities
- Breakroom sinks and drinking water fixtures
- Plumbing sized for approximately 150 occupants (40 km site) or 100 occupants (20 km site)

Low flow fixtures shall be used throughout to minimize potable water demand.

Community / Education Building (CEB)

The CEB shall accommodate large but intermittent occupancy and shall include:

- Public restrooms sized for up to 200 visitors
- Drinking fountains and bottle filling stations
- Plumbing for exhibit and classroom support areas

Peak event occupancy governs fixture counts and supply sizing.

5.7.5 Sustainability

Plumbing sustainability strategies for the CE Facility include:

- High-efficiency, low-flow plumbing fixtures throughout all buildings
- Minimization of potable water use at remote stations
- Evaluation of greywater reuse and condensate recovery where permitted
- On-site storage optimization to reduce pumping energy
- Alignment with broader CE sustainability and renewable energy goals

Water conservation is a critical driver, particularly given the likelihood of arid site locations analogous to LIGO Hanford.

5.7.6 Risks

Key plumbing-related risks identified at the feasibility stage include:

- Uncertainty in municipal utility availability
- Variability in groundwater depth, yield, and quality
- Regulatory differences across potential host jurisdictions
- Long linear piping runs increasing leakage and maintenance risk
- Integration with vibration-sensitive scientific facilities
- Fire protection water storage volume requirements impacting site layout and cost

These risks underscore the need for modular, resilient plumbing solutions and confirm that final system designs must be refined after site selection and geotechnical investigation.

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5^{.8} FIRE PROTECTION SYSTEMS



5^{.8} FIRE PROTECTION SYSTEMS

5.8.1 Fire Protection Systems

5.8.1.1 Overview

This section defines the fire protection design criteria for the Cosmic Explorer (CE) facility, based exclusively on the CE Facility Architectural Requirements (CE-T2500017) and the Feasibility Study workshop materials. The intent is to protect life, preserve mission-critical scientific assets, and support safe emergency response across a geographically extensive, low-occupancy research campus composed of surface buildings, semi-buried and buried spaces, and long linear beamline infrastructure.

CE facilities are characterized by controlled access, trained personnel, and generally low occupancy during normal operations, with temporary increases during installation and maintenance periods. This operational profile supports a life safety strategy emphasizing early detection, clear emergency notification, controlled egress, compartmentation, and emergency access, rather than continuous public-occupancy assumptions.

All fire protection and life safety systems are defined at a feasibility-study level and are intentionally site-agnostic. Final system types, capacities, and code triggers will be confirmed once specific jurisdictions and Authorities Having Jurisdiction (AHJs) are identified during site selection.

5.8.1.2 Codes, Standards, and General Assumptions

For the purposes formulating cost model and concept planning, life safety and fire protection systems are assumed to comply with the building codes and regulatory requirements applicable at the final site. Where site-specific requirements are not yet known, nationally recognized U.S. model codes and standards are used as a baseline.

In accordance with the CE Facility Architectural Requirements, all buildings are assumed to include, as a minimum:

- Fire detection and alarm systems, including smoke detection and manual pull stations
- Audible and visual alarm notification devices

The need for automatic fire suppression systems (e.g., sprinklers or alternative systems) will be determined during site-specific code analysis. No radioactive or explosive materials are used in CE facilities, and only limited quantities of solvents and other combustibles are anticipated; therefore, no extraordinary hazardous material fire protection measures are currently assumed.

5.8.2 Fire Protection

- Selection of suppression systems will consider ceiling heights, crane operation, compartment sizes, and coordination with structural and architectural systems.
- System Description
 - All buildings will be provided with a fire protection system. Conditioned spaces will be provided with an automatic wet-pipe sprinkler system. Unconditioned, enclosed spaces and exterior spaces will be provided with an automatic dry-pipe sprinkler system.
 - Clean agent (gaseous) fire suppression systems will be provided for sensitive equipment areas, including server rooms, laboratories, and laboratory equipment rooms. Double-interlock preaction systems may also be provided in lieu of wet-pipe sprinkler systems in these rooms and areas.
 - A standpipe system is not anticipated for any of the buildings. Final determination of whether or not a standpipe system is required shall be made once a site is selected.

- **Water Supply**
 - Dedicated fire water storage tanks and fire pump room facilities are explicitly included at End Station and Corner Station complexes as part of the Pump Room and Water Tank Building (PRB). Fire water volumes, pump capacities, and redundancy requirements will be confirmed during sitespecific design in coordination with local codes and responding fire departments. For feasibilitylevel planning, fire water infrastructure is assumed to be selfsufficient and capable of supporting both suppression systems and emergency response operations.
 - The tanks shall be sized to accommodate the largest hydraulic demand plus a safety factor. The final size for the tanks shall depend on the number of tanks provided, hydraulic demand of each building, and local AHJ requirements.
 - Recycled water may be used in wet-pipe sprinkler systems if permitted by the local jurisdiction.
- **Fire Pump**
 - A fire pump is anticipated for the Corner Station (CS) and Observations Support Building (OSB) based on the anticipated use and available water supply.
 - The fire pump may be an electric-driven or diesel-driven motor. If an electric fire pump is used, normal and emergency power for the fire pump shall be provided via an on-site generator.
- **Design Criteria**
 - Sprinkler design criteria shall be in accordance with NFPA 13, local AHJ requirements, and the owner’s insurance requirements as applicable. See below for applicable design criteria.

Hazard Classification	Rooms or Areas	Design Density	Maximum Sprinkler Spacing
Light	Offices, conference rooms, auditorium, circulation	0.10 gpm over 1500 sq. ft.	15 ft x 15 ft (225 sq. ft)
Ordinary, Group 1	Laboratories, storage rooms, MEP spaces	0.15 gpm over 1500 sq. ft.	15 ft x 15 ft (130 sq. ft)
Ordinary, Group 2	Machine shops, repair shops	0.20 gpm over 1500 sq. ft.	15 ft x 15 ft (130 sq. ft)

5.8.3 Fire Alarm

- **System Description**
 - All buildings on the site will be provided with a fire alarm and detection system equipped with emergency voice/alarm communication. Fire alarm systems will be networked where appropriate to allow centralized monitoring, particularly at the Main Campus and Operations Support Building. Given the distributed nature of the site and periods of minimal staffing, alarm systems are assumed to support offsite monitoring and notification to ensure timely response when buildings are unoccupied.
 - If required by the owner, the fire alarm system may be combined with building mass notification systems. Further coordination with the owner and AHJ is required to determine if this is necessary.
- **Initiation**
 - Initiation methods will include smoke detection, sprinkler water flow, and manual pull stations. A very early smoke detection apparatus (VESDA) system shall be provided in areas protected by preaction and clean agent fire suppression systems.
 - Early smoke detection and radiant energy fire detectors are recommended for areas where Lithium-

ion batteries are used or stored in order to detect early signs of fire. Off-gassing detectors may also be considered to detect early signs of thermal runaway in battery storage areas.

- Low-frequency smoke alarms shall be provided in staff sleeping areas.
- Notification
 - Visual notification shall be provided through all occupiable areas of the buildings. Visual notification will be provided via strobes and combination speaker/strobe appliances. The spacing and candela ratings of visual notification appliances shall be provided in accordance with NFPA 72.
 - Audible notification will be provided via speakers and speaker/strobe appliances. Speakers will be located to provide audibility throughout all buildings and enclosed exterior areas. Intelligibility will be provided throughout all public areas and where required by NFPA 72.
- Secondary Power
 - Distributed generation and backup power systems identified for major facilities will be coordinated to maintain life safety functionality during utility outages. Battery backup shall be provided via batteries to provide a minimum of 24 hour backup power during standby conditions and 15 minutes in alarm. An on-site generator is provided may be used to provide additional power to the fire alarm system.
- Supervision and Monitoring
 - The fire alarm system shall supervise the building fire protection systems, including the fire water storage tanks. Life safety equipment, including generators, fire pumps, and emergency communications systems, will also be supervised by the fire alarm system.

5.8.4 Risks

Key life safety and fire protection risks identified at the feasibility stage include:

- **Jurisdictional uncertainty:** Final code requirements will depend on the selected site and AHJ, potentially affecting system scope, redundancy, and cost.
- **Fire water availability:** Large on-site storage requirements may impact site planning and constructability, particularly in arid regions.
- **Equipment sensitivity:** Fire suppression strategies must balance life safety with the risk of damage to high-value scientific equipment.
- **Emergency response logistics:** The extreme length and distributed nature of the beamlines require careful coordination of access and response strategies.

These risks will be addressed through early AHJ engagement, detailed code analysis during site selection, and close coordination across architectural, civil, structural, and MEP disciplines in subsequent design phases.

5^{.9} ELECTRICAL AND LIGHTING



SMITHGROUP

5^{.9} ELECTRICAL AND LIGHTING

5.9.1 Overview

The Cosmic Explorer (CE) observatory requires substantial electrical service distributed over long distances to support Corner Stations, End Stations, Mid Stations, Vacuum Valve Stations, Beam Tube Enclosures (BTEs), and the Main Campus. A buried medium-voltage distribution system running along the beamline supplies these facilities.

For feasibility planning, a buried 13 kV electrical distribution line is assumed to run along each beamline arm to provide power to station complexes and to support both normal operation and occasional high-demand activities, such as vacuum system bake-out. Substations located within station complexes step voltage down to utilization levels appropriate for building systems and equipment.

5.9.2 Codes, Standards and Guidance

All electrical and lighting systems are assumed to comply with applicable electrical, building, energy, and life safety codes in effect at the final project sites. Where site-specific requirements are not yet known, nationally recognized U.S. standards are assumed as a baseline. Designs will also accommodate requirements associated with worker safety, emergency egress, lightning protection, grounding of sensitive equipment, and integration with fire protection and life safety systems. ADAAG - Americans with Disabilities Act Accessibility Guidelines.

- ANSI - American National Standards Institute, Inc.
- NEC – National Electrical Code
- IECC – International Energy Conservation Code
- OSHA - Occupational Safety Hazard Authority
- FM - Factory Mutual (dependent on Owner and NSF requirements)
- NFPA - National Fire Prevention Association
- UL - Underwriter’s Laboratories, Inc.

5.9.3 Electrical Service and Site Power Distribution

Station-Level Distribution

Each major station complex includes a dedicated Substation and Chiller-Yard (SCY) building housing electrical transformers, switchgear, and distribution equipment. These SCY facilities are intentionally located away from sensitive experimental halls to minimize vibration and electromagnetic interference.

Secondary power distribution is anticipated at 277/480-volt, 3-phase, 4-wire that originates from the building main switchgear and is routed throughout the building via electrical feeders to switchboards, distribution panelboards, lighting panelboards and step-down transformers. 120/208-volt power is distributed through distribution panelboards on the secondary of step-down transformers to branch circuit panelboards throughout the building.

Mechanical system loads are anticipated to be served by 277/480-volt, 3-phase, 4-wire power panelboards located in mechanical rooms equipment rooms and utility yards.

Experiment loads are served by 277/480-volt, 3-phase, 4-wire power panelboards and 120/208- volt, 3-phase, 4-wire panelboards.

Electrical capacity assumptions by facility type include:

Corner Station Complex: Total estimated connected load on the order of 1,200 kW, including experimental equipment, HVAC, and ancillary loads.

End Station Complexes: Approximately 200 kW per station, plus HVAC and supporting systems.

Mid Station Complexes: Approximately 150 kW per station, plus HVAC and supporting systems.

Vacuum Valve Stations: Approximately 50 kW per station, primarily for vacuum equipment and local HVAC.

Beam Tube Enclosures: Approximately 100 kW continuous load per arm for normal operations, with significant temporary demand during bake-out activities.

Main Campus Buildings: Loads associated with office, operations, community, and educational functions, including server rooms and workshops.

These values are planning-level estimates and will be refined during detailed design and site selection.

BTE High-level Electrical Requirements

Normal Operating and Maintenance Power

Each pump port shall be provided with the following electrical infrastructure to support routine operations and maintenance:

- Five (5) 120 V, 20 A outlets
- Two (2) 240 V, 40 A outlets

This infrastructure shall support roughing pumps, turbo pumps, 1000 L/s ion pumps, and leak-checking equipment.

The electrical load at any single pump port shall not exceed 15 kW under normal operating conditions. The total connected load for all pump ports on a single beamline arm shall not exceed 100 kW.

Temporary and Specialized Power for Bake-Out

The BTE shall also accommodate a one-time or infrequent (e.g., once per decade) specialized electrical demand of up to 500 kW for vacuum bake-out activities. This power shall be available at multiple designated beamline stations, including:

- End Stations
- Mid Stations
- Vacuum Valve locations

Bake-out power will be supplied via temporary electrical installations connected to a buried 13 kV power distribution line running along the beamline. This distribution line is required to ensure adequate capacity to support these high-demand, short-duration activities.

CS High-level Electrical Requirements

The Corner Station (CS) will require substantial electrical and HVAC infrastructure to support its operations. Under normal operating conditions, the total estimated electrical demand is approximately 1,200 kW.

The primary loads are as follows:

- VEA systems: 150 kW under normal conditions, with 10 kW supported by backup distributed generation (DG).
- HVAC and heating systems: 1,000 kW under normal conditions, with 300 kW supported by DG.
- Site office: 40 kW under normal conditions, with 20 kW supported by DG.
- External road lighting: 10 kW (not supported by DG).

The 1,200 kW total represents the combined normal operating load of all systems. Backup DG capacity shall be selectively allocated to critical functions to ensure continuity during power outages.

MS High-level Electrical Requirements

Each mid station is anticipated to have a peak electrical demand of approximately 150 kW, consisting of 50 kW of base station load and an additional 100 kW for HVAC and occupant requirements.

VS High-level Electrical Requirements

Each vacuum valve station is anticipated to have a peak electrical demand of approximately 50 kW, consisting of 30 kW of base station load and an additional 20 kW for HVAC requirements.

SPS High-level Electrical Requirements

Under normal operating conditions, the SPS requires an electrical supply of 150 kW. An additional 25 kW of distributed generation capacity is needed to meet estimated peak demand.

MEV High-level Electrical Requirements

The MEV will require an electrical supply of 150 kW.

5.9.4 Lighting Systems

Interior Lighting

Interior lighting systems will be designed to support safe operation, maintenance, and occasional installation activities while minimizing heat generation, power consumption, and electromagnetic interference. Lighting requirements vary widely by space type:

- Experimental and technical spaces: Functional task and area lighting coordinated with equipment layouts and crane operations.
- Mechanical and utility spaces: Code-compliant illumination levels for safe maintenance and inspection.
- Office, support, and educational spaces: Lighting appropriate for administrative, control room, educational, and visitor uses.

Lighting controls will support occupancy patterns characterized by low routine staffing in many areas and intermittent high activity during installation periods.

Exterior and Site Lighting

Exterior lighting will be provided to support safe movement of personnel and vehicles within station complexes and the Main Campus while minimizing light pollution and disturbance to surrounding environments. Exterior lighting includes:

- Building entry and exit lighting
- Roadway and parking area lighting at stations and campus areas
- Security and wayfinding illumination

Given the sensitivity of the scientific mission to environmental disturbances, exterior lighting levels will be carefully controlled, with emphasis on shielding, fixture selection, and zoning to limit unnecessary illumination.

Beam Tube Enclosure Lighting

Lighting within the BTE is required primarily for inspection and maintenance access. Given the low occupancy and linear geometry of the enclosure, lighting systems will emphasize durability, ease of maintenance, and minimal heat generation. Continuous fulllength illumination is not assumed; instead, lighting will be coordinated with access points and maintenance activities.

Integration with Life Safety Systems

Electrical and lighting systems are closely integrated with fire protection and life safety systems, providing power for fire detection, emergency notification, and egress lighting. Electrical system zoning and redundancy will support continued operation of these functions during fault and outage conditions.

5.9.5 Sustainability

Electrical and lighting system design supports CE sustainability goals by emphasizing efficient power distribution, durable infrastructure, and compatibility with future clean-energy strategies. Use of buried medium-voltage distribution minimizes visual impacts and enhances long-term reliability. Task-appropriate lighting and controlled exterior illumination reduce operational energy use and environmental disturbance.

The electrical infrastructure is intentionally flexible to allow integration of future on-site or off-site clean energy resources, consistent with sustainability frameworks discussed in the feasibility study. Coordination between electrical distribution, distributed generation, and energy monitoring lays the groundwork for long-term energy optimization.

5.9.6 Risks

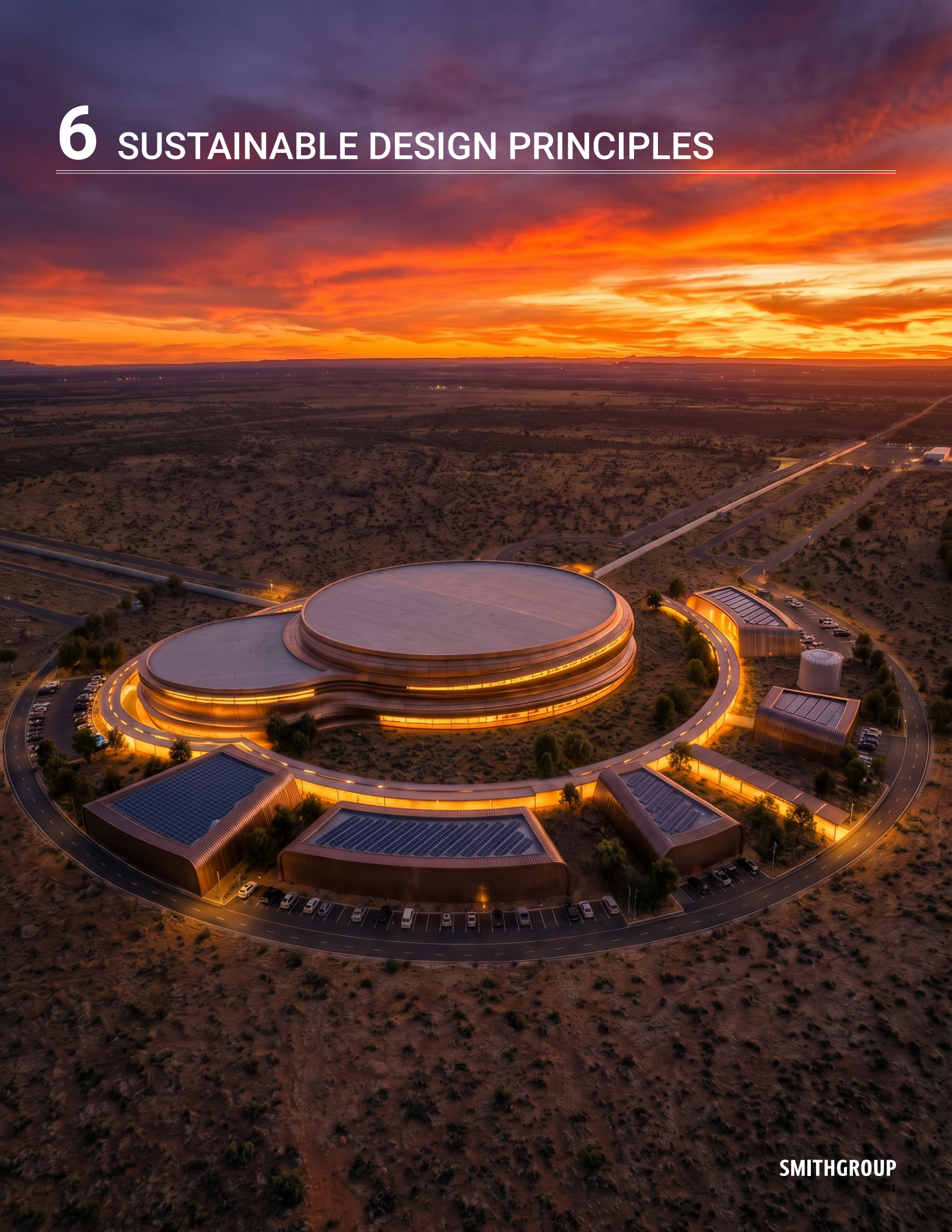
Key electrical and lighting system risks identified at the feasibility stage include:

- Site specific utility uncertainty: Electrical service voltage, capacity, and reliability will vary by site and may affect infrastructure scope and cost.
- Long distance distribution: Extended beamline lengths increase exposure to faults and maintenance challenges along buried distribution systems.
- Intermittent high loads: Accommodation of periodic high power bake out activities requires careful planning to avoid over building permanent infrastructure.
- Sensitivity of equipment: Electrical noise, grounding deficiencies, or lighting interference could impact scientific operations if not carefully managed.

These risks will be mitigated through early coordination with utilities, detailed system studies during site selection, and integrated design across electrical, structural, mechanical, and scientific disciplines in future phases.

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6 SUSTAINABLE DESIGN PRINCIPLES



6 SUSTAINABLE DESIGN PRINCIPLES

6.1 Introduction

Planning and designing for clear, realistic sustainability goals is key to Cosmic Explorer’s environmental, economic, and resilience success. The project shall allocate 1% of the total construction budget to sustainable design efforts and target Zero Carbon Certification, with anticipated investments in on-site solar, battery storage, low-carbon material procurement, and one-time carbon offsets.

This section first outlines a high-level analysis of regional differences in grid emissions, reliability, long-term investment trends, and competing electricity demand as they relate to project location selection. It then defines the Zero Carbon Certification criteria and recommends additional sustainability frameworks to support detailed design.

A comprehensive assessment of cost and carbon reduction strategies is presented, addressing both embodied and operational carbon over the project life cycle. Given the scale of the project and its demanding scientific program, these factors have a significant influence on cost, carbon emissions, and impacts to the surrounding community.

Preliminary material quantities and industry-average embodied carbon emissions factors were used to develop order-of-magnitude comparisons for embodied carbon emissions. Operational performance is informed by utility data from existing LIGO facilities and client input to establish energy use intensity (EUI) benchmarks, providing insight into potential photovoltaic and battery energy storage system design.

Finally, the section highlights innovative strategies to extend the positive impact of Cosmic Explorer. Together, these analyses identify opportunities to minimize carbon impacts while supporting the scientific mission and delivering meaningful benefits to surrounding communities.

6.2 Site Selection Considerations

Grid Utility and Equitability

When considering potential site locations, it is important to overlay utility, infrastructure, and demographic information. These insights help to prioritize project goals, performance, and related impacts. Choosing a site with good grid emissions, stability, and capacity is critical, even with generous amounts of on-site solar. The scale of Cosmic Explorer provides an opportunity for the site to become a local and regional asset, potentially providing further grid stability or on-site renewable power for surrounding communities. For this reason, overlaying potential project locations with various data sets helps us gain a broader understanding of how grid performance varies across US regions.

For instance, marginal emissions illustrate how much carbon (in pounds) would be emitted to serve one additional MWh of electricity demand. This graphic offers a helpful comparison of what an operational emissions profile may look like today based on the project’s selected location. Some regions of the U.S. have lower grid-related emissions on a marginal basis, meaning the carbon emissions associated with consuming an additional MWh of electricity can vary significantly by location; for example, an incremental MWh consumed in eastern Colorado is likely to result in higher carbon emissions than the same MWh consumed in eastern Oregon. Conversely, when considering offsets from on-site renewables, photovoltaics could offer a larger positive impact in areas where the grid is marginally worse.

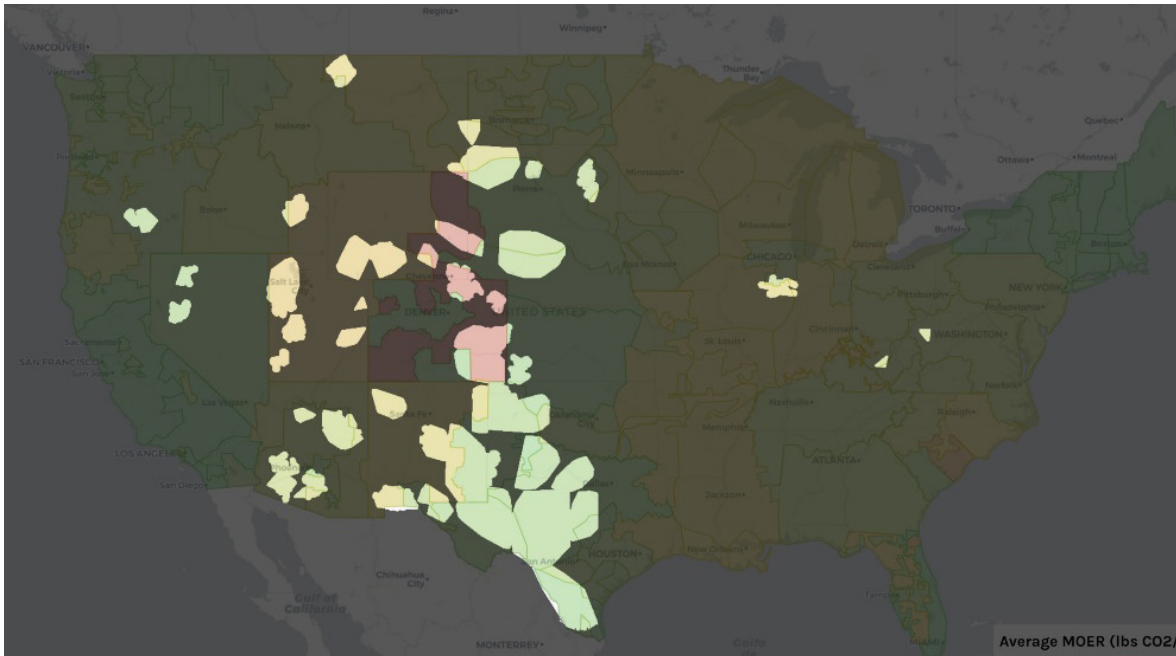


Figure 6.2.1: US Grid Marginal Carbon Emissions

Regionally, this Department of Energy (DOE) graphic illustrates grid reliability applied over different various balancing authorities via Loss of Load Hours (LOLH). LOLH estimates how many hours per year the grid may be unable to fully meet electricity demand. As an example, Texas has a relatively higher annual LOLH given the state-isolated grid infrastructure. This has implications for backup power design, self-sufficient resiliency, as well as down-time effects during a power outage.

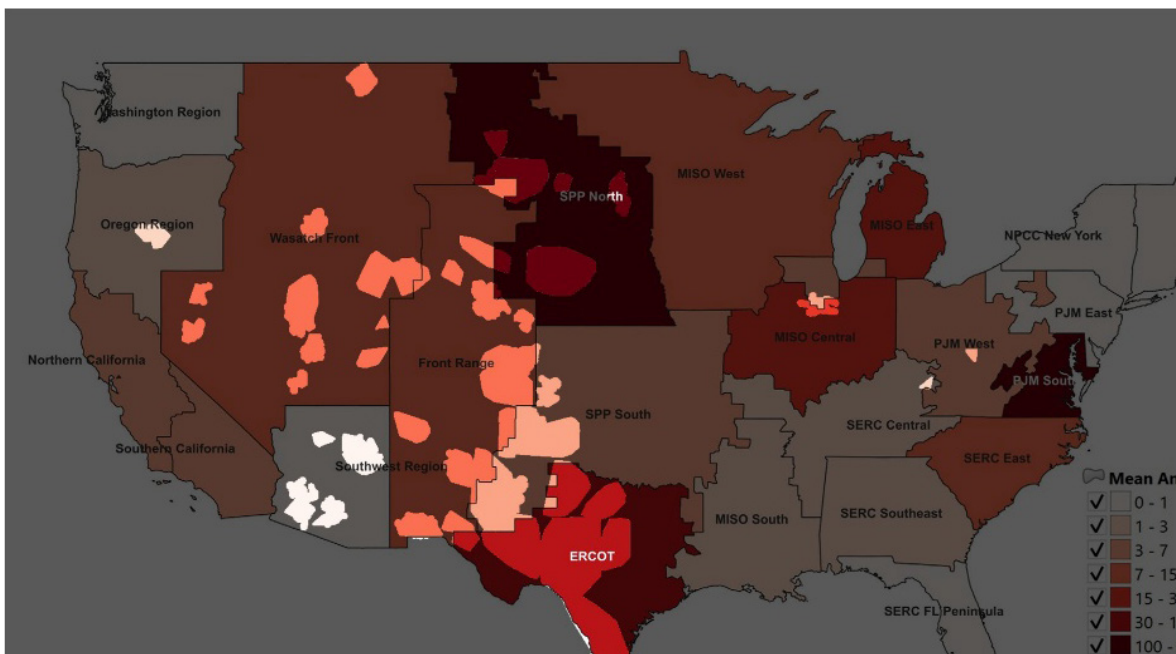


Figure 6.2.2: DOE Grid Reliability – 2030 LOLH Prediction

Looking ahead ten years, both national distribution (figure 6.2.3) and power generation sources (figure 6.2.4) illustrate the predicted new infrastructure to support feeding power to the CE site. This analysis ties into the local grid region emissions profiles over time. These figures are useful for identifying regions with stronger longterm clean energy and

transmission investment trends, which may influence future emissions intensity, interconnection feasibility, and system flexibility — though actual emissions and reliability outcomes will remain dependent on dispatch, marginal generation, and grid operations.

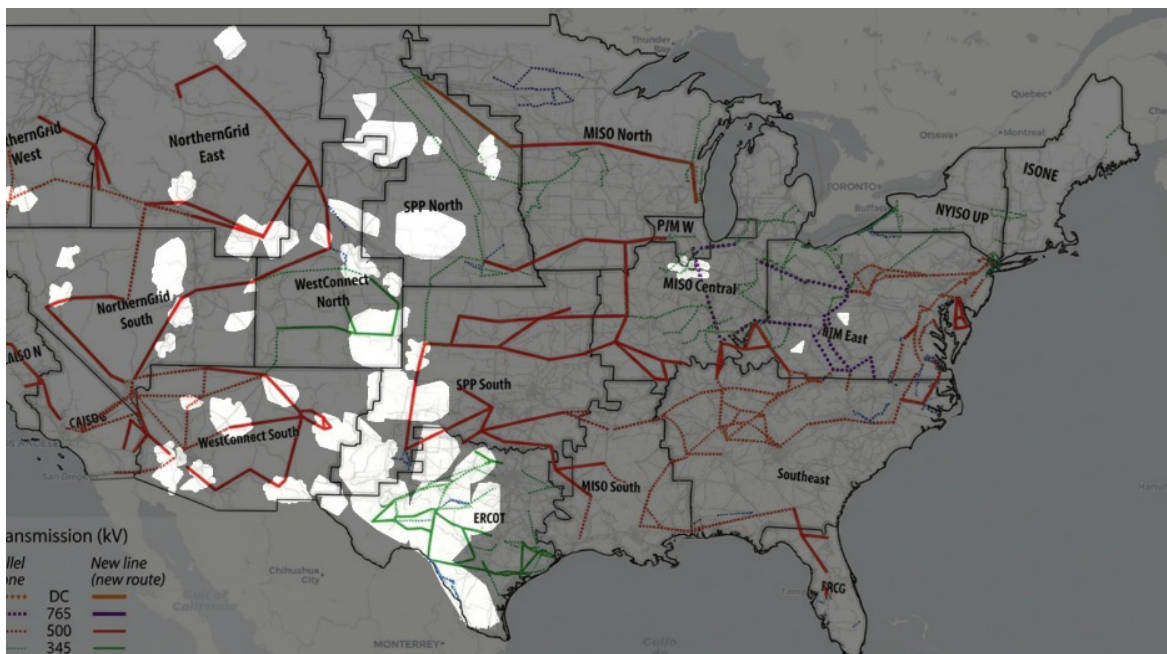


Figure 6.2.3: 2035 Grid Distribution Projection

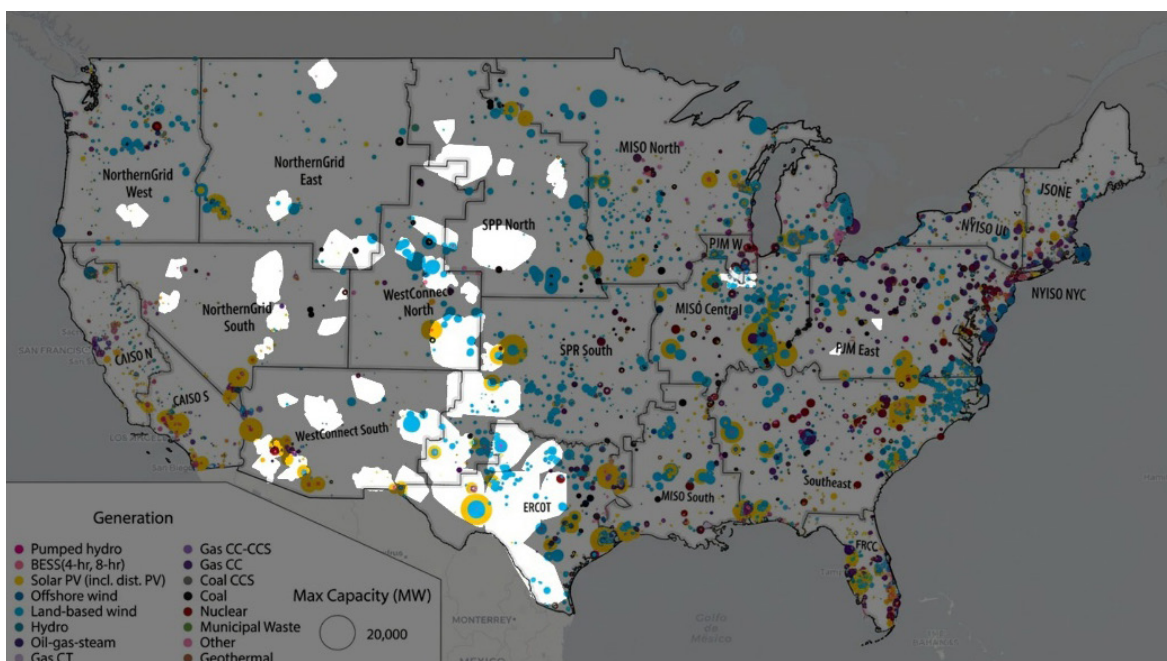


Figure 6.2.4: 2035 Grid Capacity Projection

The final two graphics highlight current and forecasted high performance computation (HPC) demand areas and projects, such as data centers. Locating CE near major HPC demand centers could require additional grid infrastructure and may influence longterm electricity cost considerations.

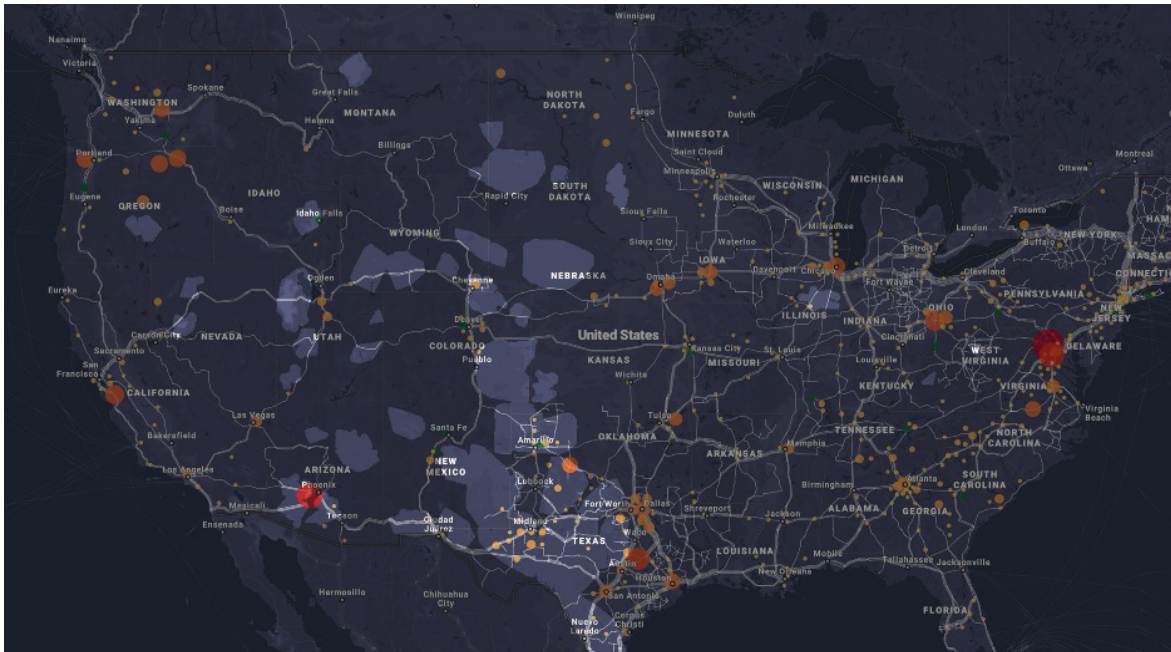


Figure 6.2.5: Power Competition – National HPC Today

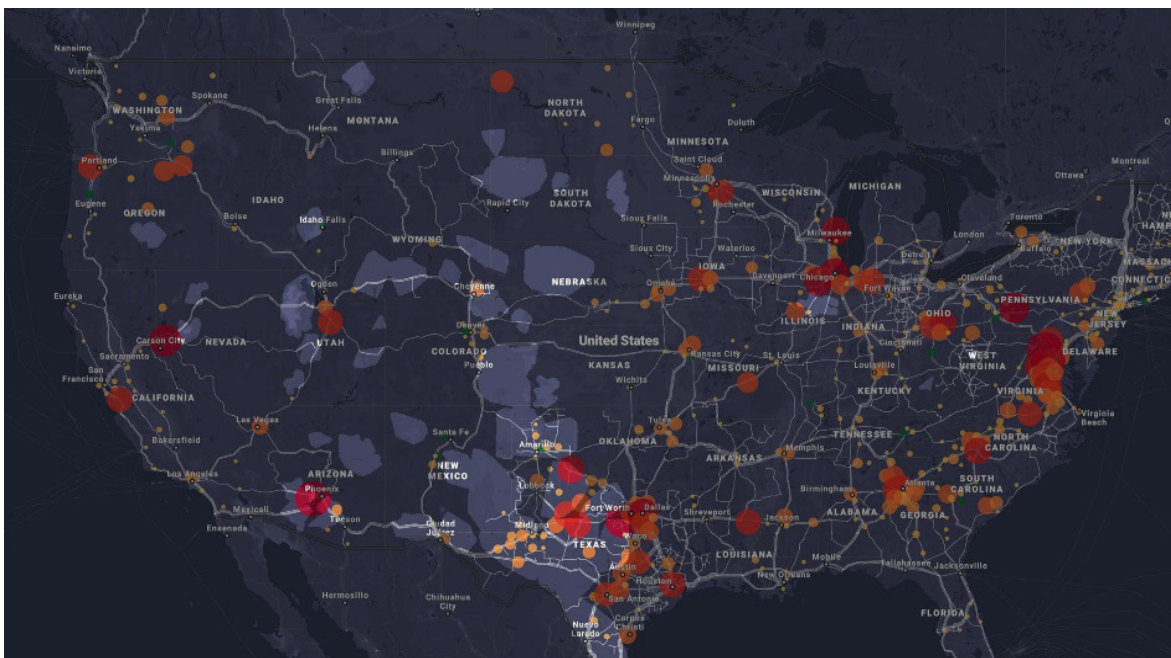


Figure 6.2.6: Power Competition – HPC Today & Construction & Planned

When comparing potential project locations across the U.S., no single site emerges as optimal; instead, the analyses highlight meaningful regional differences in grid emissions, reliability, longterm investment trends, and competing electricity demand. Marginal emissions and reliability metrics emphasize how location influences operational carbon and resiliency risk, while longterm transmission and generation projections provide insight into future flexibility for interconnection and clean power procurement. Regions with concentrated HPC demand may introduce additional grid capacity and cost considerations. Together, these factors serve as contextual screening inputs to inform site selection decisions, rather than deterministic predictors of sitespecific performance outcomes.

6.3 Sustainability Framework

Zero Carbon Certification

The project's primary sustainability goal will be to achieve Zero Carbon Certification. This certification will have the highest real-world impact on both Cosmic Explorer and the surrounding community in which it is ultimately located. Zero Carbon Certification was developed by the International Living Future Institute (ILFI) and requires thoughtful planning and execution during design and construction. To meet this certification, the project team has agreed to allocate 1% of the construction budget to sustainability.

Under this certification, there are two core objectives:

1. Operational Carbon
 - a. 20% improvement beyond the energy consumption levels required by ASHRAE Standard 90.1-2019 or later (Appendix G compliance)
 - b. Procure 100% clean electricity
 - c. Zero fossil fuel combustion once operating
 - d. Meter the energy used by the project
 - e. Implement maintenance plan to monitor and reduce fugitive refrigerant emissions
2. Embodied Carbon
 - a. 20% reduction in the embodied carbon emissions of primary materials and exterior materials compared to a baseline building of equivalent size, function, and energy performance
 - b. Must disclose and offset 100% of the embodied carbon emissions associated with life cycle stages A1-A5 through on-site carbon-sequestering materials...
 - c. and/or by a one-time carbon offset purchase through an ILFI-approved carbon offset provider.

As it relates to this project, future grid decarbonization paired with some on-site solar photovoltaics will help to achieve the first objective for operational carbon. Regarding purchased offsets for 100% of the embodied carbon emissions, it is important to consider offset projects that have a meaningful environmental and local community impact. This purchase of one-time offsets should focus on offset projects impacting the immediate surrounding community, such as reforestation efforts in an adjacent forest, or investment in a microgrid for a nearby indigenous Sovereign Nation.

Additional Sustainability Benchmarking References

While the priority for investment and maximum impact on the project and local community will be Zero Carbon Certification, during detailed design, the team will consider additional useful sustainability benchmarks to guide decisions and tasks.

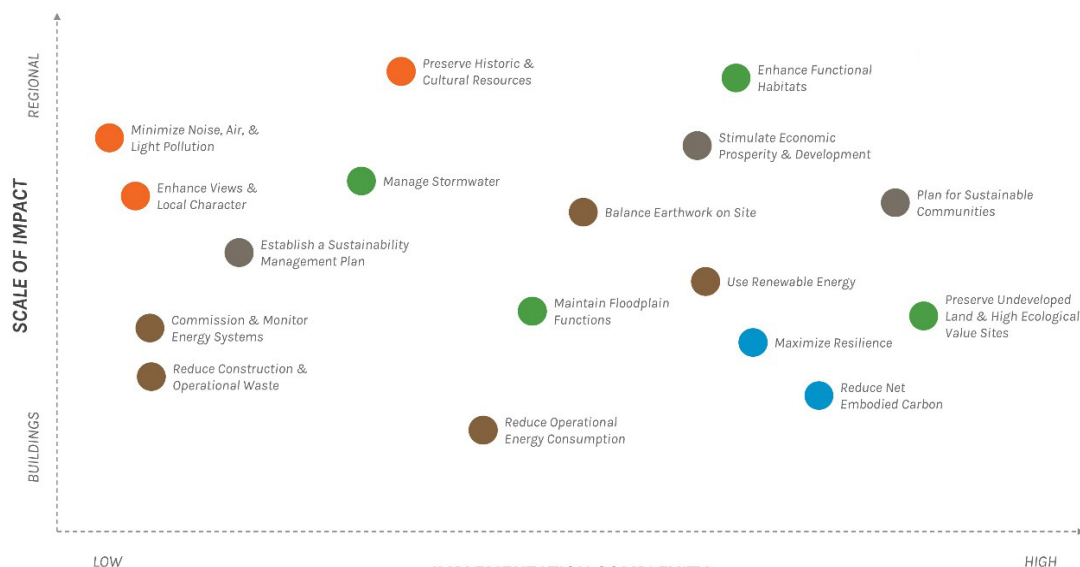
For the campus specifically, it is recommended to target LEED (Leadership in Energy and Environmental Design) Gold certification for all office and administrative buildings. LEED version 5 intentionally prioritizes three key concepts: decarbonization, quality of life, and ecological conservation and resilience. LEED certification has strong alignment with Zero Carbon certification, supporting the pursuit for LEED Gold. Additionally, LEED v5 incorporates key requirements on resilience planning and climate risk assessments. These are in strong alignment with project goals and provide useful frameworks for site selection and design development decisions.

Many LEED credits align with industry best-practices and project goals to minimize the impact on the surrounding environment and community. The credits with strong alignment to industry best-practices, referenced from LEED v5, include:

- Integrative Design Processes – multidisciplinary design teams with early analysis to evaluate decarbonization, quality of life, and ecological considerations.
- Minimized Site Disturbance – preconstruction site assessments to conserve special-status vegetation, maintain healthy habitats, and address invasive vegetation. Erosion control measures implemented during construction.
- Rainwater Management – retain runoff from rainfall events.
- Heat Island and Light Pollution Reduction – site design and material specification to reduce heat island and light pollution.
- Indoor and Outdoor Water Efficiency and Water Metering – reduces potable water consumption and tracks usage to inform better operations and leak detection.
- Energy Efficiency and Energy Metering – reduce and monitor the energy usage of the building and includes encouragement of low-carbon fuels and refrigerants.
- Commissioning – verification of proper equipment operation at building startup, and encouragement of ongoing monitoring of operations.
- Construction Waste Management – reduction and diversion of waste materials during construction.
- Materials Procurement – prioritization of low embodied carbon materials, healthy materials, and sustainable sourcing criteria.
- Indoor Air and Environmental Quality - prioritization of quality indoor environments and clean indoor air for human health and wellbeing.

On the civil infrastructure scale, it is recommended to target the Envision Sustainability Framework. The Envision rating system would cover the extents of the project including the corner station, end stations, and beam tube enclosures. While not intended to evaluate interior conditioned spaces, this framework is like LEED in organization and methodology but is focused on infrastructure requirements and project typology. Figure 6.3.1 below indicates a non-exhaustive list of project-specific credits within the Envision rating system, mapped across implementation complexity and scale of impact.

SUSTAINABILITY DESIGN PRIORITIES



To support a holistic sustainability strategy, the project team is encouraged to achieve a minimum of Envision Verified certification (the lowest threshold of certification). This approach will complement LEED Gold certification and help the project team prioritize design decisions, scheduling, and budgeting. Once a site is selected, preliminary scorecards across all certifications can be developed to leverage synergies in line with project and regionally specific contexts and demonstrate the holistic sustainability strategy.

6.4 Embodied Carbon

Beam Tube Enclosures

Inherently, because of the material requirements of reinforced concrete, the Beam Tube Enclosures (BTE) will be high in embodied emissions. To address this, innovative reduction strategies should be considered early in the project. Preliminary analysis compares the anticipated differences in embodied emissions of the various BTE types being considered, see Figure 6.4.1. To show order of magnitude, Figure 6.4.1 also includes a comparative impact of driving a car from Los Angeles to New York City. These results show that the at-grade BTE type has far lower embodied emissions than all other types that require additional material quantities or earth moving. Site optimization efforts to maximize the at-grade BTE type for cost and schedule efficiencies will also benefit overall embodied carbon emissions. Elevated viaducts should be avoided as much as possible due to their high embodied carbon footprint from the significant additional reinforced concrete required.

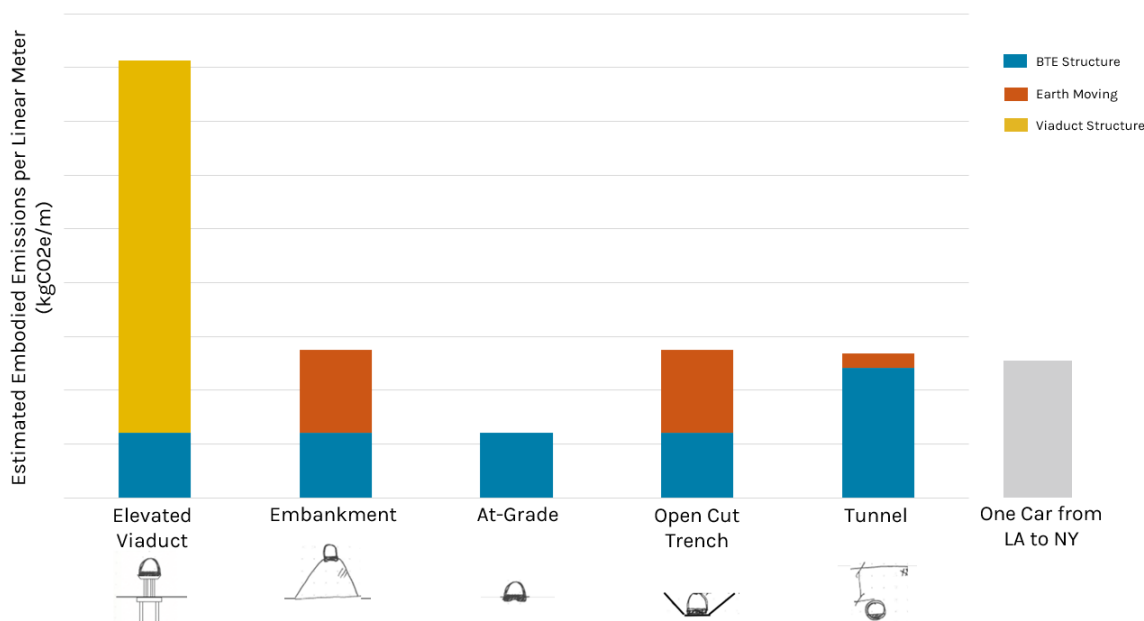


Figure 6.4.1: Embodied Carbon Emissions of BTE Types

Preliminary analysis also demonstrates the assumed combined embodied carbon footprint of the full BTE's for the project, see Figure 6.4.2. This analysis multiplies the per-meter emissions for each BTE type from the previous chart by the assumed percentage that each type occurs over the entire project. This demonstrates the importance of optimizing the site to minimize high-emissions BTE types as the emissions from a short segment of elevated viaduct, for example, can quickly exceed emissions from several kilometers of on-grade BTE. And again, to show order of magnitude, Figure 6.4.2 includes a comparative impact of 1,000 flights around the Earth.

This chart also suggests the potential reductions from current best practices and aggressive reductions incorporating the reduction strategies explained below.

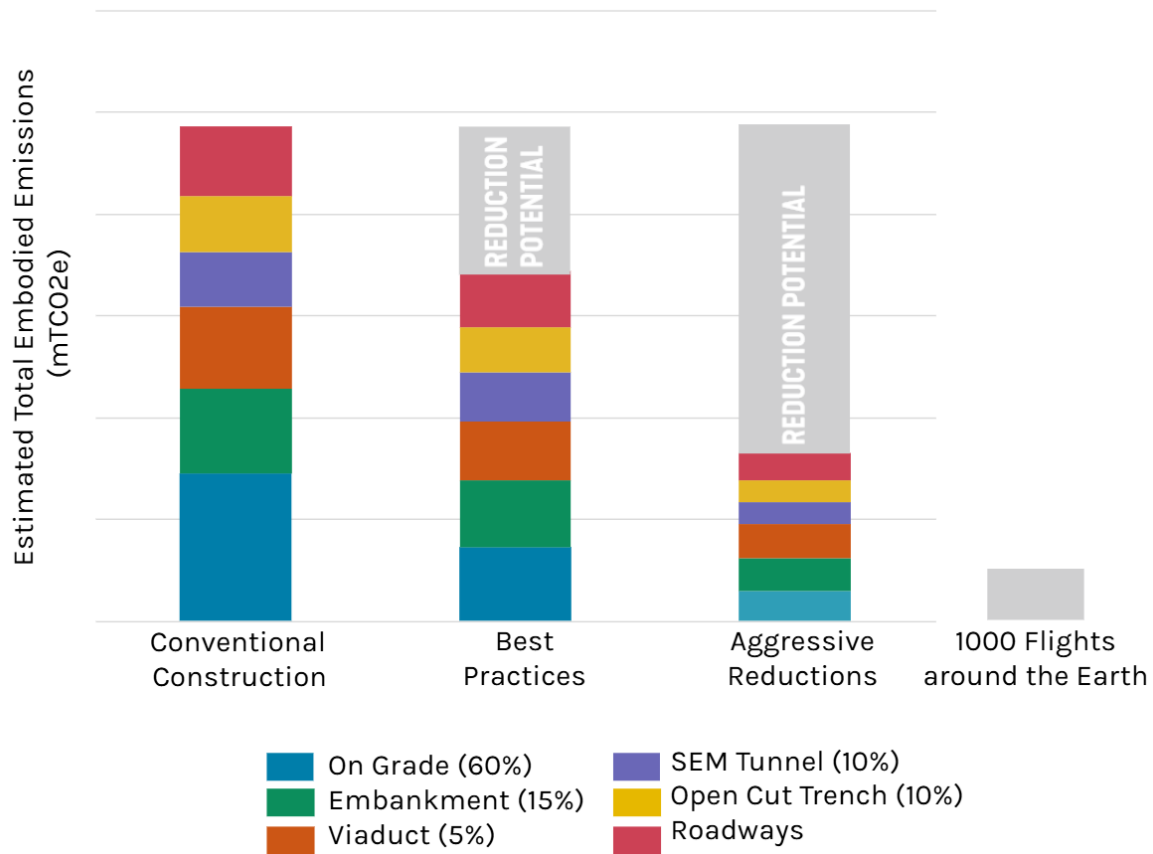


Figure 6.4.2: Embodied Carbon Footprint of All BTE's

Reduction Strategies

Assuming site optimization efforts have maximized the at-grade BTE type and minimized elevated viaducts as much as possible, the following additional reduction strategies should be considered.

1. Low Carbon Concrete and Steel

- Current best practices can reduce the carbon impact of concrete by 20-30%, including optimizing the strength and curing requirements of concrete during the design phases. Emerging technologies can achieve closer to 50-80% reduction and are worth considering for a project of this scale. Emerging technologies include supplementary cementitious materials (SCMs) such as recycled glass pozzolan and industrial by-products, and carbon-sequestering admixtures such as biochar and other industrial waste feedstocks. Partnerships with innovative companies in this space can maximize the opportunities for carbon reductions while spurring more rapid deployment to the industry beyond the project boundary.
- Similarly, supporting low-carbon steel for concrete reinforcing can contribute to meaningful reductions. Sourcing from local steel manufacturers with electric-arc furnaces and maximizing the usage of recycled steel should be considered.

2. Optimized and Balanced Cut/Fill

- Disposal or importing of soil can double emissions associated with earthwork. Optimizing construction sequencing to reduce the handling of soil can significantly reduce emissions, while also reducing disruptions to local ecosystems and soil health.

3. All-Electric Construction Vehicles

- Tailpipe emissions could be eliminated with all-electric vehicles, significantly reducing emissions associated with earthwork and material transport to site. A project of this scale could significantly support the emergence of all-electric construction vehicles in the industry. Grid emissions for vehicle charging should also be considered.

6.5 Operational Carbon

Energy Use Intensity

To help benchmark energy consumption of this project, the research team provided existing LIGO facility site energy consumption. The research team also estimated that Cosmic Explorer will have an operational load approximately twice that of the existing facilities. Hanford consumes ~8.4mm kWh while Livingston consumes ~6.8mm kWh annually. Averaging the two values, we estimate Cosmic Explorer will consume ~15mm kWh annually.

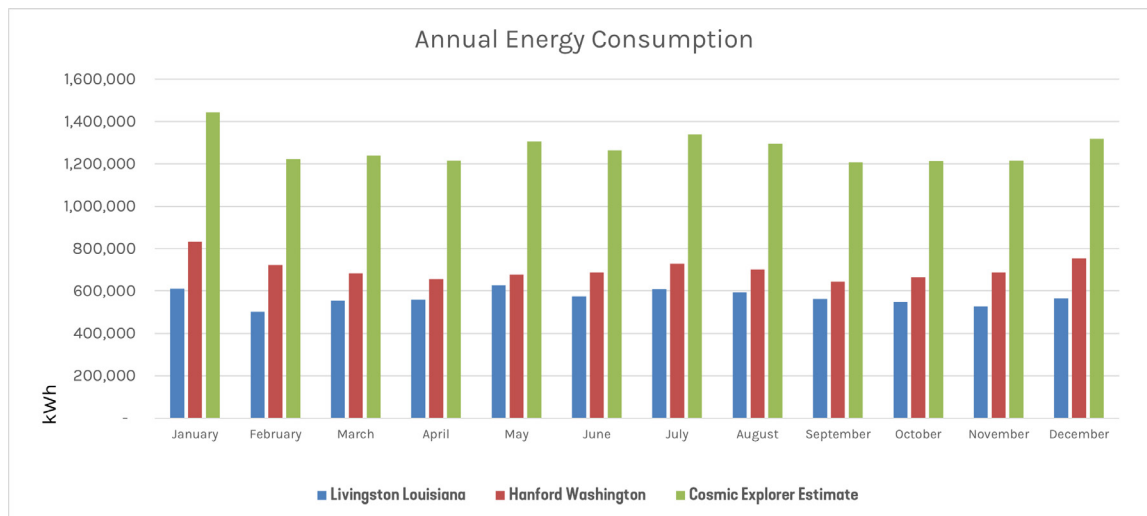


Figure 6.5.1: Annual Energy Consumption of Existing and New LIGO Facilities

Energy use intensity (EUI) refers to operational performance and is the total energy consumed by the project divided by the total program area. While Cosmic Explorer will house substantially more program areas than the existing facilities, it will bring more building area that has lower energy density than the corner and end stations which dominate program at Hanford and Livingston.

Hanford has an estimated site EUI:

- 485 kBTU/ft²/yr (excluding beam tune enclosure area)
- 95 kBTU/ft²/yr (including beam tube enclosure area)

Livingston has an estimated site EUI:

- 393 kBTU/ft²/yr (excluding beam tune enclosure area)
- 77 kBTU/ft²/yr (including beam tube enclosure area)

It is estimated that Cosmic Explorer will have a site EUI:

- 150 kBTU/ft²/yr (excluding beam tune enclosure area)
- 20 kBTU/ft²/yr (including beam tube enclosure area)

Grid Region and Emissions

As mentioned in Section 6.2, the site location relative to the local grid changes the carbon dioxide emissions profile. Marginal operating emissions rate (MOER) describes the grid impact of this project's expected electricity use. Assuming CE consumes 15mm kWh (15,000 MWh) annually, the projected marginal CO₂ emissions, expressed in metric tonnes, are estimated below. Simply locating the site in eastern Colorado instead of eastern Oregon can double source emissions.

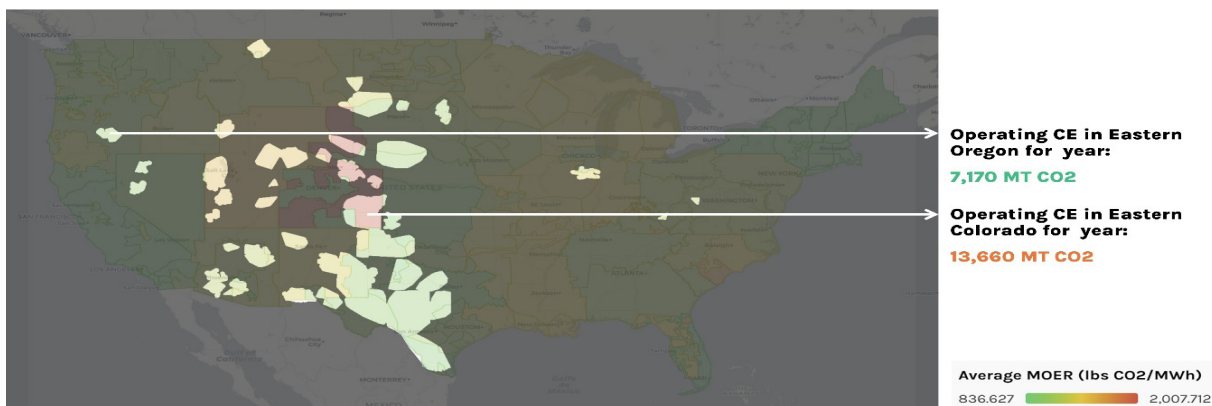


Figure 6.5.2: MT CO₂ Emissions Based on Grid Average MOER

Photovoltaic (PV) Array

On-site solar generation is critical to meeting project sustainability and operating goals. Given the high energy consumption of Cosmic Explorer, the PV arrays being considered are mostly ground-mounted large-scale systems. As an example, a 4 MW PV installation near Hanford can produce ~5.2mm kWh/yr. This equates to a PV installation area of 1100' x 585' or about 15 acres. To offset 15mm kWh of energy consumed (see section above), three of these 4 MW arrays would need to be considered.

15,000 MWh FROM PV?

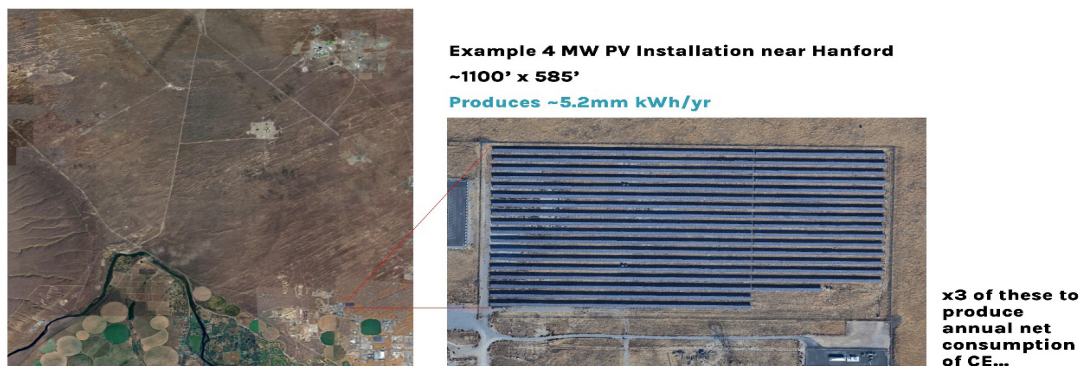


Figure 6.5.3: PV Installation near Hanford

It may not be financially responsible to assume a net-zero energy design via on-site solar generation alone, but a partial offset from PV is highly recommended. Annually, a 12 MW solar array could produce approximately 15mm kWh consumed by CE, however the time of use and time of production are notably out of sync.

The chart below shows the daily potential production of a 12 MW solar array in orange, and an approximate CE demand profile in black. The hourly volume of overproduction is shown in green as a negative value, representing the amount of kWh that could go back to the grid and local community or into battery storage.

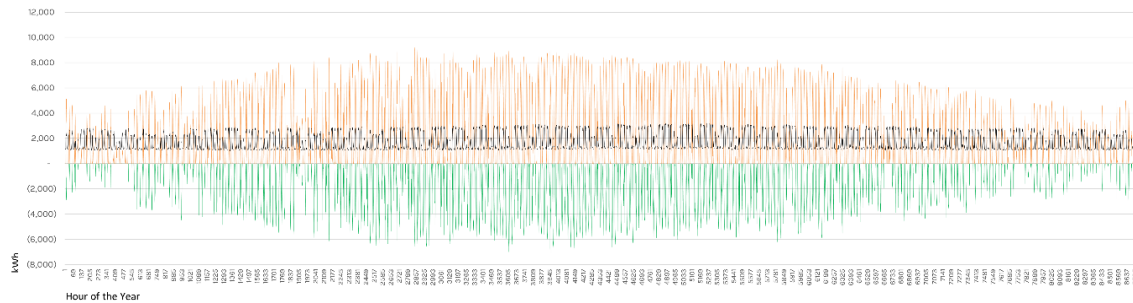


Figure 6.5.4: Daily Potential Production of 12 MW Solar Array vs. Demand

Careful consideration of final site selection and the local grid resources will be key to finalizing the size of on-site solar. If there is local grid region demand for excess renewable production, a large 10 MW+ solar array could have meaningful and positive impact on the local community. If the project ends up in a grid region with other abundant renewables, adding more overproduction would not serve anyone responsibly. At a minimum, the on-site solar should be sized to accommodate maximum self-consumption of PV generated electricity in addition to sufficient overproduction to fill battery storage to the desired 24-hour backup capacity. If the project includes BESS, the backup power needed should support 24-hours as this allows the site to be self-sufficient. On days where solar generation exceeds needs, power can be exported to the grid and on days where solar generation is less than required, power can be pulled from the grid to augment solar generation.

6.6 Additional Sustainable Strategies

Climate-Informed Design

Regardless of the location, climate informed planning should be a part of the structured design framework, explicitly accounting for uncertainty and future conditions using recognized processes and risk frameworks instead of relying on historical data. Strategies outlined should be vetted and tailored to specific climate to ensure informed decisions. Passive solar design starting with orientation and form will play a key role in reducing lifecycle energy and can be achieved by locating the most thermally sensitive spaces (vacuum support rooms, clean/control areas) in compact building volumes with limited exterior surface area and controlled glazing, while using noncritical support spaces as thermal buffers. Use external shading (deep overhangs, fins, screened service yards) and high-albedo materials to cut peak solar gains to help stabilize indoor temperatures during heat events and reduce stress on the cooling systems. Where daylight is needed, prefer north-biased clerestories or shaded apertures to reduce glare and thermal gradients. Prioritizing envelope stability through high thermal resistance, air tightness and minimized thermal bridges will help reduce internal temperature gradient and lower HVAC intensity, supporting the stringent controls facilities like these require.

Wind resilience should be honed towards protecting sensitive areas by understanding the regional wind patterns and extremes. It is recommended to perform computational fluid dynamics (CFD)–based microclimate modeling at the site and building scale to assess wind velocity fields, localized acceleration effects, and wind-induced pressure concentrations, particularly near corners and between closely spaced structures. Below is an example wind analysis. From research^{1,2}, wind speeds beyond 15 miles per hour may induce either structural vibration or ground tilt that is measured by the facilities sensors and measuring devices.

Use a combination of site layout and orientation, architectural design, and landscape measures to manage winds—diffusing, slowing, and redirecting flow, and avoiding unintentional channeling that can increase local wind speeds—so sensitive areas are protected. Preserve or create vegetated windbreaks, supported by berms and sheltered courtyards, to reduce wind speeds at end stations and the corner station, and add porous wind screens where CFD identifies localized acceleration and turbulence. To limit wind-induced vibrations, minimize tall, flexible elements and keep rooftop equipment off vibration-sensitive structures; where building form contributes, consider aerodynamic tapering of profiles as part of an integrated mitigation approach (see Figure 6.6.4).

WIND ANALYSIS

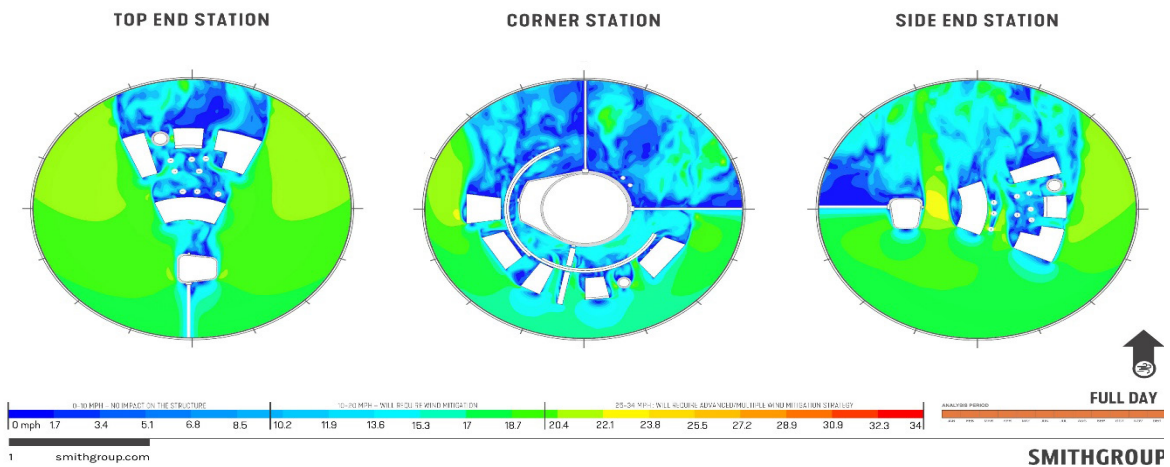


Figure 6.6.1: South Winds

WIND ANALYSIS

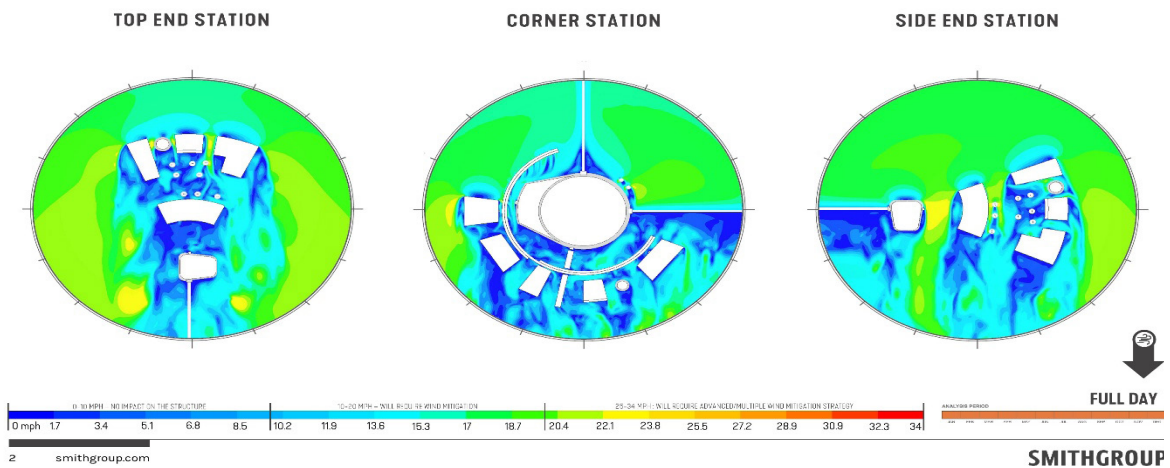


Figure 6.6.2: North Winds

WIND ANALYSIS

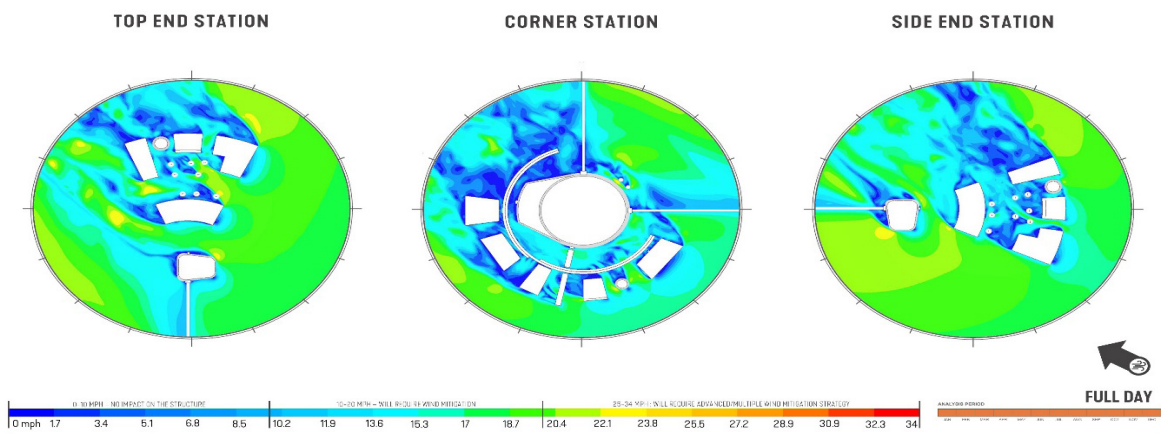


Figure 6.6.3: Southeast Winds

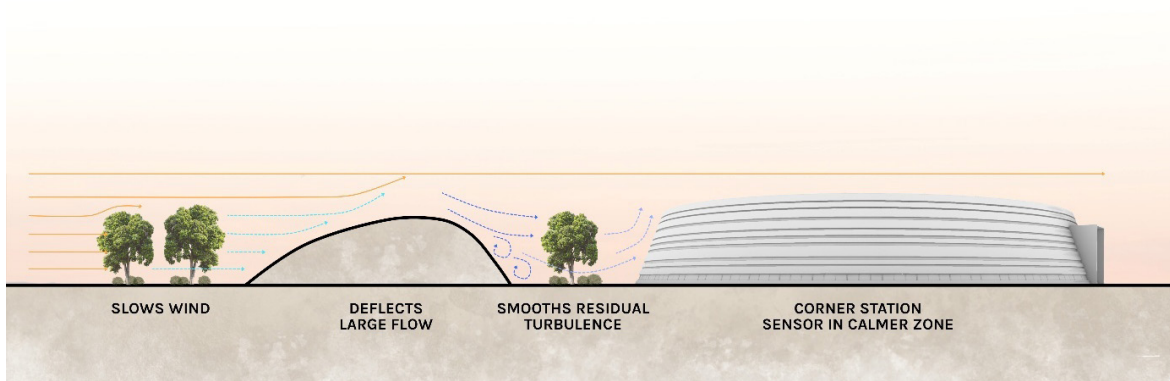


Figure 6.6.4: Conceptual Section - Wind Mitigation Strategies (not to scale)

Sovereign Nations

If Cosmic Explorer is located near Tribal land, it presents an opportunity to form a sustainability partnership that strengthens sovereignty, builds longterm livelihoods, and supports costewardship of land and resources. Given the facility’s multi-decade operations and specialized maintenance needs, partnerships with Tribal Colleges and Universities can establish enduring education and career pathways while building local research capacity aligned with site needs. Economic sustainability can be reinforced through local procurement and intentional structuring of work packages to support Tribal and Native-owned firms, consistent with the Buy Indian Act. Energy sovereignty and environmental stewardship can be advanced through co-developed, micro-grid-ready energy systems and Tribeled monitoring programs, supported by technical assistance from the DOE Office of Indian Energy.

Innovative Soil Reuse

A construction approach that treats excavated soil and rock as a resource rather than waste will benefit the development in creating long, stable enclosures that are critical to protecting the scientific performance. A practical approach for this should begin by creating a waste hierarchy to first avoid and reduce excavation through early mass-balance design; then prioritize on site reuse; then process for higher value uses; and only then consider off site beneficial reuse or disposal. Referencing the Future Circular Collider feasibility study³, innovative pathways include reusing limestone for concrete production and construction stabilization, backfilling quarries/mines, and transforming excavated material into fertile soil for rewilding, demonstrating how large-scale science projects can embed circular economy outcomes.

Environmental Measuring Tool

The facility can be intentionally designed as a high-resolution environmental measuring tool, since its primary mission already requires continuous, multimodal monitoring of local conditions. Equipped with a suite of sensors, it can generate high-quality data on seismic activity, storms, and other large-scale environmental phenomena, with daily and seasonal patterns in wind, wave activity, rainfall, temperature, humidity, and radiation detectable through their effects on ground motion and monitoring systems. Partnerships with local agencies and universities could support co-management of monitoring stations and periodic “state of the environment” reporting. Similar collaborations already exist, such as the partnership between the Virgo detector and the University of Pisa, which uses interferometer data to study coastal wave dynamics, seismic activity, and climate driven environmental change.⁴

Water

With an assumed site that has no available municipal water connections, and a high likelihood of either current or future water scarcity in the site region, the mindful design of water systems will be important for the project. Site

selection criteria should consider the availability of ground and rainwater, and the potential impacts of future climate projections, increasing instability in weather patterns, and drought conditions. Net zero water use for the campus should be a stretch goal, achieved through rainwater capture and storage where feasible, no potable water use for irrigation, and greywater reuse for non-potable uses such as toilet flushing. These strategies would be in addition to best practices for water conservation measures through low-flow fixtures and optimization of any process water uses.

6.7 References

1. Ross, Michael P. and others. “Towards Windproofing LIGO: Reducing the Effect of Wind-Driven Floor Tilt by Using Rotation Sensors in Active Seismic Isolation.” *Class. Quant. Grav.* 37, no. 18 (2020): 185018. <https://doi.org/10.1088/1361-6382/ab9d5c>.
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7 CODE ANALYSIS



7 CODE ANALYSIS

7.1 Applicable Code and Guidelines

7.1.1 Introduction

The proposed Cosmic Explorer (CE) Observatory facility will provide state-of-the-art research spaces, support spaces, and equipment spaces to support the CE's mission. The campus will include the main observatory as well as buildings to provide living spaces for staff, exhibition spaces for presentations, and utility spaces to support buildings on the site.

The design and construction of the new facility will comply with the codes adopted by the local jurisdiction. The design team will meet with the local building code and fire code officials to review the proposed design, establish design criteria, and applicable codes. It is anticipated that all buildings will be fully sprinklered and equipped with a fire alarm system.

Due to the lack of information on the project site, all code references and requirements will refer to the 2024 edition of the International Building Code (IBC). A complete code analysis will be conducted for each building once a location is selected. Note compliance with the U.S. National Science Foundation (NSF) design guidelines and standards may be required.

7.1.2 Brief Description of Buildings

The CE observatory will house straight laser beams enclosed within Beam Tube Enclosure (BTE) connecting between Corner Station (CS), Mid Stations (MS), and End Stations (ES) in each direction of the L-shape footprint of observatory. The laser beam will be transported within steel beam tubes that are maintained to be in vacuum. The purpose of the enclosure is to protect the beamline vacuum system (beam tube, pump ports, etc.) from the environment and other potential external threats. The Beam Tube Enclosures (BTEs) are long, linear, lowoccupancy structures intended primarily to protect the vacuum beam tube and associated equipment from environmental exposure, physical damage, and vandalism. Equipment housed within the BTE does not require temperature control but must maintain a noncondensing environment.

In addition to the observatory building, additional buildings will be provided on the site. The Observations Support Building (OSB) will function as the operational and technical hub of the CE observatory. The OSB will provide an office-quality environment for the operations team, as well as shops and clean labs for precision assembly and maintenance of detector hardware. Additional technical spaces will include data storage areas and other specialty laboratories. Staff support spaces, such as offices, meeting rooms, lounges, a pantry, and storage areas will also be included.

The Office Building (OB) will serve as the administrative hub for the site. The building will include offices and staff support spaces, including a dining hall, conference room, pantry, and storage spaces. The main server room shall be provided in the OB.

The Community/Education Building (CEB) provides exhibition and educational facilities for CE to connect with the local community and host external events. This building will include assembly spaces such as an exhibit hall, classroom, auditorium, office spaces, and support spaces. The final program for the CEB will be determined once a site has been selected.

7.2 Fire Department Access

Fire department access will be provided to each building in accordance with the applicable codes and local fire department requirements. Site infrastructure has been explicitly planned to accommodate emergency response vehicles. Roads, bridges, overpasses, and underpasses are designed to support vehicles with gross weights of up to 40 tons, ensuring access for fire apparatus and heavy rescue equipment.

Fire access roads will be minimum 20 feet in width. Where aerial fire apparatus access is required, roads will be constructed with a minimum width of 28 feet. Due to the low occupancy of the site, it is not anticipated to have parking along fire access roads. Vertical clearances will be provided above all fire access roads for ladder access where required.

Building access and security features will be coordinated with local first responder requirements. Exterior doors are assumed to include controlled access systems with physical overrides compatible with emergency response protocols. Knox boxes or other approved opening methods will be provided for all vehicle gates where obstructing a fire access road.

Fire hydrants will be provided throughout the site. These hydrants may required to be supplied by an on-site water storage tank in lieu of a municipal water supply.

7.3 Wildfire Hazard

Potential project sites shall be evaluated for wildfire hazard severity zone risks. Where a project site is in an identified wildfire hazard severity zone, all buildings and the site shall comply with the requirements of the International Wildl- and-Urban Interface Code (IWUIC). The classification of the site shall be confirmed with the fire code official.

7.4 Fuel Storage

To supply on-site generators and fire pumps (if required), an on-site fuel storage tank shall be provided. It is anticipated that diesel fuel will be utilized and stored. The tank will comply with NFPA 30 as diesel is classified as a combustible liquid. The final size and quantity of fuel tanks shall be determined during the design phase.

The tank will be aboveground storage tank equipped with emergency relief venting to maintain pressures below 2.5 psi. A fire suppression system will not be provided for the tank. Protection from exposures as defined in NFPA 30 will not be provided for the buildings. The fuel tank will be located away from adjacent buildings and public ways in accordance with NFPA 30.

7.5 Battery Storage

On-site battery storage will be provided for the site to store energy generated by the on-site solar photovoltaic (PV) power system. It is anticipated that lithium-ion batteries will be utilized. The battery storage system will be classified as a stationary energy storage system in accordance with the International Fire Code (IFC). The battery storage system will be located outside and will be separated from adjacent buildings and structures in accordance with IFC requirements.

7.6 Preliminary Building Analysis

7.6.1 Occupancy

Each building will be classified based on the intended use and occupancy in accordance with Chapter 3 of the International Building Code. Based on the proposed use and program of each building, the following occupancies are anticipated below:

- CE: Groups B, F-1, S-1
- OB: Groups B, S-1
- CEB: Groups A-3, B

7.6.2 Construction Type, Building Height, and Building Area

Each building on campus shall be constructed of noncombustible materials (i.e., steel, concrete). The minimum construction type for the buildings will be Type IIB. The final construction type for each building will be dictated by the proposed occupancy and overall building height and area.

The building height for each building shall not exceed the allowable limits dictated in IBC Section 504 for the associated occupancies and construction type. Based on the program and proposed design, no high-rise buildings are anticipated for the project.

The building area for each building shall not exceed the allowable limits dictated in IBC Section 506 for the associated occupancies and construction type. Allowable area increases for fully sprinklered, one-story buildings with a minimum of 60 feet of open space shall be permitted for the CE observatory.

7.6.3 Fire Resistance Rated Construction

Structural Fire Resistance

Fire resistance ratings for building structural members shall be provided in accordance with IBC Table 601. Fire resistance for steel beams and columns may be achieved with spray-applied fireproofing, intumescent paint, or individual encasement using gypsum board.

Additional Fire Resistance Ratings

Interior rooms shall be rated in accordance with the IBC. Vertical exit enclosures and shafts will be fire resistance rated in accordance with IBC 713.4. A compartmentation and isolation strategy is recommended for the CE observatory; therefore, fire-rated construction will be provided to subdivide building areas to mitigate fire spread.

7.6.4 Fire Protection and Life Safety Systems

Each building will be fully sprinklered with an automatic wet-pipe sprinkler. On-site water storage tanks shall be provided to serve the sprinkler systems and on-site fire protection (fire hydrants). Specialty areas, including server rooms, equipment rooms, and labs, may utilize double-interlock preaction systems and/or clean agent (gaseous) fire suppression systems). Recycled water may be used in wet-pipe sprinkler systems if permitted by the local jurisdiction.

- Note: Sprinklers may be omitted from the normally-unoccupied tunnel due to the low combustible loading. Further discussion and coordination is required with local jurisdiction once site has been selected.

A fire alarm and detection system equipped with emergency alarm/voice communication will be provided throughout each building. Initiation methods will include smoke detection, sprinkler water flow, and manual pull stations. A very early smoke detection apparatus (VESDA) system shall be provided in areas protected by preaction and clean agent fire suppression systems. Notification shall be provided via visual (strobes) and audible (speakers) notification. Battery

backup shall be provided via batteries to provide a minimum of 24 hour backup power during standby conditions and 15 minutes in alarm. A digital alarm communicator transmitter (DACT) will be provided to report fire alarm system signals to a central or remote supervising station.

Based on the remoteness of the site and building construction, it is assumed an Emergency Responder Communication Enhancement System (ERCES) will be required. Further coordination with the local fire code official is required.

7.6.5 Means of Egress

The means of egress from each building will comply with IBC Chapter 10 and NFPA 101, if applicable. The general egress strategy includes total evacuation of the affected building (i.e., no defend-in-place strategy). Further discussions with the owner are required to determine if this strategy is acceptable.

Means of egress will be designed to comply with code requirements applicable to each building's size, configuration, and occupancy category. Clearly marked and unobstructed egress paths will be provided from all normally occupied spaces.

Emergency egress lighting and illuminated exit signage will be provided at all required locations and supported by codecompliant emergency or standby power systems. For underground or partially buried spaces, including basements within Vacuum Equipment Area (VEA) buildings, egress design will account for increased travel distances, protected stairways, and refuge or staging areas as required by code and operational planning.

In lieu of egressing to a public way, safe dispersal areas will be provided on the site. Safe dispersal areas will be a minimum of 50 feet away from the associated building. Further coordination is required with the building code official to determine if this strategy is acceptable.

7.7 Risks and Considerations

7.7.1 National Science Foundation (NSF): The project will be funded in part by the NSF. The NSF is a federal agency, which often times have additional design guidelines and requirements to be met.

7.7.2 FM Global: FM Global is an insurance company that insures buildings with high-value or specialty equipment and commodities. They have additional design standards that are more stringent than the base requirements found in nationally adopted codes, especially those pertaining to fire protection. The owner shall confirm if they carry FM Global as an insurance carrier prior to the design phase.

7.7.3 Authority Having Jurisdiction (AHJ): The AHJ will depend on the project location and entities funding the project. Depending on the location and project funding, there may be multiple AHJs for the project. In addition, there may be various approving agencies not related to building and fire. For example, a county health department may have jurisdiction over a commercial kitchen used for food preparation. The full list of AHJs for the project shall be established in the earliest phase of design possible.

7.7.4 Wildfire Risk: The site will be located in a remote area where other manmade structures and access will be minimal. In addition, the surrounding area may contain large amounts of wildland plants and debris, which may not be well managed by the enforcing agency. This elevates the risk of wildfire to the site, where fire department response may exceed standard response times in more urban areas. Wildfire risk shall be taken into consideration when selecting a site for the CE facility.

- 7.7.5 Battery Storage:** The use of lithium-ion batteries for battery storage systems poses an elevated risk of fire. Lithium-ion batteries can undergo thermal runaway, which can go undetected for long portions of time. To mitigate this risk, the battery storage system should be located far away from structures or in rated enclosures where near buildings. Fire suppression and fire detection systems shall be provided to protect the battery storage system. Another mitigation would be provided redundant battery storage systems separated from each other to provide redundancy and reduce risk of fire spread.
- 7.7.6 Water Supply and Quality:** Chosen project site may likely be too remote to be served by a municipal water supply. Therefore, on-site water storage for fire water and domestic water systems is required. The fire water storage tanks must serve both the hydraulic demands for building sprinkler systems as well as those required for firefighting purposes. In addition, this water must be treated for use in sprinkler systems and fire water distribution piping. On-site water treatment facilities may be required depending on the quantity of water needed and the quality of water available.
- 7.7.7 Redundancy:** Business continuity is paramount to the mission of the CE. In addition, many systems on the site are critical to occupant health and safety. Redundancy is a key component for mechanical, electrical, plumbing, fire, and specialty systems. Fire and life safety systems shall be provided with backup power as required by code. Due to the remoteness of the site and business continuity requirements, it is recommended an additional level of redundancy is provided.

These risks will be addressed through early AHJ engagement, detailed code analysis during site selection, and close coordination across architectural, civil, structural, and MEP disciplines in subsequent design phases.

8 RISK AND CONSIDERATIONS



8 RISK AND CONSIDERATIONS

8.1 Site-driven Risks

The 25mile L-shaped footprint of the Cosmic Explorer (CE) facility presents project risks driven primarily by civil and site development considerations rather than by individual engineering disciplines. Given the scale of the facility, civil engineering uncertainties are expected to outweigh other engineering risks. Accordingly, civil and site development risks reflect the facility’s unprecedented linear extent and early stage of definition rather than any specific construction typology. Key sources of uncertainty include but not limited to:

- Variability in ground conditions along long beamline corridors,
- Sensitivity of earthworks and structural quantities to site topography,
- Environmental and permitting requirements, and
- Constructability of civil systems across remote or constrained areas.

Site selection will be a major driver in mitigating long-term operational and maintenance risks. The science team should continue identifying geographic and geologic site types that reduce costs associated with different construction typologies, earthwork quantities, and special structures requiring engineered materials imported from off-site.

Different approaches – such as at-grade construction, structures founded in cut or on fill, bridges, or tunneling – present distinct risk profiles that must be balanced against site context, surface impacts, safety considerations, and long-term operational needs. At the feasibility stage, these risks are managed through simplified, site-agnostic assumptions and representative typologies, with the expectation that site selection, targeted investigations, and progressive design development will enable refinement and mitigation in subsequent project phases.

Each chapter’s Risk sub-section outlines the risks and considerations specific to that system.

8.2 Conceptual Risk Register

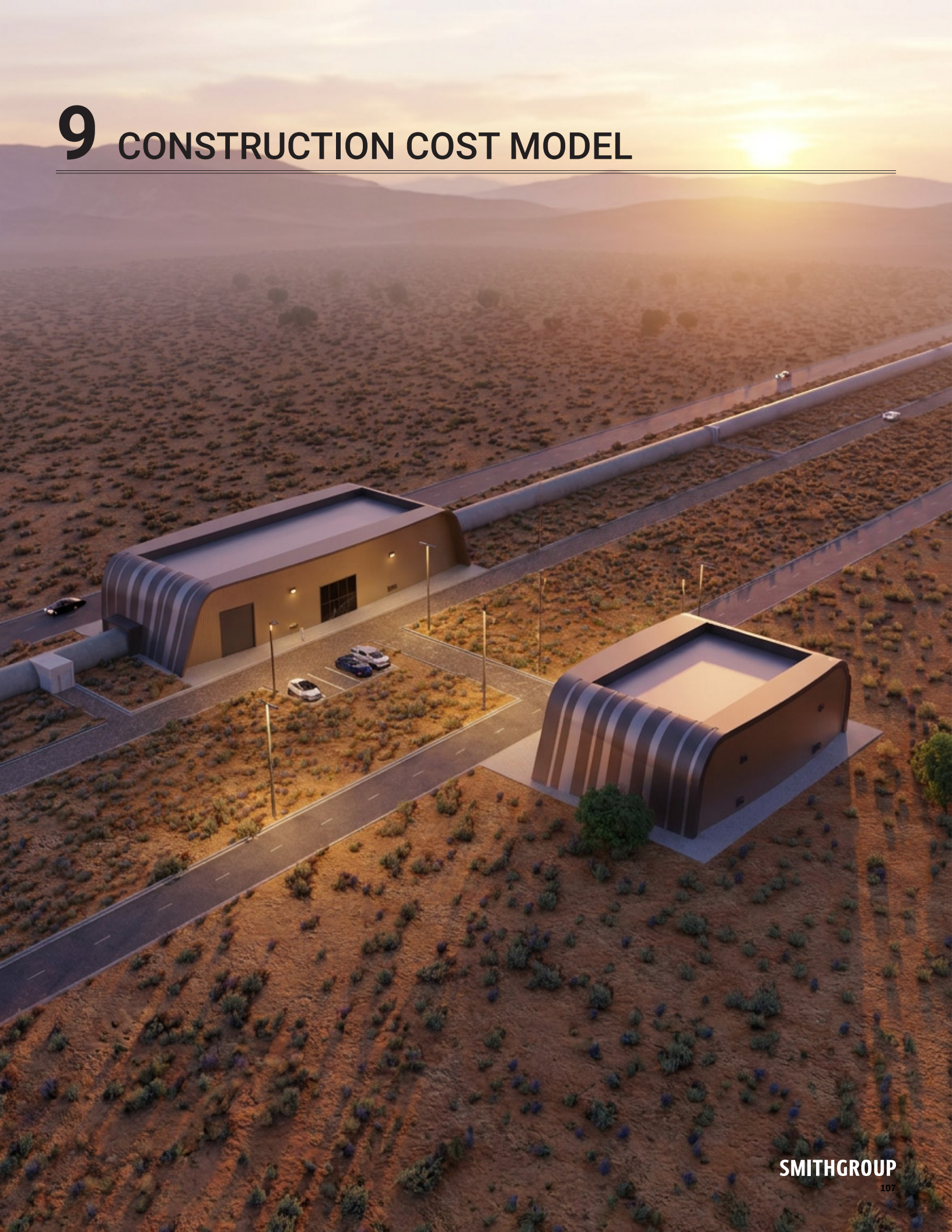
Table 8.1 presents a conceptual risk register summarizing key civil engineering and site development risks identified at the feasibility stage for consideration during site selection and analysis. Likelihood and consequence are scored qualitatively as Low/ Medium / High; the overall rating reflects the combination of the two, which shall be refined as site-specific data, cost models, and schedules mature. The content within this conceptual risk register is based on engineering judgment from civil engineering and site development team; these items are suggested to be included in a high-level project-wide risk register as the project develops in future phases.

Table 8.1 Civil Engineering and Site Development Conceptual Risk Register

ID	Risk	Cause / Condition	Impact	Likelihood	Consequence	Rating	Mitigation / Response	Trigger / Indicator
CE-CIV-01	Site selected requires high quantities of special structures (bridges/tunnels) and engineered imports	Unfavorable topography, crossings, or geologic setting; corridor constraints	Cost growth, schedule extension, increased lifecycle maintenance burden	Medium	High	High	Refine site screening criteria; favor bowl-shaped basins / low-crossing corridors; early quantity sensitivity studies	High % bridge/tunnel in corridor statistics; large cut/fill imbalance
CE-CIV-02	Subsurface conditions differ materially from feasibility assumptions	Limited geotechnical characterization at feasibility stage; variable stratigraphy / depth to rock	Excavation method changes, ground improvement, settlement risk; cost/schedule impacts	High	High	High	Phase geotechnical investigations; define “red flag” exclusions; develop GBR at procurement stage	Unexpected borings; high variability in profiles; karst/fault indicators
CE-CIV-03	Earthwork quantities highly sensitive to topography and Earth-curvature geometry	Long, straight alignment; limited grading optimization at feasibility; bowl vs flat effects	Large cost uncertainty; constructability impacts (haul routes, balancing cut/fill)	Medium	High	High	Use representative profiles + sensitivity ranges; prioritize sites with favorable curvature/topography; refine grading model	High modeled cut/fill volumes; imbalance requiring import/export
CE-CIV-04	Environmental/permitting constraints delay or constrain corridor development	Jurisdictional requirements; sensitive habitats; stormwater/wetland impacts; long corridor crossings	Schedule delay; redesign; added mitigation and cost	Medium	High	High	Early desktop permitting scan; route alternatives; consider tunneling to reduce fragmentation; stakeholder plan	Protected areas, wetland delineations, agency feedback
CE-CIV-05	Groundwater inflow / dewatering requirements exceed assumptions (construction and operations)	High water table; variable aquifers; pressurized groundwater; groundwater-dependent ecosystems	Constructability, environmental impacts, ingress management, cost/schedule growth	Medium	High	High	Early hydrogeologic modeling + monitoring; prefer sites with manageable groundwater; define allowable ingress criteria	Piezometric levels; inflow during test excavations; ecology constraints

ID	Risk	Cause / Condition	Impact	Likelihood	Consequence	Rating	Mitigation / Response	Trigger / Indicator
CE-CIV-06	Ambient vibration levels (or variability) exceed operational tolerances	Microseisms (0.1–1 Hz), seasonal storms, anthropogenic activity; soil amplification; future land-use changes	Performance shortfall; additional civil depth/controls; O&M complexity	Medium	High	High	Long-duration monitoring; preference for competent rock and/or subsurface alignments; control construction vibration	High peak spectra; strong seasonal variability; nearby development
CE-CIV-07	Tunneling method feasibility / productivity risk	Variable geology; groundwater; need for frequent method changes; reliance on heavy ground treatment	Schedule/cost growth; increased safety and QA/QC demands; residual deformation risks	Medium	High	High	Prefer corridors supporting continuous SEM/TBM approach; early probe drilling; define method-selection decision tree	High support class, low advance rates, high inflow during pilot works
CE-CIV-08	Right-of-way, crossings, and third-party interface constraints	Natural/man-made crossings; utility corridors; access limitations; remote/controlle d lands	Redesign, added bridges/tunnels, schedule delay, stakeholder disputes	Medium	Medium	Medium	Early corridor mapping; utility coordination; develop crossing typologies and allowances in ROM	ROW gaps; high crossing density; stakeholder objections
CE-CIV-09	Stormwater approach inadequate for local hydrology/regulatory criteria	Feasibility assumptions (swales, infiltration, basins) not compatible with soils, climate, or permitting	Design changes; additional land take; increased capex/opex; schedule delay	Medium	Medium	Medium	Site-specific hydrology and permitting basis; flexible design standards; early infiltration testing	Poor infiltration; agency requirements for detention/treatment
CE-CIV-10	Long-term settlement/deformation affects BTE alignment and maintainability	Soft ground, variable strata, groundwater drawdown/subsidence, time-dependent creep	Ongoing realignment needs, higher O&M cost, potential performance degradation	Medium	High	High	Exclude subsidence-prone regions; deformation monitoring plan; select stable formations; design allowances	Historical subsidence; predicted settlement; monitoring trends
CE-CIV-11	Longer distance from nearest urban area or highway, resulting in increased roadway quantities	Remote site; limited access; new/upgraded roads/bridges needed for construction and O&M access.	Higher roadwork capex; permitting/ROW delays; increased O&M/logistics costs.	Medium	Medium	Medium	Prioritize sites near highways/towns; use existing roads; advance access works early; coordinate with agencies/landowners.	Access distance exceeds screening threshold; limited all-weather routes; many upgrades/crossings flagged in desktop routing.

9 CONSTRUCTION COST MODEL



9 CONSTRUCTION COST MODEL

9.1 Introduction

A site-agnostic, parametric construction cost model was developed as an interactive tool to support the Cosmic Explorer (CE) team's ongoing endeavor in managing the project budget that may help inform site selection from construction budget standpoint. The cost model allows for limited evaluation of varying site conditions and program changes within its defined scope to support high-level budget updates for conventional facilities.

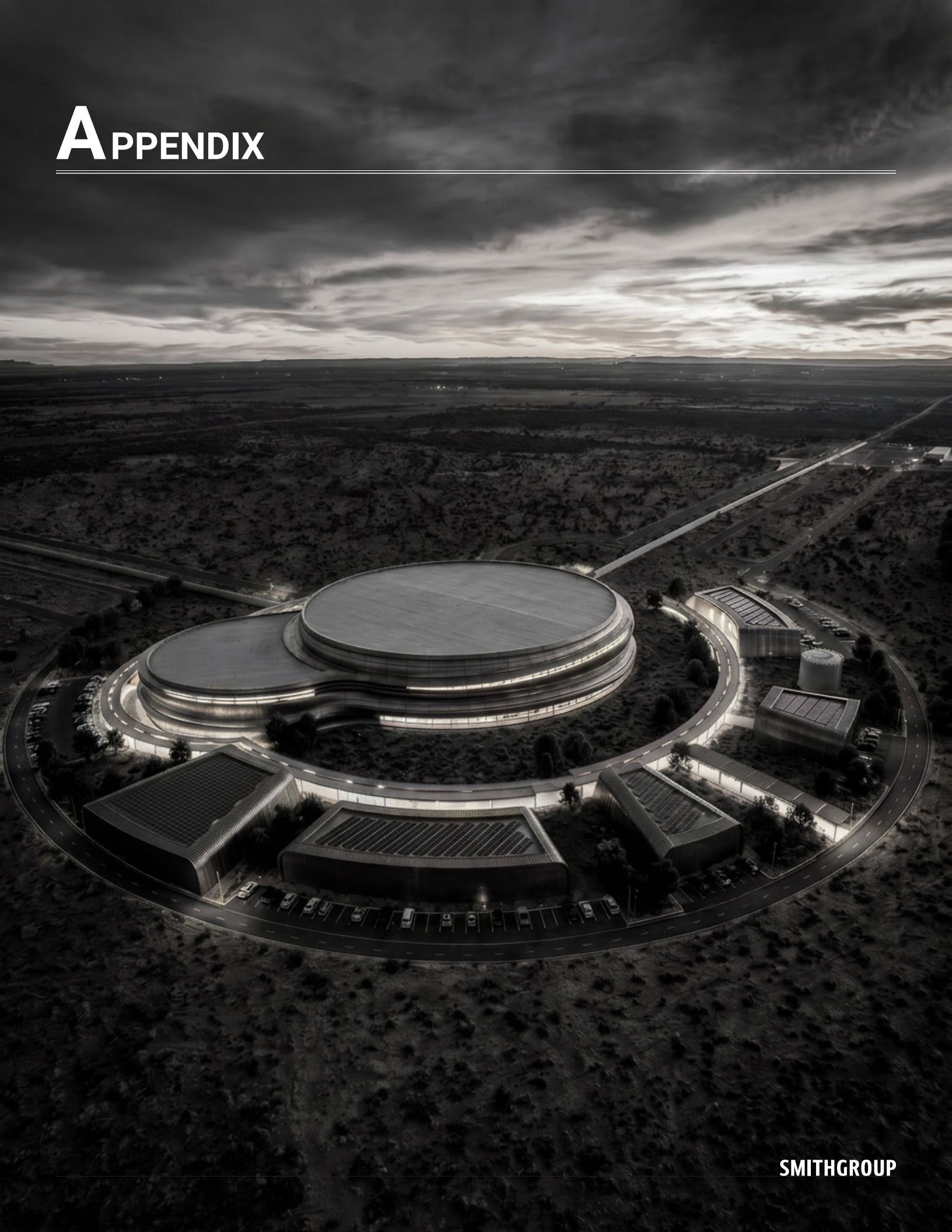
The model was initially developed using Phoenix, Arizona as the baseline location and was subsequently revised to Roswell, New Mexico based on CE team input during workshops. The construction schedule is assumed to span approximately 78 weeks, with completion in December 2032 and a midpoint in July 2031. For modeling purposes, observatory construction is assumed to occur as a single-phase construction, as confirmed during workshops.

The cost model is based on standardized geographic cost factors to support an early stage, site-agnostic assessment due to lack of chosen project site(s). As a result, the cost model does not reflect jurisdiction-specific codes, regulatory requirements, or site-specific conditions, which will be addressed following site selection in future phase. Additionally, this Feasibility Study was conducted without conceptual design development and the cost model inputs are based on high-level narratives of program and major building system requirements.

The cost model is based on an assessment of Program requirements (Section 3), assumed Site conditions (Section 5.2), Utility infrastructure (Section 5.3), various Building systems descriptions (applicable subsections of Section 5), and input from the design team.

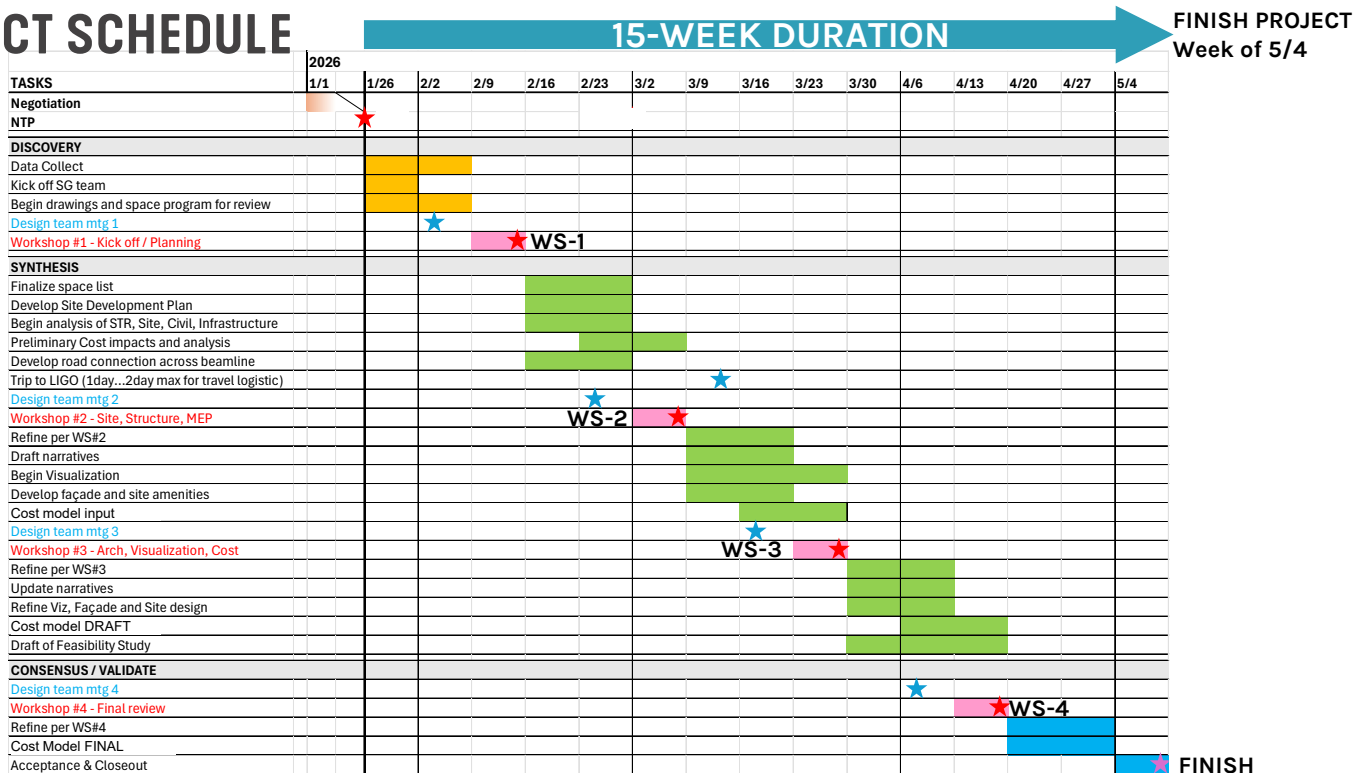
The detailed cost model and more in-depth assumptions is provided in the Appendix of this report.

APPENDIX



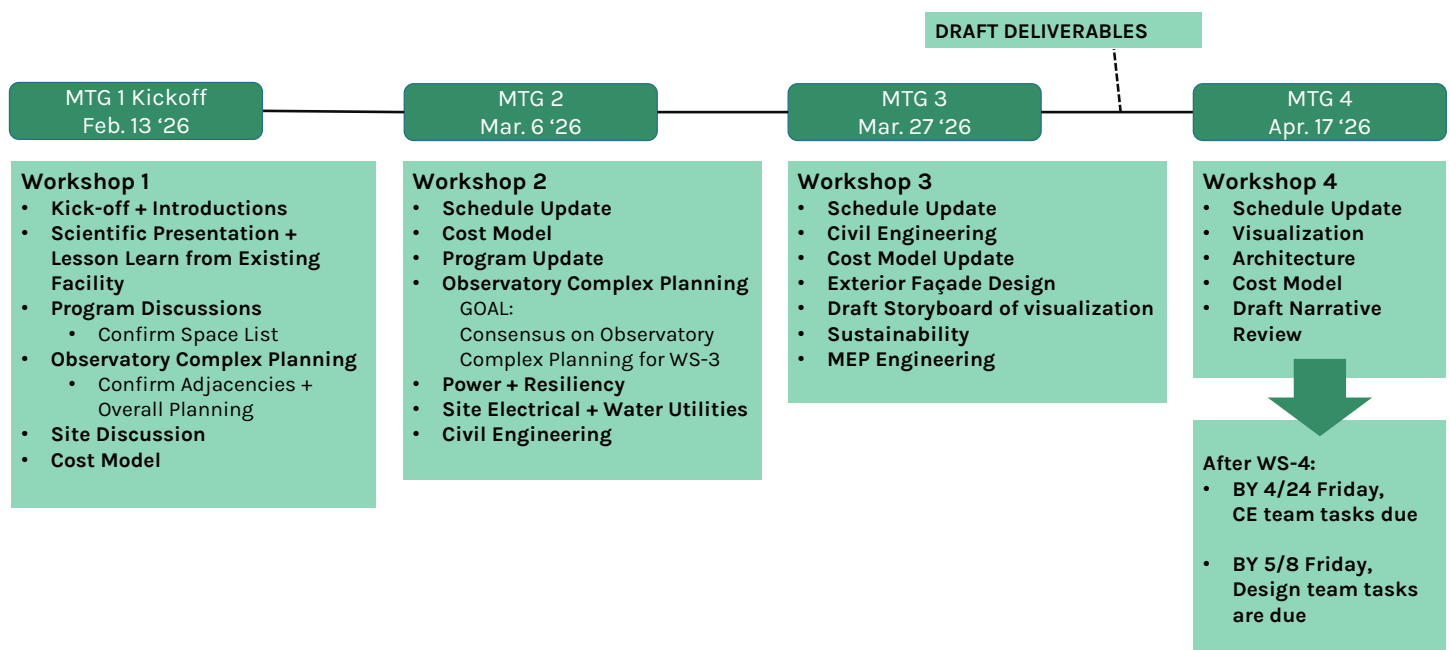
A⁰ FEASIBILITY STUDY PROJECT SCHEDULE

PROJECT SCHEDULE



WORKSHOPS

Fridays = Workshops
Start at 9am (West) / 12 noon (East)



COSMIC EXPLORER FEASIBILITY STUDY KICK-OFF (WS-1)

COSMIC EXPLORER FEASIBILITY STUDY

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AGENDA

1. INTRODUCTIONS
2. GOALS & SCHEDULE
3. COSMIC EXPLORER TEAM SCIENTIFIC PRESENTATION
4. LESSONS LEARNED, CHALLENGES WITH EXISTING FACILITIES
5. WORKSHOP-1 DISCUSSIONS
 1. PROGRAM DISCUSSION
 2. OBSERVATORY COMPLEX PLANNING
 3. SITE DISCUSSION
 4. COST MODEL
6. NEXT STEPS

INTRODUCTIONS

COSMIC EXPLORER FEASIBILITY STUDY

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INTRODUCTIONS

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Brett Leavitt
Façade Design Lead



Atiya Hasan
Mechanical
Engineer

Feb. 13, 2026

INTRODUCTIONS

ARUP

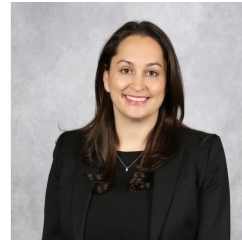
Arup Team



Josh Yacknowitz
Project Director



Mario Perez
Project Manager



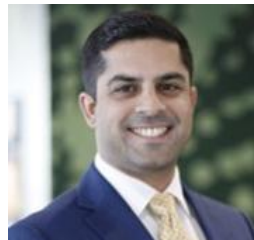
Olga Gorbunova
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Nik Sokol
Geotechnics & Tunneling Lead



Jennifer Sudario
Bridges & Civil Structures Lead



Sean Ahdi
Geohazards/Deputy PM

Feb. 13, 2026

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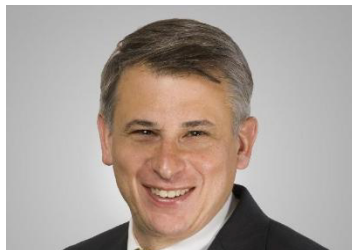
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COSMIC EXPLORER FEASIBILITY STUDY

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INTRODUCTIONS

RUTHERFORD + CHEKENE AND CUMMING TEAM



David Bleiman
Structural Engineer



Nick Mata
Cost Estimator

Feb. 13, 2026

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COSMIC EXPLORER FEASIBILITY STUDY

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GOALS AND SCHEDULE

COSMIC EXPLORER FEASIBILITY STUDY

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OUR GOAL FOR WORKSHOP 1

UNDERSTANDING THE SCIENCE

VALIDATE PROGRAM AND SPACE LISTS

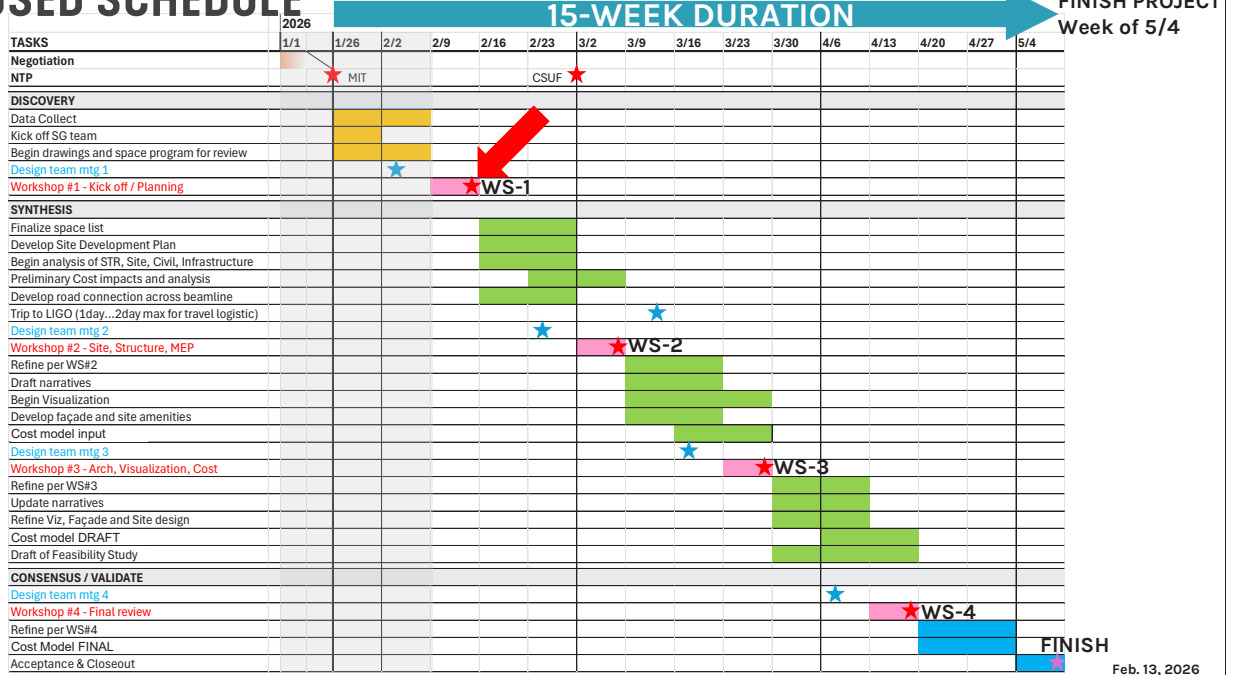
VALIDATE SITE PLANNING OF 40KM OBSERVATORY

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Feb. 13, 2026

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PROPOSED SCHEDULE



WORKSHOPS

Fridays = Workshops
Start at 9am (West) / 12 noon (East)

MTG 1 Kickoff
Feb. 13 '26

- Workshop 1**
- Kick-off + Introductions
 - Scientific Presentation + Lesson Learn from Existing Facility
 - Program Discussions
 - Confirm Space List
 - Observatory Campus Planning
 - Confirm Adjacencies + Overall Planning
 - Site Discussion
 - Cost Model

MTG 2
Mar. 6 '26

- Workshop 2**
- Progress Updates from WS-1
 - Consensus on Campus Planning to proceed to WS-3
 - Civil Engineering
 - Roads & Under/overpath strategies
 - Site Utilities strategies
 - Structural & MEP Engineering
 - Structural+Constructability
 - Confirm Loads+Capacity
 - Redundancy+ Resilience
 - MEP+Fire Protection
 - Sustainability
 - Cost Model

MTG 3
Mar. 27 '26

- Workshop 3**
DRAFT DELIVERABLES
- Exterior Façade Design
 - Architectural style
 - Climate / Sustainability
 - Massing
 - Preview Flythrough+ Rendering
 - Draft storyboard of visualization.
 - Cost Model

MTG 4
Apr. 17 '26

- Workshop 4**
- Review Site, Planning, and Engineering Updates
 - Review Final Flythrough+ Rendering
 - Pre-Finalize Report
 - Cost Model



COSMIC EXPLORER TEAM PRESENTATION

COSMIC EXPLORER FEASIBILITY STUDY

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PROGRAM DISCUSSION

COSMIC EXPLORER FEASIBILITY STUDY

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Name	designa- tion	quantity	floor area (1000 sqft)	height max (ft)	electrical max each (kW)	electrical max total (kW)
Beamline Buildings						
Corner Station Complex	CS	1	100	65	1500	1500
End Station Complex	ES	2	10	65	200	400
Mid Station Complex	MS	12	10	21	150	1000
Vacuum Valve Station	VS	26	2.5	21	50	500
Beam Tube Enclosures	BTE	2	1,200	10	100 (500*)	200 (500*)
Staging, Prep and Storage Building	SPS	1	22	tbd		
Main Campus Buildings						
Operation Support Building	OSB	1	20	25	600	600
Community/Education Building	CEB	1	15	tbd	50?	50?
Office Building	OB	1	11	tbd	50?	50?

CE Project CE-T2500017

5.2 Staging, Prep and Storage Building (SPS)
The SPS for CE shall be located approximately 100 ft [30 m] from the VEA building, ensuring

CE Project CE-T25(00)17

CE-T25(00)17

Valve station HVAC system requirements are intermediate between VEAs and BTEs. The VS HVAC will maintain a temperature of $73 \pm 10^\circ\text{F}$ ($23 \pm 5^\circ\text{C}$) with $55 \pm 15\%$ relative humidity (e.g., ensuring a non-condensing environment). Each VS will require electrical power capacity of 30 kW in addition to the HVAC power requirements (expected to be roughly 20 kW).

5 Corner Station Complex Requirements

The heart of the CE observatory is the VEA in the Corner Station complex (CS). The Corner Station complex will be broadly modeled after LIGO and [LIGO India](#) facilities. The CS complex will include the following buildings:

- Main corner station building, which houses the Vacuum Equipment Area (VEA)
- Staging, Prep and Storage Building for clean detector parts (SPS)
- Machine, Electronics and Vacuum shops building (MEV)
- Services building, which houses the Substation and Chiller-Yard (SCY)
- Pump Room and water tank Building (PRB)

In addition to housing precision interferometer components in the VEA, the corner station complex provides facilities for the assembly of detector components that require a **cleanroom environment (class 10, ISO 7)**. The workflow for these components (receiving, cleaning, assembling, storage, etc.) is contained within the SPS building. The SPS building should be in close proximity to the work spaces in the VEA building to facilitate the transport of clean parts (see section 5.2 for more information). The CS complex also provides for testing and maintenance of optical, mechanical and electrical components with the MEV building, as well as clean laboratory spaces in the VEA building.

As with other beamline stations, the CS complex includes auxiliary buildings for the Substation and Chiller-Yard and Pump Room and water tank (SCY and PRB). The scale of these buildings in the CS complex may be significantly larger than at other stations due to the greater power usage and occupancy. These buildings should be located at least 330 ft [100m] away from the VEA.

5.1 Corner Station (CS) Requirements

The CE Corner Station will have a layout and use case similar to the LIGO [Corner Station](#) and the more recent [LIGO India Corner Station](#), with the primary difference being a [smaller Office Support Building \(OSB\) footprint](#). Most office space will be relocated to the main campus, which is offset by 2 km along the X-arm (see figure 4). In addition to the large experimental hall, building components of the CS include a small control room (for installation and commissioning periods), bathrooms and other accessory facilities, but again with a minimal OSB for CE relative to LIGO.

The experimental hall will have approximate dimensions 390 ft x 390 ft [120m x 120m] floor plan to accommodate the vacuum equipment layout (see figure 15 and the [lone-crab 1 design](#) document for more information) and a floor-to-hook height of 14m. The crane shall have a rated capacity of

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Feb. 13, 2026

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PROGRAM DIFFERENCE BETWEEN SECTION 4~6 DESCRIPTIONS vs. SECTION 3 TABLE 1

PROGRAM SUMMARY / BREAKDOWN

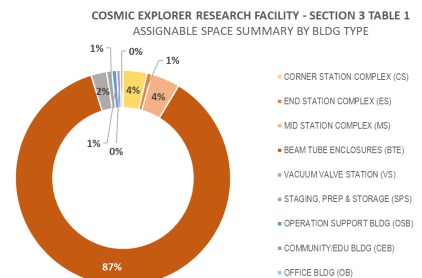
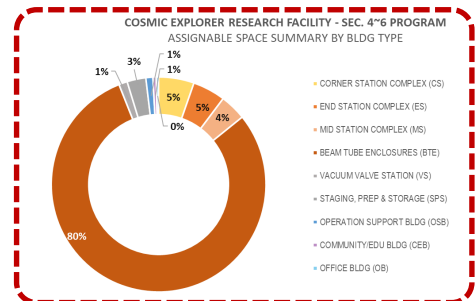
(N) COSMIC EXPLORER RESEARCH FACILITY

(N) COSMIC EXPLORER RESEARCH FACILITY		Program Summary from Sec. 4-6 (ASF)	Program Summary from Sec.3 TBL 1 (ASF)	Difference Between Sec.4-6 & Table 1
BEAMLINE BUILDINGS:				
1.0	CORNER STATION COMPLEX (CS)	162,600	100,000	62,600
2.0	END STATION COMPLEX (ES)	150,000	20,000	130,000
3.0	MID STATION COMPLEX (MS)	120,000	120,000	0
4.0	BEAM TUBE ENCLOSURES (BTE)	2,428,000	2,400,000	28,000
5.0	VACUUM VALVE STATION (VS)	39,000	65,000	-26,000
6.0	STAGING, PREP & STORAGE (SPS)	86,000	22,000	64,000
MAIN CAMPUS BUILDINGS:				
7.0	OPERATION SUPPORT BLDG (OSB)	32,250	20,000	12,250
8.0	COMMUNITY/EDU BLDG (CEB)	15,000	15,000	0
9.0	OFFICE BLDG (OB)	10,800	11,000	-200
Total ASF		2,860,600	2,640,000	220,600
Building Efficiency Gross Sq. Foot		1,907,067	1,760,000	147,067
Total GSF		4,767,667	4,400,000	367,667

ASF = Assignable Square Feet

Building Efficiency = Area for mechanical, toilets, circulation, walls, structure, etc. / Total Area = 60%

GSF = Gross Square Feet



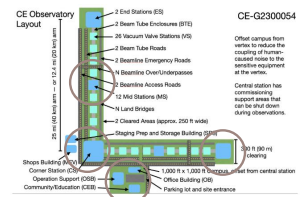
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OUR UNDERSTANDING



CS

CORNER STATION COMPLEX

MC

**MAIN
CAMPUS
COMPLEX**

MS

MID STATION COMPLEX

ES

END STATION COMPLEX

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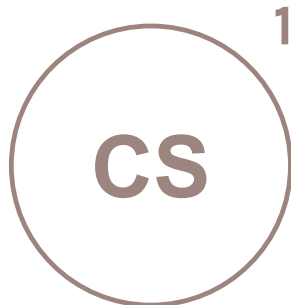
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OUR UNDERSTANDING

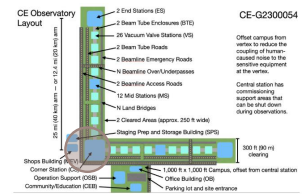
COMPLEX COMPONENTS



CORNER
STATION
COMPLEX

- Main Building housing basement Vacuum Equipment Area (VEA)
- Staging, Prep, and Storage Building (SPS)
- Machine, Equipment, and Vacuum Shops (MEV)
- Services Building housing the Substation and Chiller Yard (SCY)
- Pump Room and water tank Building (PRB)
- Office Support Building (OSB) – smaller than LIGO

❖ SPS and MEV to maintain 100m distance from VEA



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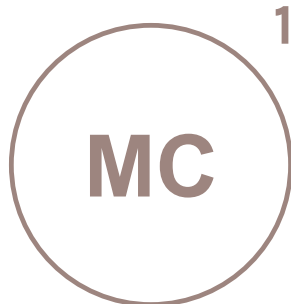
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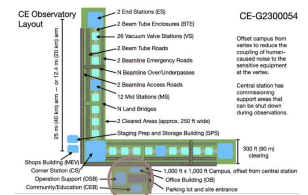
OUR UNDERSTANDING

COMPLEX COMPONENTS



MAIN
CAMPUS
COMPLEX

- Operations Support Building (OSB)
- Office Building (OB)
- Community Education Building (CEB)
- Parking for 300 vehicles (100 FTE and 200 visitors)
- Bus parking
- Park area for lunch and / or Events



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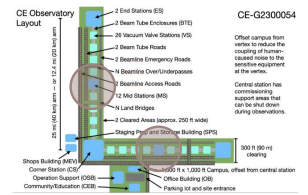
OUR UNDERSTANDING

COMPLEX COMPONENTS



12

- Main Building housing the Vacuum Equipment Area (**VEA**)
- Services Building housing the Substation and Chiller Yard (**SCY**)
- Parking for 4 vehicles



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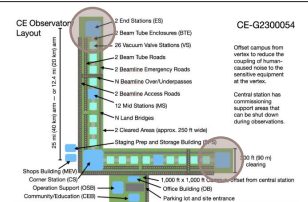
COMPLEX COMPONENTS



2

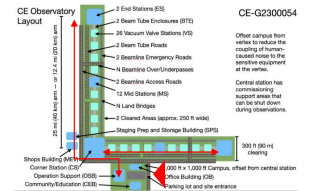
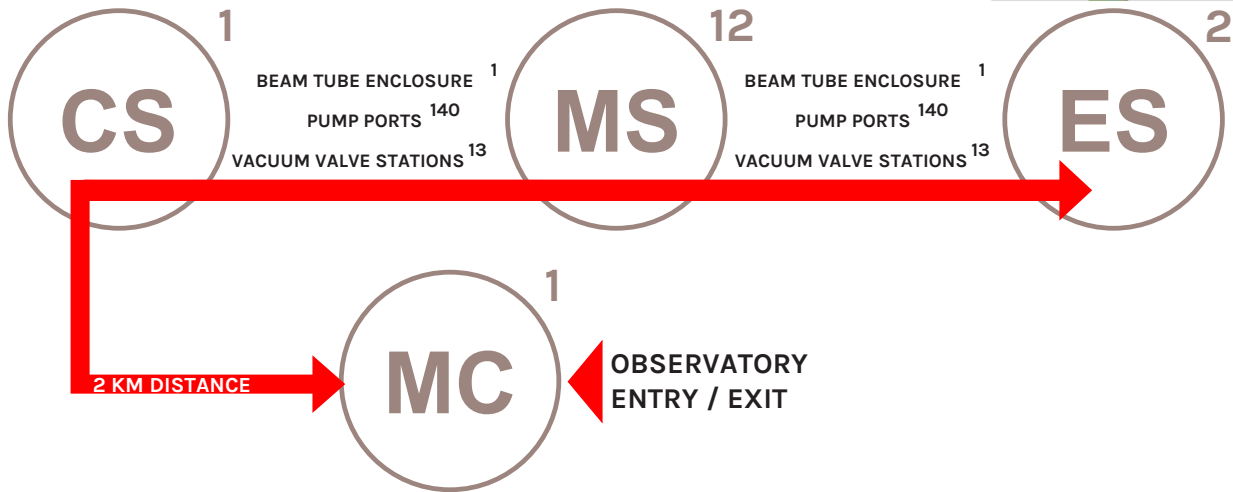
- Main Building housing basement Vacuum Equipment Area (**VEA**)
- Services Building housing the Substation and Chiller Yard (**SCY**)
- Pump Room and water tank Building (**PRB**)
- End Station Support Building (**ESB**)
- Parking for 10 vehicles

❖ **SCY** and **PRB** to maintain 100m distance from **VEA**



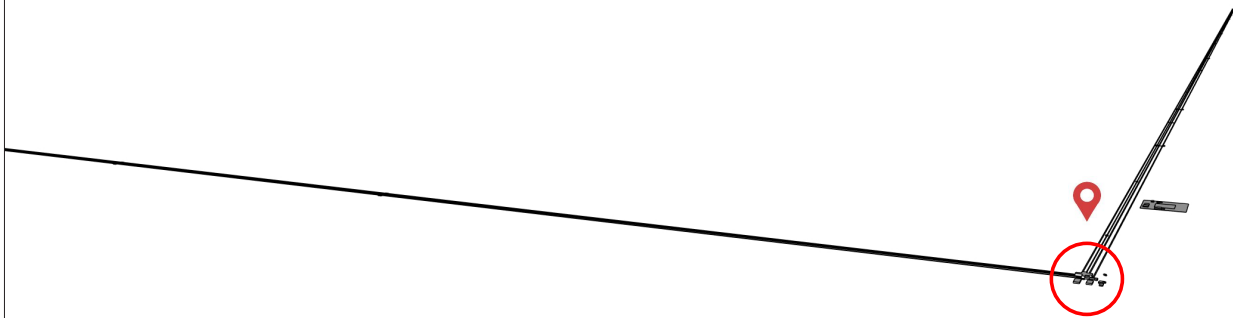
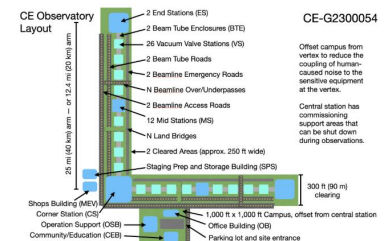
OUR UNDERSTANDING

ACCESS FLOW



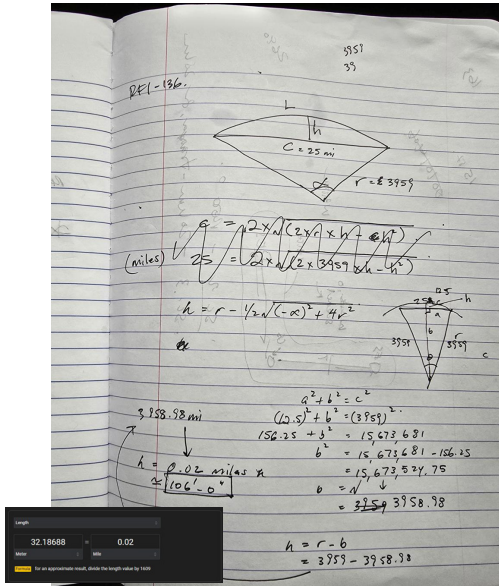
OUR UNDERSTANDING

DRAWING THE OBSERVATORY LAYOUT TO SCALE



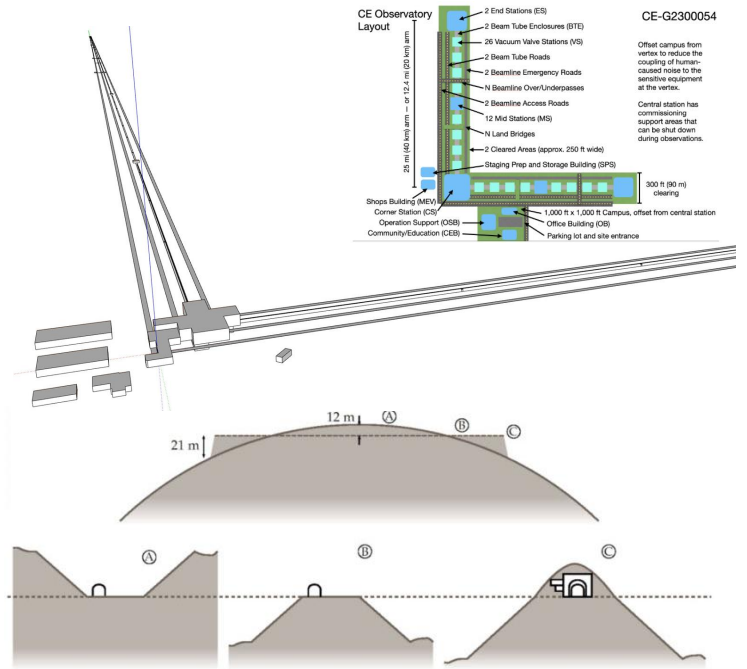
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MATH FUN



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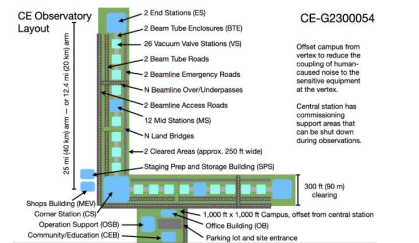
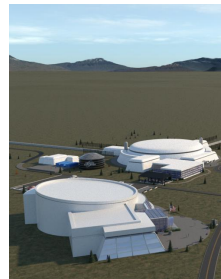


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OUR UNDERSTANDING

FORM MAKING



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SITE DISCUSSION

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SITE DIALOGUE: CIVIL & BRIDGES

ARUP

- Utilities & services: availability, relocations, and corridor conflicts
- Crossings: frequency, permitting complexity, and environmental sensitivity
- Drainage & hydrology: impoundment risk, scour exposure, floodplains
- Environmental constraints: known contamination, protected areas, regulatory risk
- Bridges: locations driven by land use, wildlife, site access, topography

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SITE DIALOGUE: GEOTECHNICS & TUNNELING

ARUP

- Sensitive/collapsible/compressible/expansive soils; differential settlement
- Seismic shaking and secondary effects of seismic/geologic hazards
- Tunneling considerations:
 - Horizontal/vertical alignment limitations;
 - anticipated tolerances based on tunneling methodology;
 - typical tunnel lining materials & durability;
 - dead/live loads in lining design;
 - groundwater ingress allowances

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SITE DIALOGUE: FATAL FLAWS

ARUP

- Hard constraints: fault crossings, floodplains, loss of system continuity
- Infrastructure access: power, water, wastewater feasibility...
- Tolerance questions: alignment movement—beamline vs. enclosure
- Precedent: lessons learned from LIGO

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COST MODEL

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COST MODEL CONSIDERATIONS – RISKS

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- **General Risks**
 - Availability of labor of and materials locally
 - Specialized material requirements
 - Lead times
 - AHJ review, permitting
 - Contracting models and risk transfer
 - Institutional construction experience
- **Site Specific Risks**
 - Subsurface conditions
 - Seismic and Environmental Noise
 - Hurricane, tornado, wind impacts on design
 - Temperature extremes and material / design impacts
- **Construction Escalation and Cost Increases**
 - Standard labor and material increases
 - Competition for labor in the broader construction landscape
 - Competition for electrical and specialty equipment



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COST MODEL BUILDUP

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- **Work Breakdown Structure**
 - Drives cost management during design and construction
 - Element-specific risk management
 - Accounting systems alignment
- **Material Considerations**
 - Availability, timing, on-site production (concrete)
 - Pre-fabricated elements vs. site built (precast)
 - Buy American clauses, Tariff impacts
 - Lead times
- **Labor**
 - Prevailing wage benchmark
 - Productivity impacts
 - Training programs
 - Tolerances
 - Housing and per diems
- **Unit Prices & Specialty Considerations**
 - Bridges, crossings, etc.
 - Boring and tunneling

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NEXT STEPS

~ONWARDS AND UPWARDS TO WS-2!

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COSMIC EXPLORER FEASIBILITY STUDY WS-2

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SCHEDULE AND AGENDA

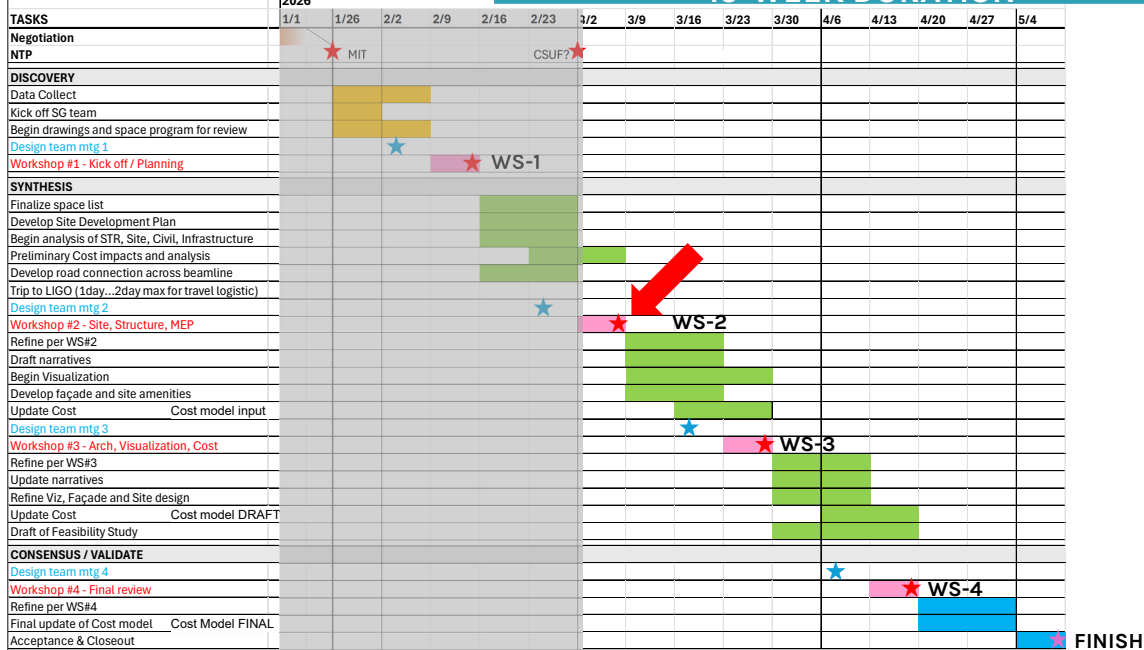
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PROPOSED SCHEDULE

15-WEEK DURATION

FINISH PROJECT
Week of 5/4



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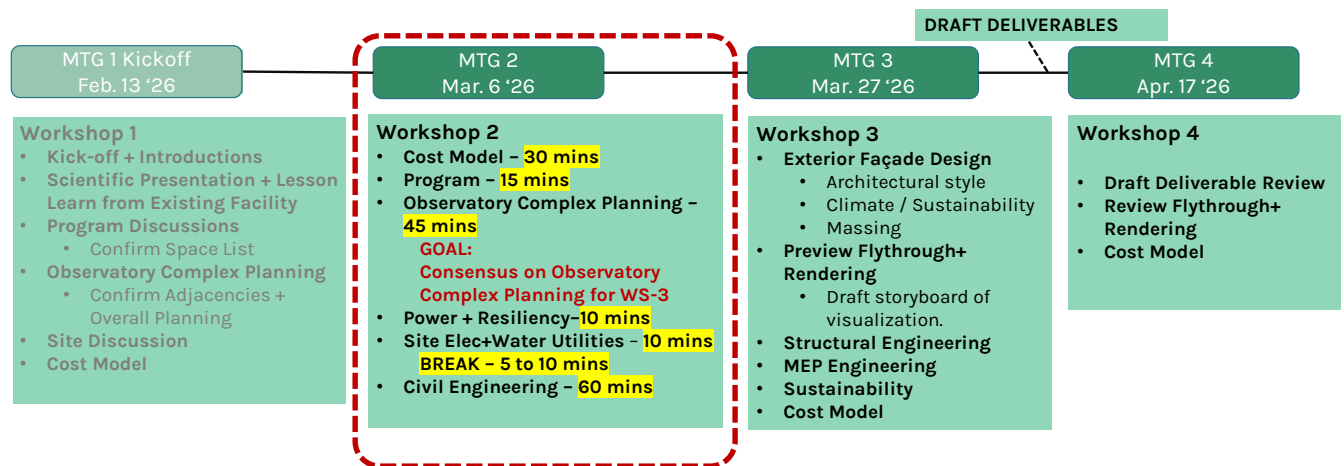
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WORKSHOPS

Fridays = Workshops
Start at 9am (West) / 12 noon (East)



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COST MODEL

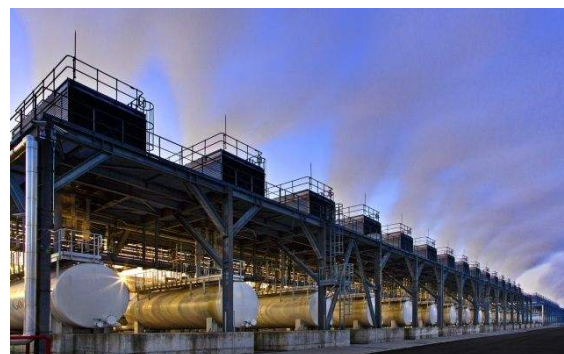
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COST MODEL CONSIDERATIONS - RISKS

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GROUP

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 - Standard labor and material increases
 - Competition for labor in the broader construction landscape
 - Competition for electrical and specialty equipment



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COST MODEL BUILDUP

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- **Labor**
 - Prevailing wage benchmark
 - Productivity impacts
 - Training programs
 - Tolerances
 - Housing and per diems
- **Unit Prices & Specialty Considerations**
 - Bridges, crossings, etc.
 - Boring and tunneling

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COST MODEL DRILL-DOWN

COST MODEL INCLUSIONS AND EXCLUSIONS – CPDC 2-7

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- **Capital Outlay Estimate Form CPDC 2-7**
 - Cost model includes scope above Line 7 (Direct / Subcontracted Costs, General Contractor Markups)
 - Outright Contingency Markup Not Allowed – Typical to Include within Unit Rates
 - Below Line 7 are Design Fees, OFOI Equipment, Legal Fees, other Markups

b.	Not Applicable.....	#DIV/0!	\$ 0	\$ 0	\$ 0
c.	Not Applicable.....	#DIV/0!	\$ 0	\$ 0	\$ 0
d.	Not Applicable.....	#DIV/0!	\$ 0	\$ 0	\$ 0
e.	Not Applicable.....	#DIV/0!	\$ 0	\$ 0	\$ 0
f.	Not Applicable.....	#DIV/0!	\$ 0	\$ 0	\$ 0
7.	TOTAL GMP.....	#DIV/0!	\$ 0	\$ 0	\$ 0
8.	FEES & CONTINGENCY (Basic Services).....				STATE
a.	A/E Services During PW.....	#DIV/0!	\$ 0		
b.	A/E Services During Construction.....	#DIV/0!	\$ 0		
c.	Project Management and Administration.....	#DIV/0!	\$ #DIV/0!		
d.	Campus Project Contingency.....	#DIV/0!	\$ 0		
e.	Total Fees & Contingency.....	#DIV/0!	\$ #DIV/0!		
9.	SUBTOTAL: CONSTRUCTION COST, FEES & CONTINGENCY (Items 7 & 8e).....	#DIV/0!	\$ #DIV/0!		
10.	CEQA On-Site/Off-Site Mitigation.....		\$ 0		
11.	Required Additional Services During PW Phase.....		\$ #DIV/0!		
12.	Required Additional Services During Construction.....		\$ #DIV/0!		
a.	Builders Risk Insurance Premium/ Seismic Fund (Enter Applicable Premium Rate in the Insurance Tab).....		\$ #DIV/0!		
b.	Owner Controlled Insurance Premium.....		\$ #DIV/0!		
13.	SUBTOTAL: PROJECT COST excl. Group II Equipment.....	#DIV/0!	\$ #DIV/0!		
14.	Group II Equipment.....		\$ 0		
15.	TOTAL: PROJECT COST incl. Group II Equipment.....	#DIV/0!	\$ #DIV/0!		
16.	Project Funds.....				

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COST MODEL DRILL-DOWN

SUMMARY-LEVEL OUTPUT AND MARKUPS

• Work Breakdown Structure

- WBS Level 2 to Match RFP (Right Image)
- WBS Level 3 to Match CPDC 2-7 (Uniformat)
- WBS Level 5-6 Anticipated (Line Items), CPDC 2-7 @ Level 4
- Cost Model Built as 100% of work Subcontracted, General Contractor Markups as per Below (Markups on Trade Costs)

Markups on Direct Construction Costs

Description	Percent
Contractor Contingency	3.00%
General Requirements	5.00%
General Conditions	7.00%
Bonds & Insurance	2.70%
Contractor's Fee	4.00%
Design Contingency	20.00%
Custom 1 - Not Applicable	0.00%
Custom 2 - Not Applicable	0.00%
Custom 3 - Not Applicable	0.00%
Escalation to MOC, 01/01/32	25.69%

Cosmic Explorer City, ST Rough Order of Magnitude			Project # 26-00xxx.00 03/05/26		
SUMMARY					
Element	Area	Cost / SF	Unit Count	Cost / Unit	Total
Office Buildings	46,000	\$0.00	N/A	N/A	\$0
Corner Station Complex	100,000	\$0.00	1 EA	\$0 /EA	\$0
End Station	20,000	\$0.00	2 EA	\$0 /EA	\$0
Mid Station Complex	120,000	\$0.00	12 EA	\$0 /EA	\$0
Vacuum Valve Station	65,000	\$0.00	26 EA	\$0 /EA	\$0
Staging Prep and Storage Bldg.	21,500	\$0.00	N/A	N/A	\$0
Beamline Construction	3,000,000	\$0.00	80 KM	\$0 /KM	\$0
Beamline Bridge	1	\$0.00	1 EA	\$0 /EA	\$0
Overpass	1	\$0.00	1 EA	\$0 /EA	\$0
Underpass	1	\$0.00	1 EA	\$0 /EA	\$0
Land Bridge	1	\$0.00	1 EA	\$0 /EA	\$0
Roads and Footpaths	1	\$0.00	N/A	N/A	\$0
Sustainable Operations Systems	1	\$0.00	N/A	N/A	\$0
Total Construction Cost	3,372,504	\$0.00			\$0

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L1

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COST MODEL DRILL-DOWN

ESCALATION

• Built-In Calculator

- Based on Overall Construction Duration
- May be used on Sub-Projects if Needed
- Calculate to Midpoint per Industry Standard, Customized to CPDC 2-7 Requirements
- 4% Standard Escalation, Intended to Account for Labor, Materials, Volume
- Pandemic-era Escalation Much Higher

Construction Dates & Escalation

Estimate Date		03/05/26		
Start Date		01/01/30		
Completion Date		12/31/33		
Duration (days)		1460		
Duration (months)		48		
Midpoint		01/01/32		
Year	Time	Rate	Total	Compounded
2026	0.82	4.00%	3.30%	3.30%
2027	1.00	4.00%	4.00%	7.43%
2028	1.00	4.00%	4.00%	11.73%
2029	1.00	4.00%	4.00%	16.20%
2030	1.00	4.00%	4.00%	20.84%
2031	1.00	4.00%	4.00%	25.68%
2032	0.00	4.00%	0.00%	25.68%
2033	0.00	4.00%	0.00%	25.68%
2034	0.00	4.00%	0.00%	25.68%
2035	0.00	4.00%	0.00%	25.68%
2036	0.00	4.00%	0.00%	25.68%
Total Escalation			25.68%	

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L1

L2

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COST MODEL DRILL-DOWN

TOGGLES & MODIFIERS

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L2

Labor/Materia/Equipment Modifiers	
Per Diems	1.35
Premium Wages, Bonuses	1.30
Air Travel	1.08
Training, Safety	1.01
Attrition	1.10
Other 1	1.00
Difficulty (Labor)	2.11
Mobilization	1.010
Maintenance, Repair, Small Tools	1.015
Fuel and Servicing	1.005
Other 1	1.000
Other 2	1.000
Other 3	1.000
Surcharge (Equipment)	1.03
Tax (Mat/Equ)	1.0860
Remote Site	1.30
Other 1	1.00
Other 1	1.00
Other 1	1.00
Other 1	1.00
Other 2	1.00
Premium (Material)	1.30

- **Global Factors, All Costs**
 - Uniform Application of Premiums
 - Not Trade, Design, or Element-Specific
 - First Principles: Base Costs + Site-Specific Modifiers
 - Customizable

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COST MODEL DRILL-DOWN

TOGGLES & MODIFIERS

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L1

L2

Division Markups			
Division	Material	Installation	Sub OH+P
02	91.63%	91.63%	115.00%
03	91.63%	91.63%	115.00%
04	91.63%	91.63%	115.00%
05	91.63%	91.63%	115.00%
06	91.63%	91.63%	115.00%
07	91.63%	91.63%	115.00%
08	91.63%	91.63%	115.00%
09	91.63%	91.63%	115.00%
10	91.63%	91.63%	115.00%
11	91.63%	91.63%	115.00%
12	91.63%	91.63%	115.00%
13	91.63%	91.63%	115.00%
14	91.63%	91.63%	115.00%
21	91.63%	91.63%	115.00%
22	91.63%	91.63%	115.00%
23	91.63%	91.63%	115.00%
25	91.63%	91.63%	115.00%
26	91.63%	91.63%	115.00%
27	91.63%	91.63%	115.00%
28	91.63%	91.63%	115.00%
31	91.63%	91.63%	115.00%
32	91.63%	91.63%	115.00%
33	91.63%	91.63%	115.00%
34	91.63%	91.63%	115.00%
40	91.63%	91.63%	115.00%
41	91.63%	91.63%	115.00%
44	91.63%	91.63%	115.00%
48	91.63%	91.63%	115.00%

GeoModifiers	Phoenix, Arizona		Cookeville, Tennessee	
Division	Material	Installation	Material	Installation
02	88.4	88.4	81.0	81.0
03	88.4	88.4	81.0	81.0
04	88.4	88.4	81.0	81.0
05	88.4	88.4	81.0	81.0
06	88.4	88.4	81.0	81.0
07	88.4	88.4	81.0	81.0
08	88.4	88.4	81.0	81.0
09	88.4	88.4	81.0	81.0
10	88.4	88.4	81.0	81.0
11	88.4	88.4	81.0	81.0
12	88.4	88.4	81.0	81.0
13	88.4	88.4	81.0	81.0
14	88.4	88.4	81.0	81.0
21	88.4	88.4	81.0	81.0
22	88.4	88.4	81.0	81.0
23	88.4	88.4	81.0	81.0
25	88.4	88.4	81.0	81.0
26	88.4	88.4	81.0	81.0
27	88.4	88.4	81.0	81.0
28	88.4	88.4	81.0	81.0
31	88.4	88.4	81.0	81.0
32	88.4	88.4	81.0	81.0
33	88.4	88.4	81.0	81.0
34	88.4	88.4	81.0	81.0
40	88.4	88.4	81.0	81.0
41	88.4	88.4	81.0	81.0
44	88.4	88.4	81.0	81.0
48	88.4	88.4	81.0	81.0

- **Base Build**
 - Base Point - Required (Pheonix)
- **Geomodifier**
 - Select Nearest Available Option
 - Final Modifiers will be Customized to Location and Division
 - Multitude of Published Modifiers: RSMeans, USACE ACF, etc.
- **Geomodifiers - Drawbacks**
 - Not Included in Geomodifiers:
 - Codes
 - Nuances of Local Jurisdictions
 - Site-Specific Conditions

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COST MODEL DRILL-DOWN

LINE ITEMS

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G1020 Site Prep & Site Improvements	Quantity	Unit	Adj. Mat.	Adj. Labor	Adj. Equip.	Other (Override)	Adj. Unit Cost	Total	Base Mat.	Base Lab.	Crew	Lab. Rate	Prod.	Base Equip.	Unit Cost	CSI Code
Site Clearing																
Field staking/layout	52,800,000	sf		\$0.17	\$0.02		\$0.19	\$10,032,000		0.09	lab1	38.7000	0.0020	0.01	0.09	31.10.05.0005
Clear and grub site	52,800,000	sf		\$0.15	\$0.03		\$0.18	\$9,504,000		0.07	trench1	61.0400	0.0011	0.03	0.10	31.10.05.0010
Earth Moving																
Excavation	1,145,833	bcy		\$1.09	\$1.34		\$2.43	\$2,784,375		0.49	trench1	61.0400	0.0080	1.14	1.63	31.30.05.0005
Loading	1,145,833	bcy		\$1.08	\$1.61		\$2.69	\$3,082,292		0.48	trench1	61.0400	0.0079	1.37	1.85	31.30.05.0005
Haul, 13 mile round trip, 18CY truck, 25MPH, 15 min wait time	1,289,063	lcy		\$3.82	\$10.26		\$14.08	\$18,150,000		0.73	truck1	39.9000	0.0430	8.70	10.42	31.20.05.0015
Fill, spread (25% bulking)	1,432,292	lcy		\$1.63	\$2.06		\$3.69	\$5,285,156		0.73	trench1	61.0400	0.0120	1.75	2.48	31.30.05.0010
Compaction	1,145,833	bcy		\$1.09	\$0.75		\$1.83	\$2,096,875		0.49	trench1	61.0400	0.0080	0.63	1.12	31.30.05.0010
Import fill, allowance, 10% of total, 50 mile round trip, 18CY truck, 55MPH, 30 min wait time	143,229	lcy	\$12.87	\$6.95	\$18.77		\$38.59	\$5,527,214	8.65	3.12	truck1	39.9000	0.0783	15.92	27.70	31.20.05.0015
Fine grading	52,800,000	sf		\$0.48	\$0.07		\$0.54	\$28,512,000		0.21	trench1	61.0400	0.0035	0.06	0.27	31.20.05.0025
Erosion control	52,800,000	sf	\$0.02	\$0.07			\$0.09	\$4,752,000	0.02	0.03	trench1	61.0400	0.0005		0.05	31.20.05.0030

- Base (Beige) = Costs Before Application of Global Factors
- Adjusted (Yellow) = Costs After Application of Global Factors
- Crews and Assumed Average Labor Rate included – Rough Calculation of Total Trade Labor
- Productivity = Base / Ideal Scenario Before Application of Global Factors

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COST MODEL DRILL-DOWN

NOTES AND CONSIDERATIONS

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- **Buildings**
 - Complex, Multiple Trades, Multiple Elements
 - Low LOD means Approximations of Specific Quantities and Systems
- **Beamline**
 - Full Length Buildup Translated to Cost per Kilometer
 - Tunneling and Other Technologies Significantly Impacted by Productivity & Economies of Scale
 - Soil Conditions May Necessitate Surcharge Schemes
- **General Cost Model & Miscellaneous**
 - Availability of Utilities: Power, Water, Sewer, Telecommunications
 - Site Development, Building Aesthetics, Amenities, Talent Attraction and Retention
 - Estimate Classification

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COSMIC EXPLORER FEASIBILITY STUDY

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PROGRAM DISCUSSION

COSMIC EXPLORER FEASIBILITY STUDY

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PROGRAM DISCUSSION

COSMIC EXPLORER BASE PROGRAM STUDY (25 mi)

BUILDING PROGRAM AREA SUMMARY & BREAKDOWN BY TYPE

PROGRAM SUMMARY / BREAKDOWN

(N) COSMIC EXPLORER RESEARCH FACILITY

	Program Summary from Sec. 4~6 (ASF)	Program Summary from Sec.3 TBL 1 (ASF)	Difference Between Sec.4~6 & Table 1
BEAMLINE BUILDINGS:			
1.0 CORNER STATION COMPLEX (CS)	104,050	100,000	4,050
2.0 END STATION COMPLEX (ES)	52,400	20,000	32,400
3.0 MID STATION COMPLEX (MS)	80,400	120,000	-39,600
4.0 BEAM TUBE ENCLOSURES (BTE)	2,428,000	2,400,000	28,000
5.0 VACUUM VALVE STATION (VS)	39,000	65,000	-26,000
6.0 STAGING, PREP & STORAGE (SPS)	17,675	22,000	-4,325
MAIN CAMPUS BUILDINGS:			
7.0 OPERATION SUPPORT BLDG (OSB)	19,050	20,000	-950
8.0 COMMUNITY/EDU BLDG (CEB)	15,568	15,000	568
9.0 OFFICE BLDG (OB)	24,530	11,000	13,530
Total ASF	2,780,673	2,773,000	7,673
Building Efficiency Gross Sq. Foot	1,853,782	1,848,667	5,115
Total GSF	4,634,454	4,621,667	12,788

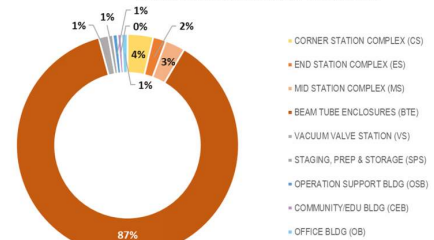
ASF = Assignable Square Feet

Building Efficiency = Area for mechanical, toilets, circulation, walls, structure,

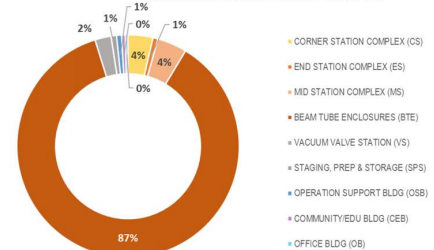
GSF = Gross Square Feet

SPS to be included in CS.

COSMIC EXPLORER RESEARCH FACILITY - SEC. 4~6 PROGRAM
ASSIGNABLE SPACE SUMMARY BY BLDG TYPE



COSMIC EXPLORER RESEARCH FACILITY - SECTION 3 TABLE 1
ASSIGNABLE SPACE SUMMARY BY BLDG TYPE



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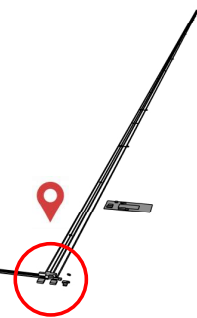
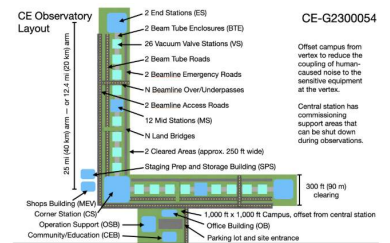
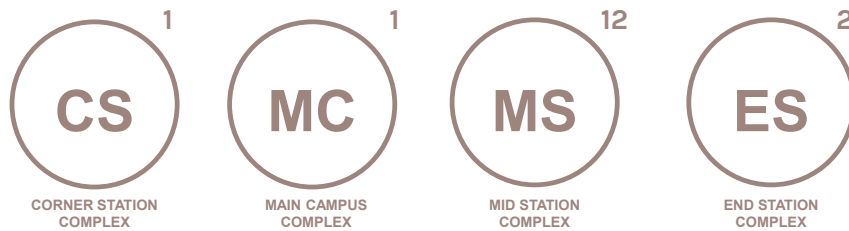
OBSERVATORY COMPLEX PLANNING

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OBSERVATORY OVERALL

DRAWING THE OBSERVATORY LAYOUT TO SCALE



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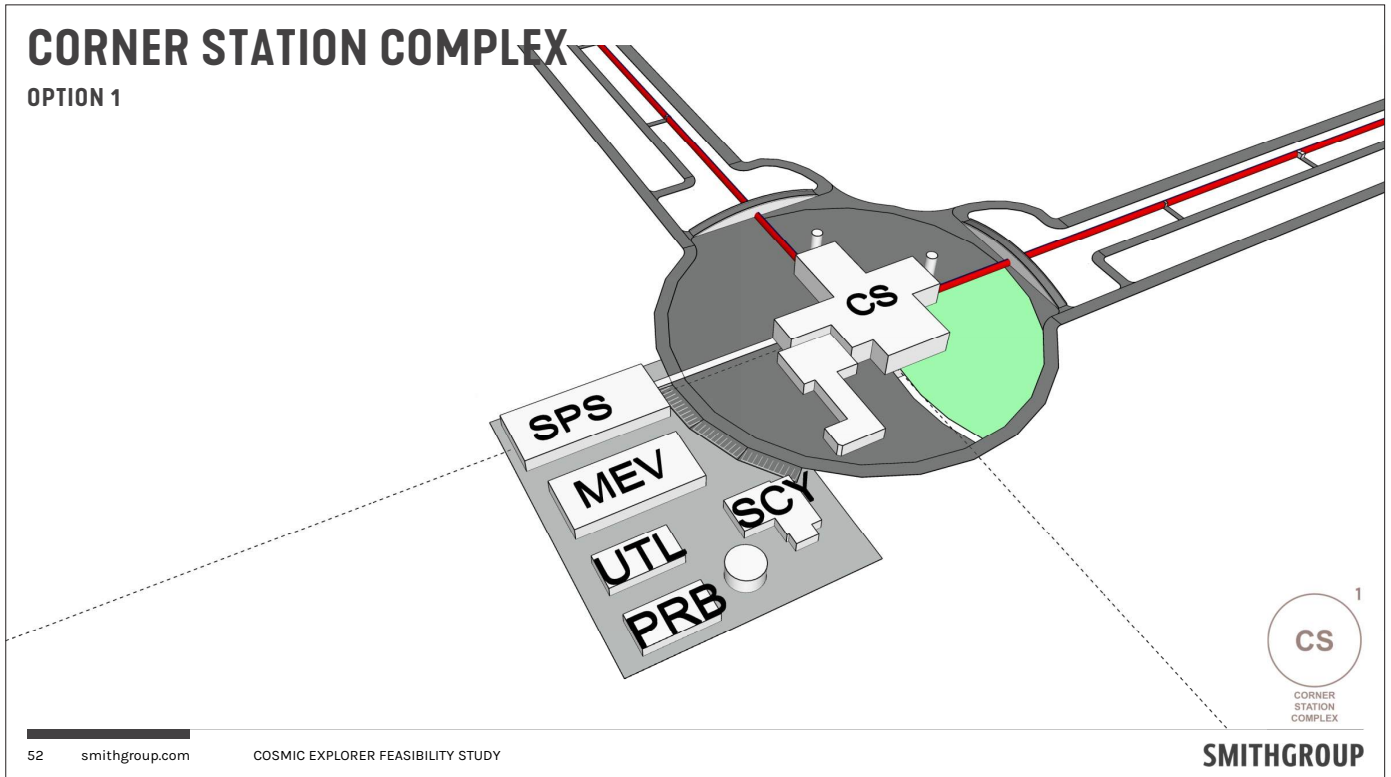
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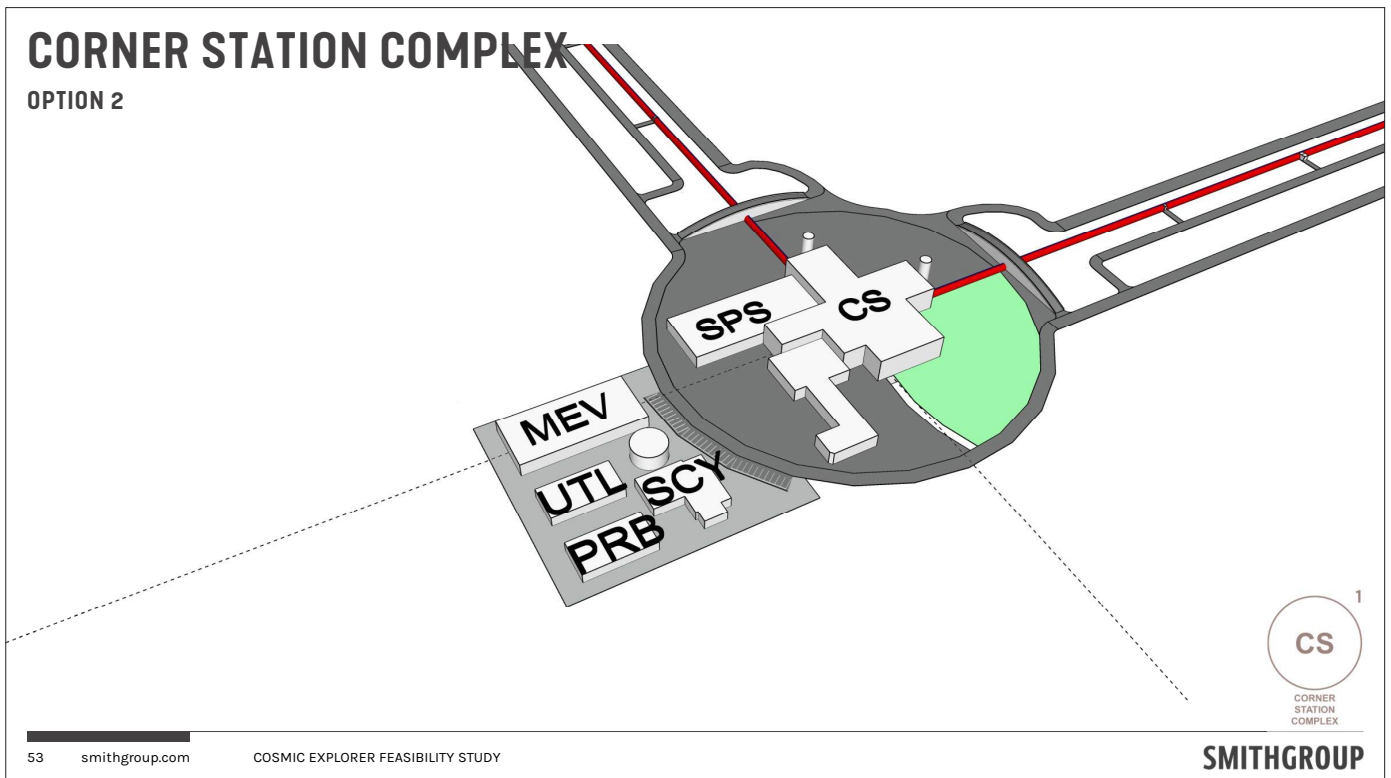
CORNER STATION COMPLEX

OPTION 1



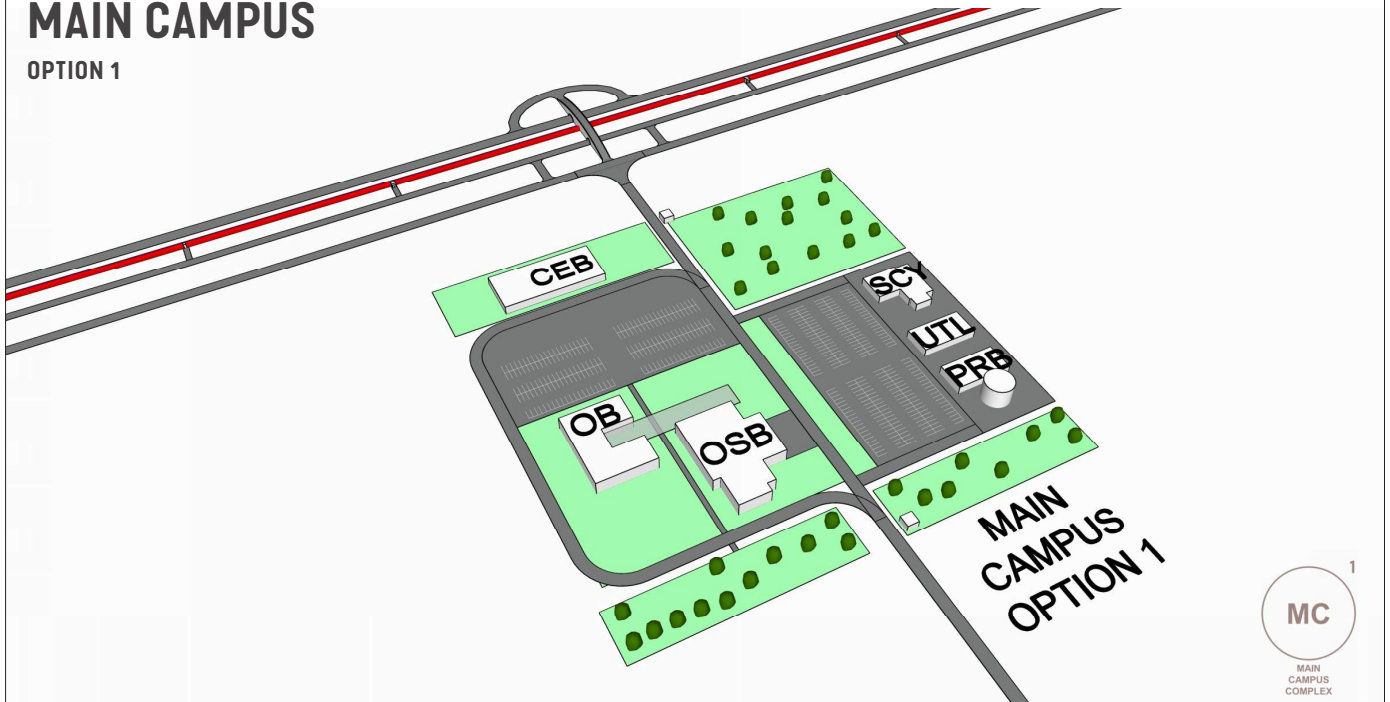
CORNER STATION COMPLEX

OPTION 2



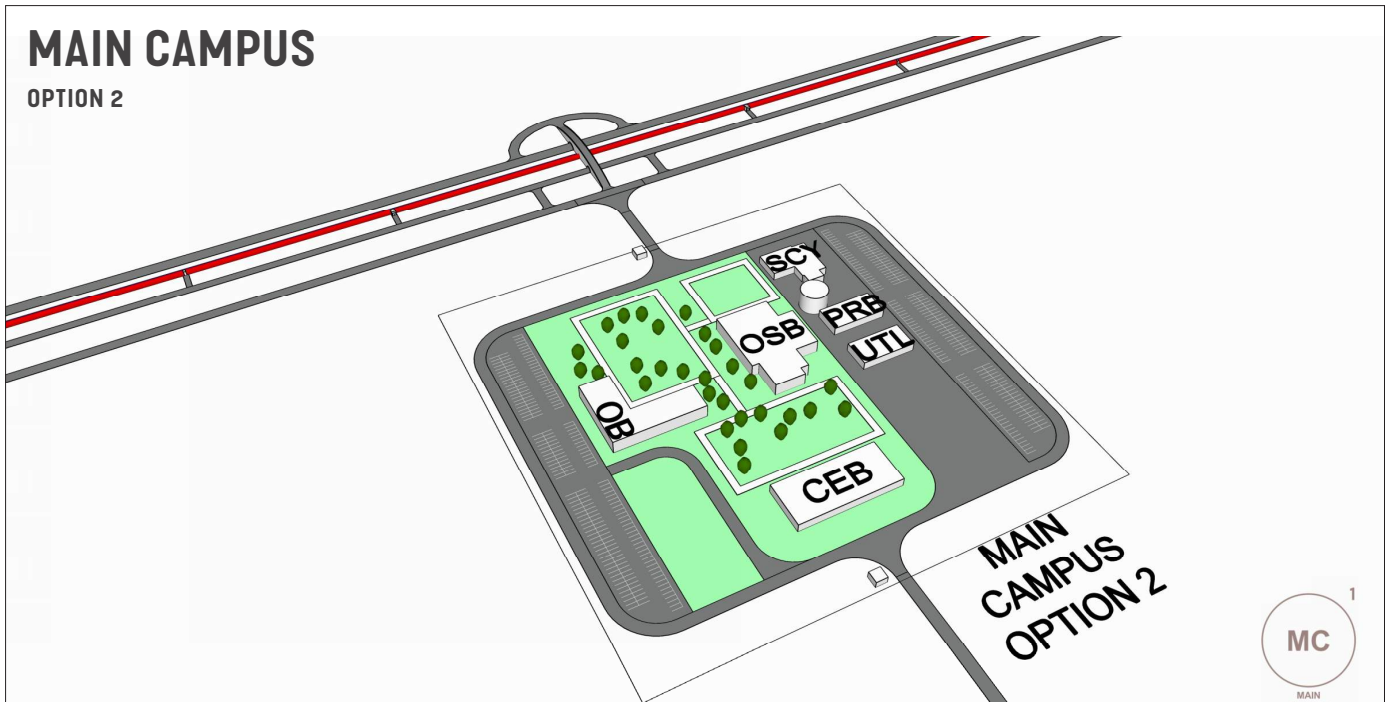
MAIN CAMPUS

OPTION 1



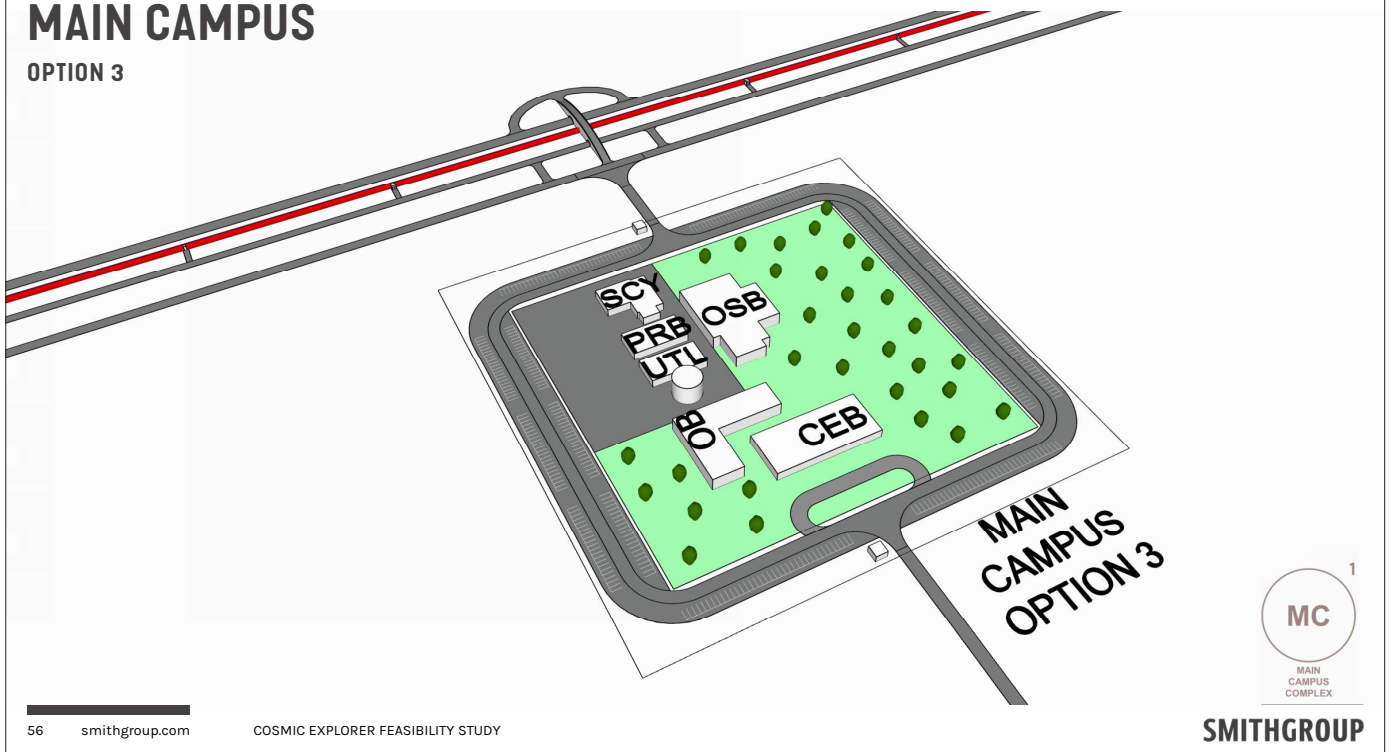
MAIN CAMPUS

OPTION 2



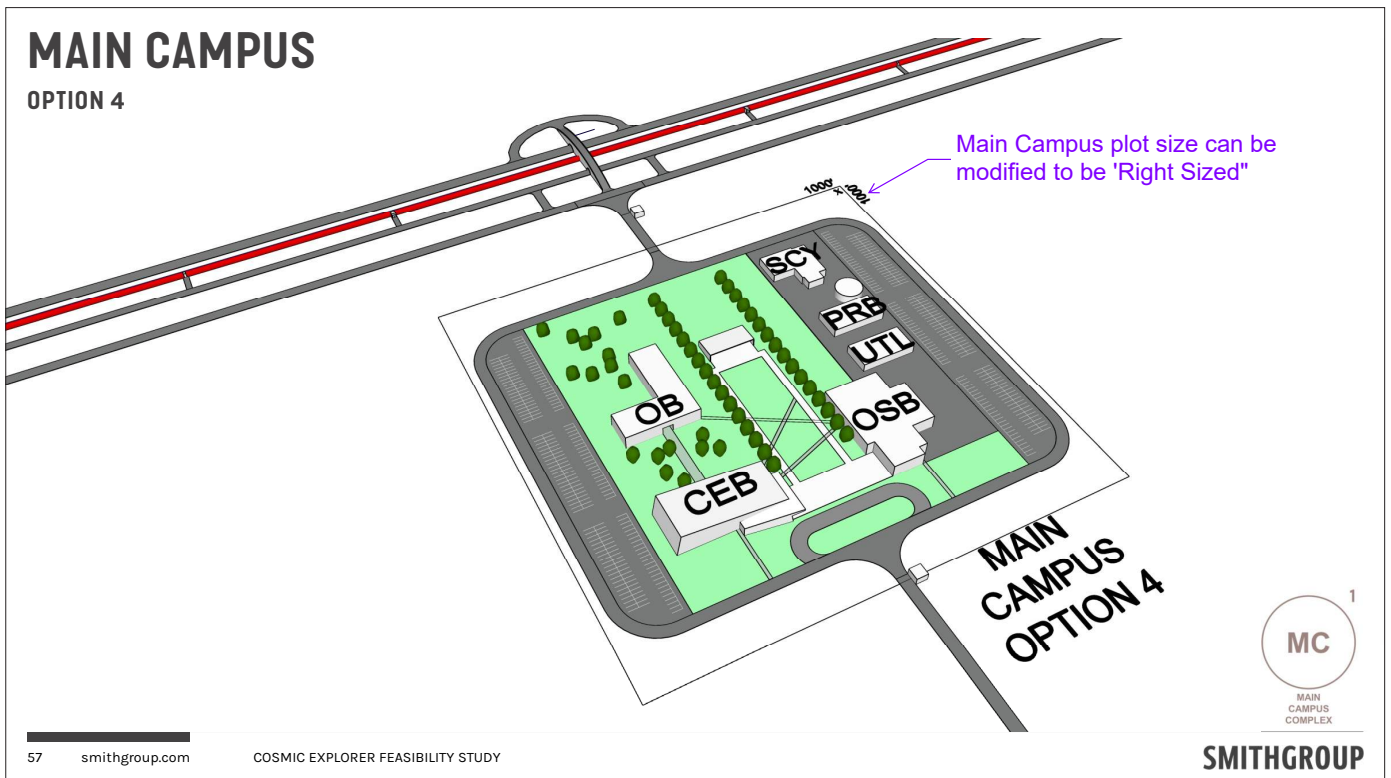
MAIN CAMPUS

OPTION 3



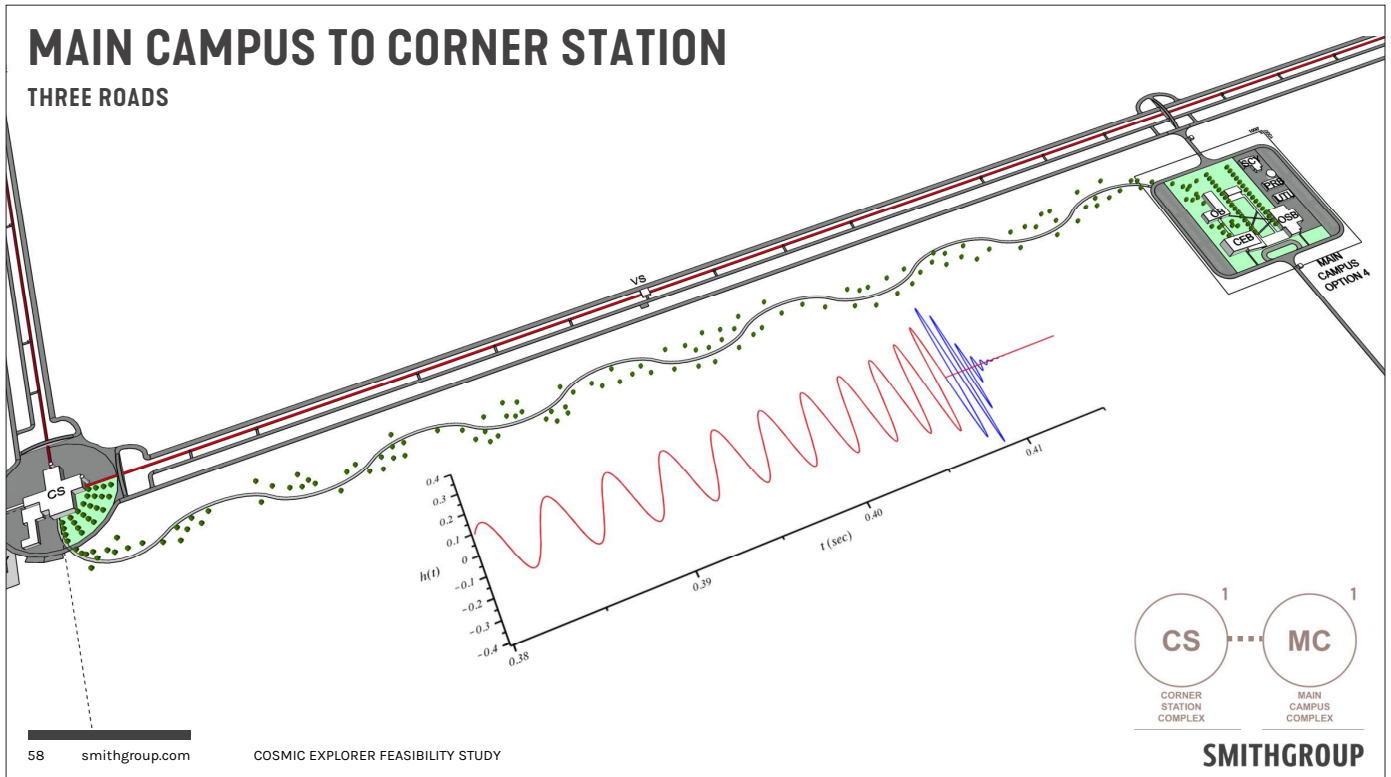
MAIN CAMPUS

OPTION 4



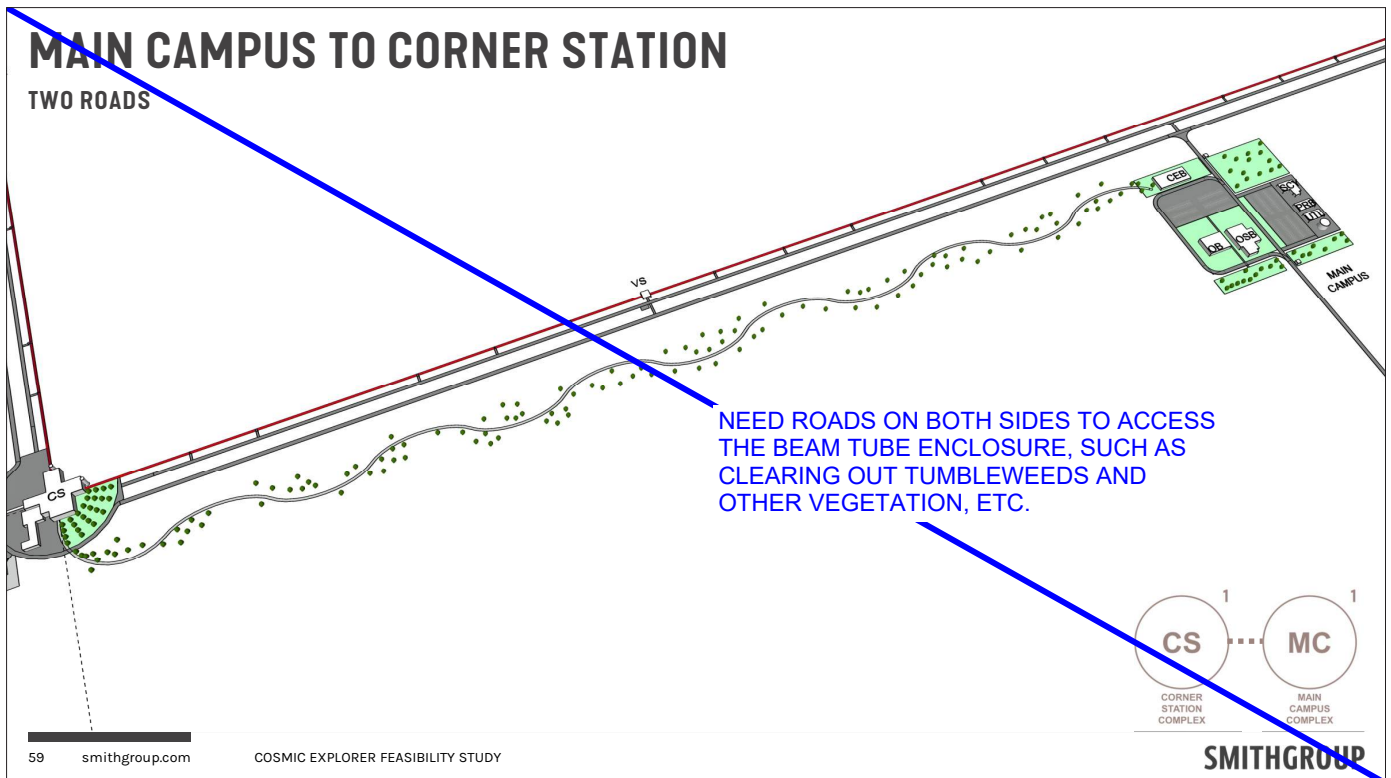
MAIN CAMPUS TO CORNER STATION

THREE ROADS

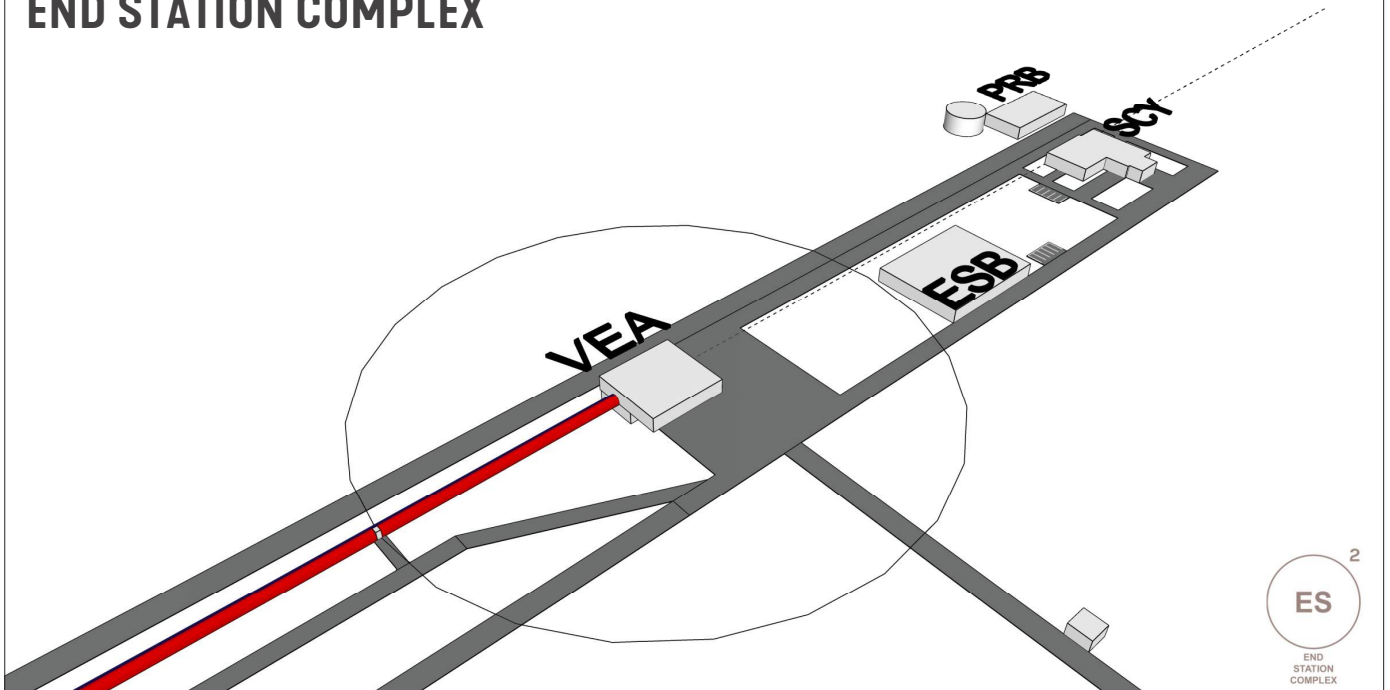


MAIN CAMPUS TO CORNER STATION

TWO ROADS



END STATION COMPLEX

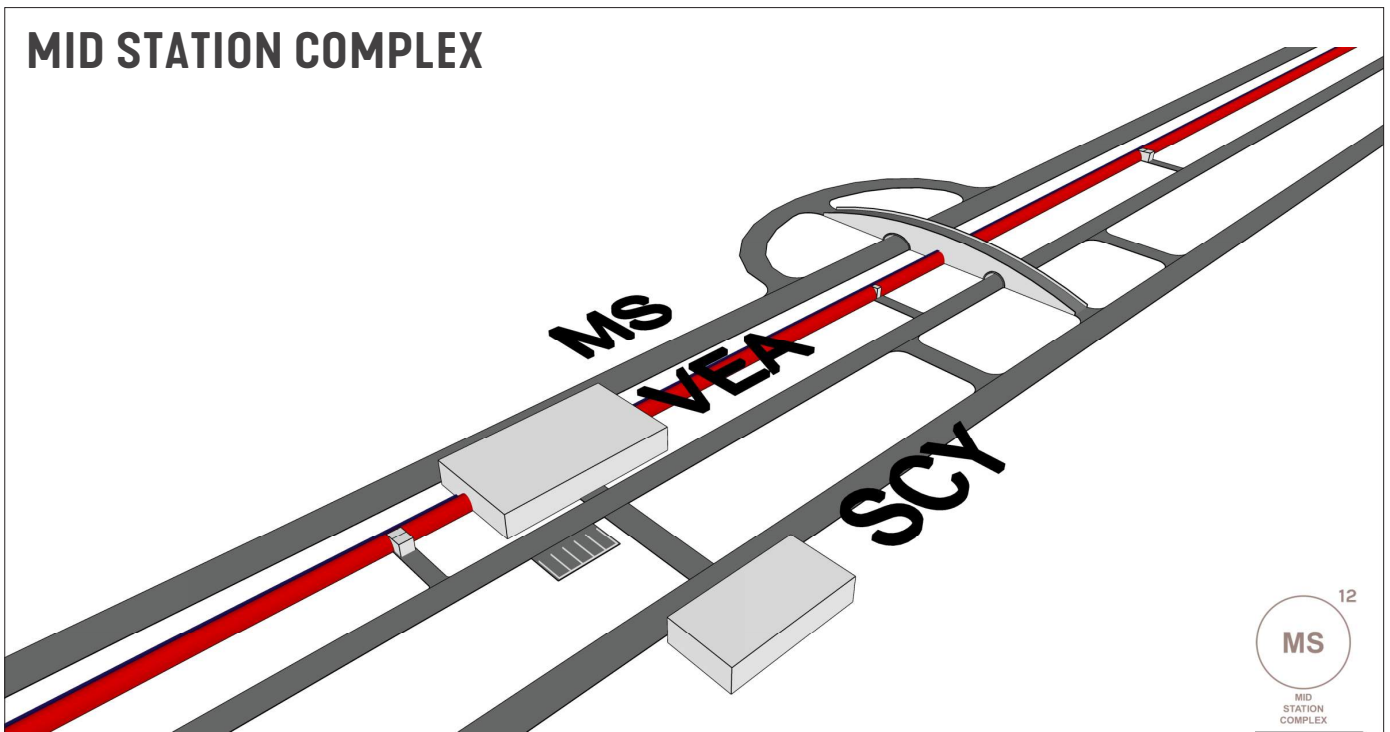


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COSMIC EXPLORER FEASIBILITY STUDY

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MID STATION COMPLEX



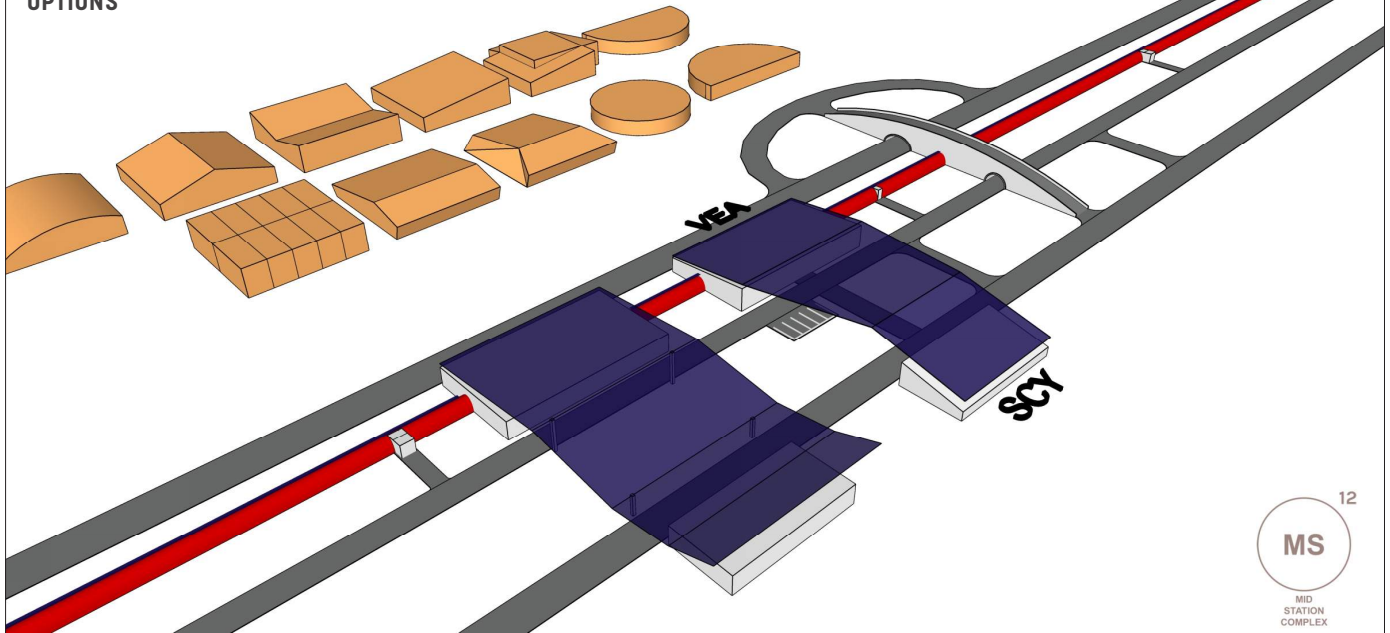
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COSMIC EXPLORER FEASIBILITY STUDY

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MID STATION COMPLEX

OPTIONS

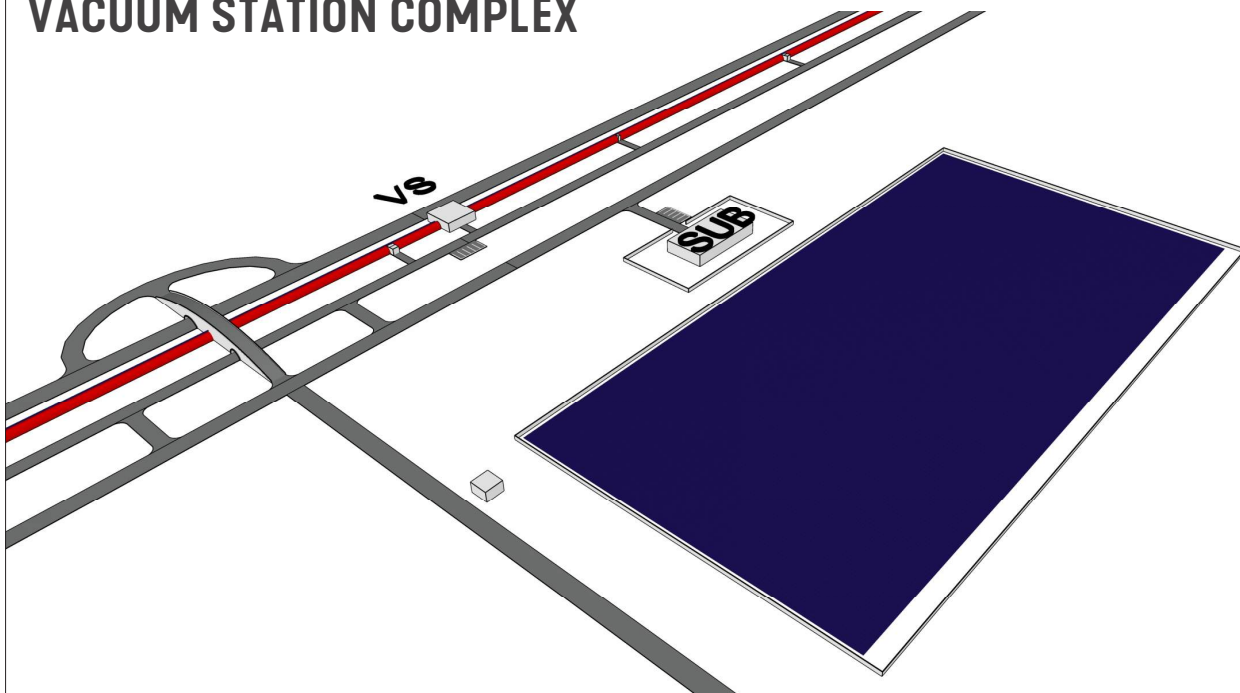


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VACUUM STATION COMPLEX



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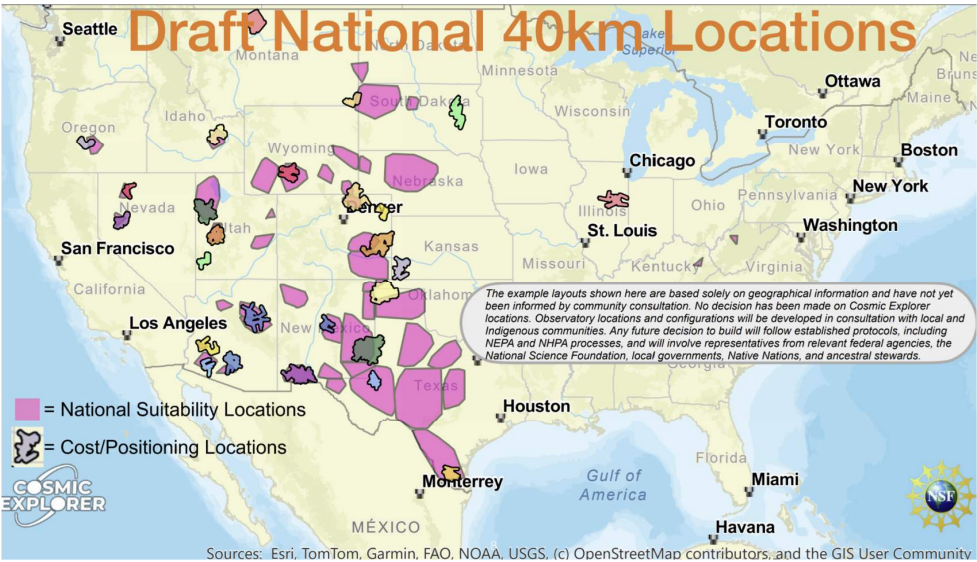
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POWER AND RESILIENCY

COSMIC EXPLORER FEASIBILITY STUDY

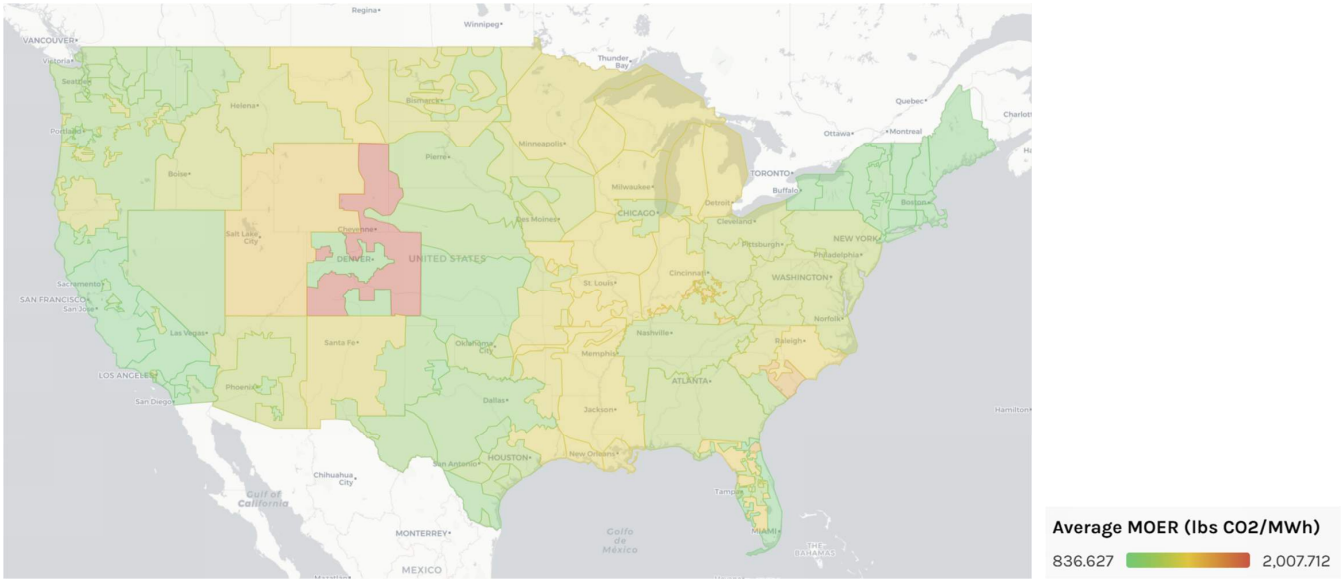
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DRAFT SITE LOCATIONS



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US GRID MARGINAL CARBON EMISSIONS

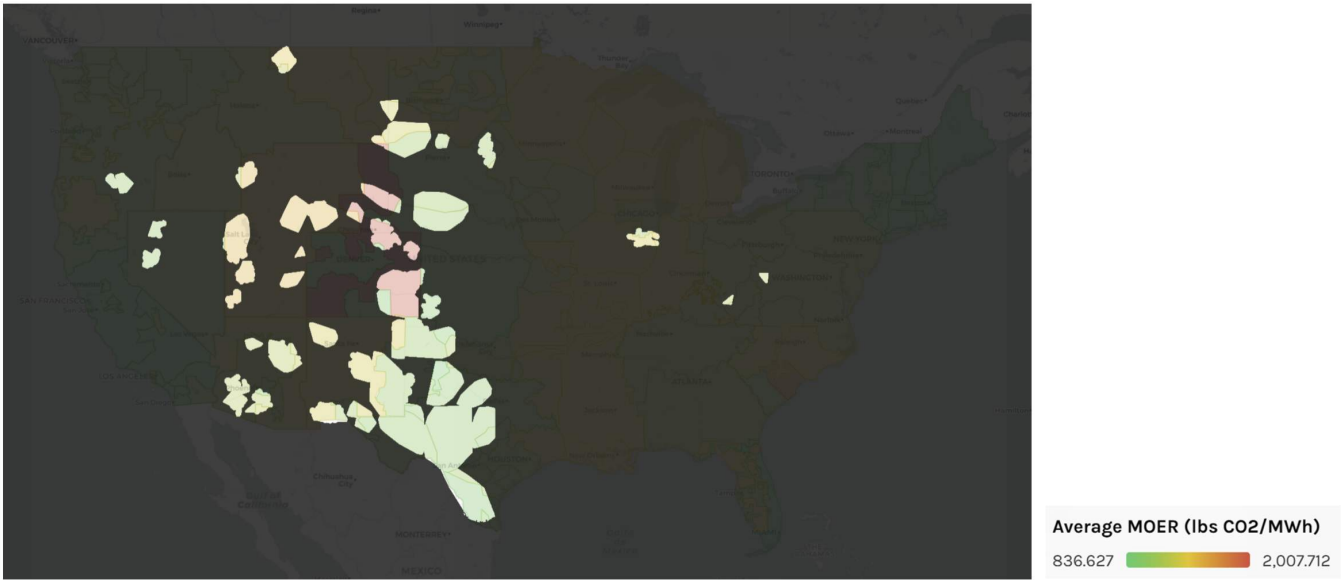


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US GRID MARGINAL CARBON EMISSIONS

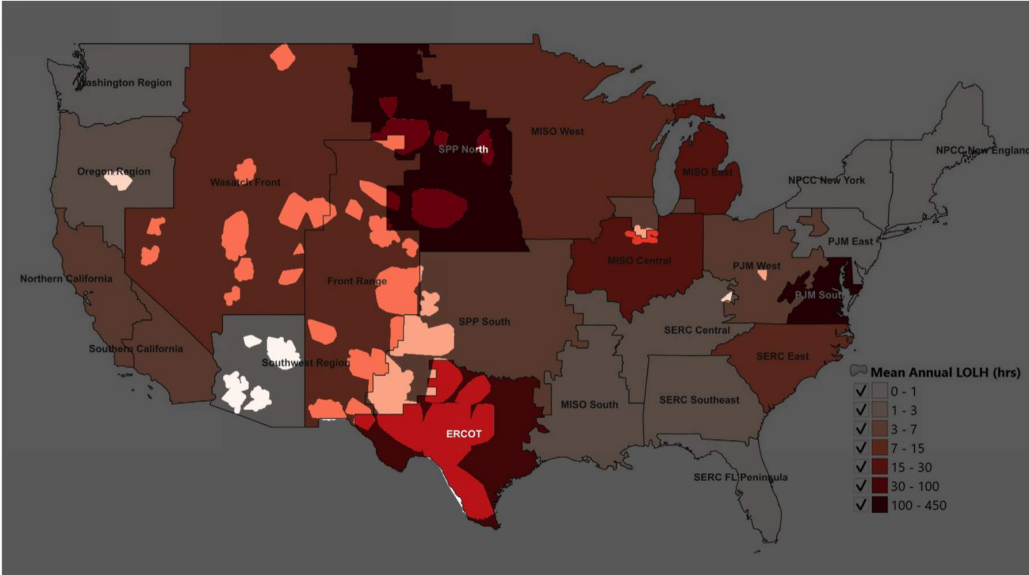


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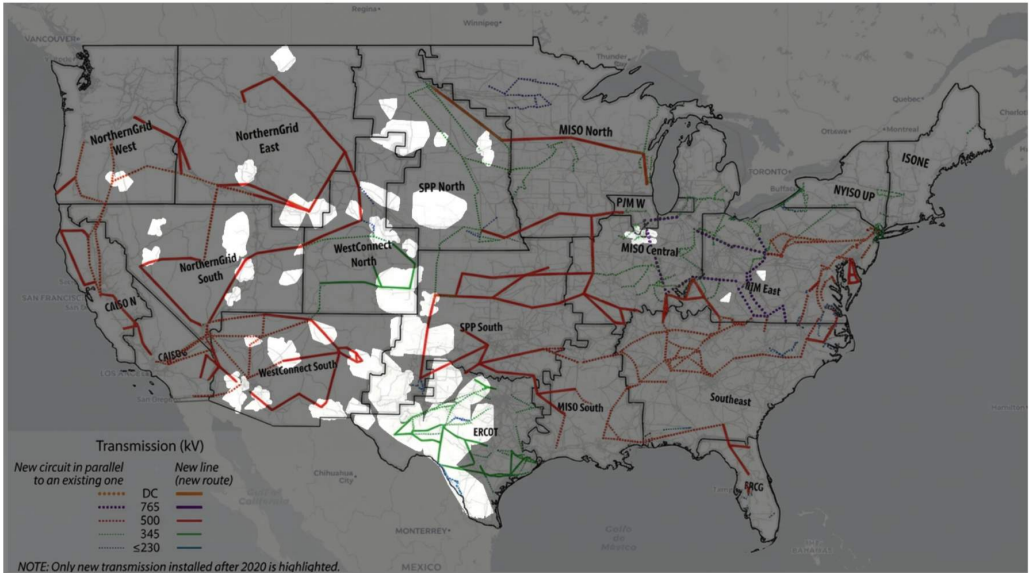
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DOE GRID RELIABILITY – 2030 LOLH PREDICTION



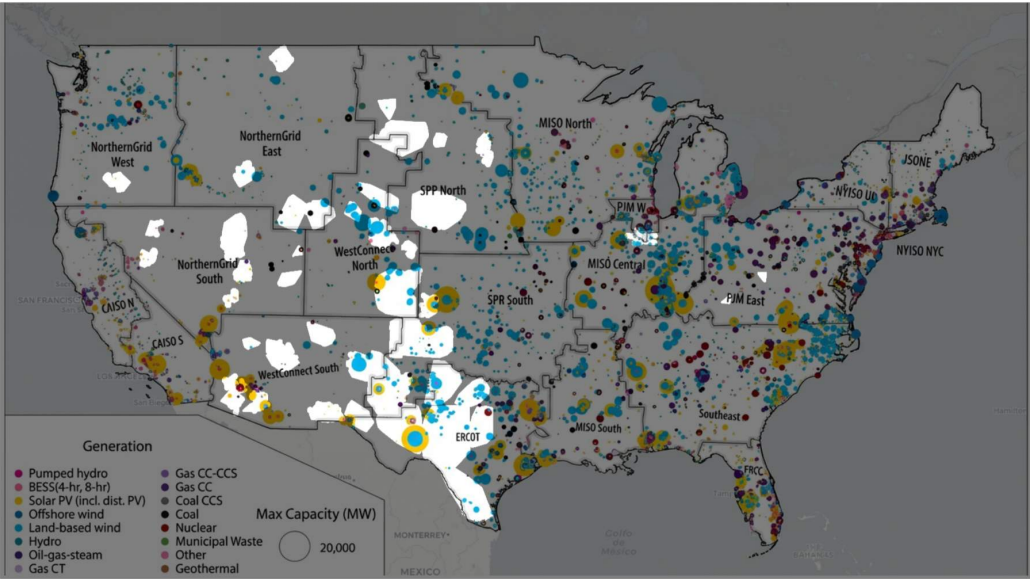
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2035 GRID DISTRIBUTION PROJECTION

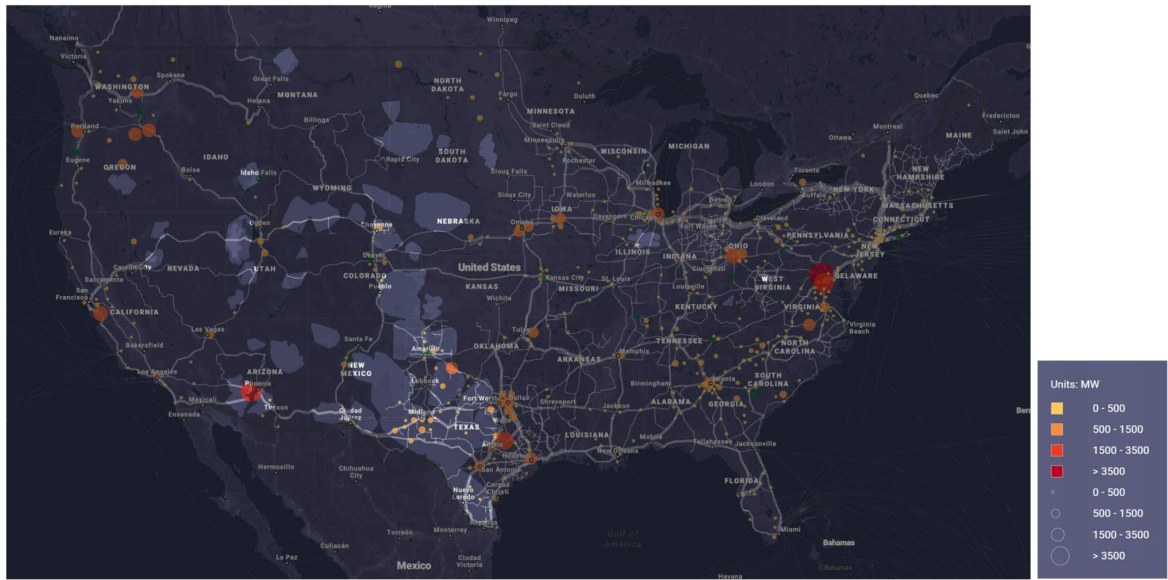


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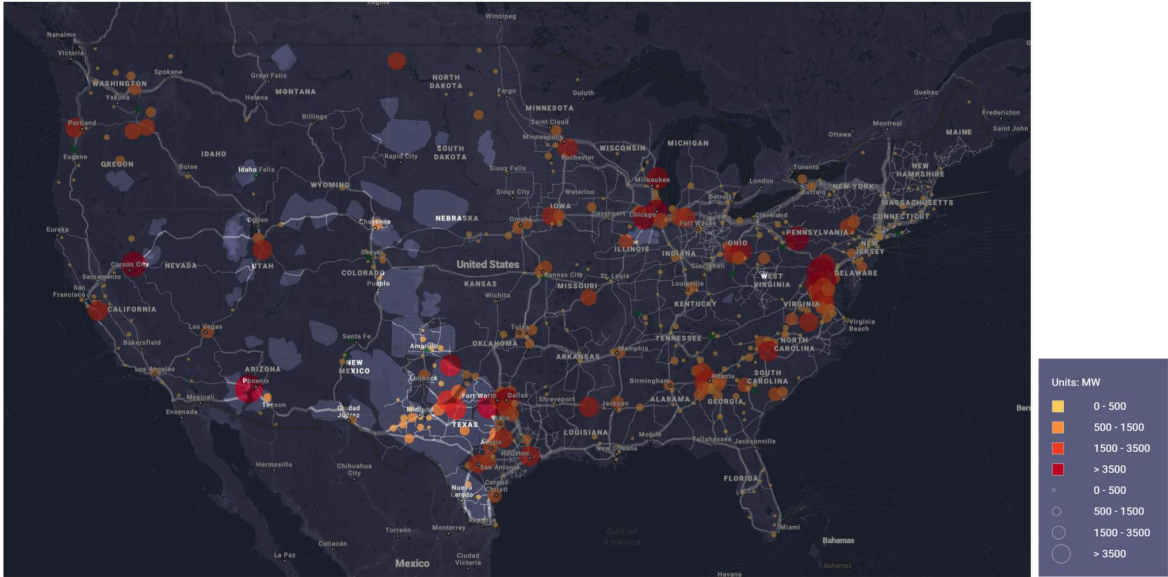
2035 GRID CAPACITY PROJECTION



POWER COMPETITION: NATIONAL HPC TODAY



POWER COMPETITION: HPC TODAY + CONSTRUCTION + PLANNED



RESILIENCY MOTIVATIONS: PV + BESS

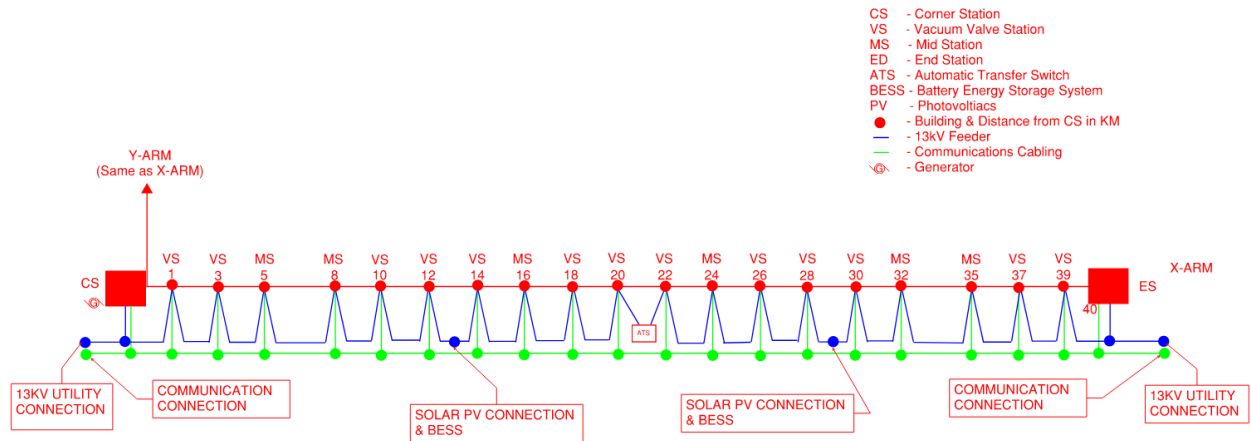


SITE UTILITIES

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ELECTRICAL ROUTING



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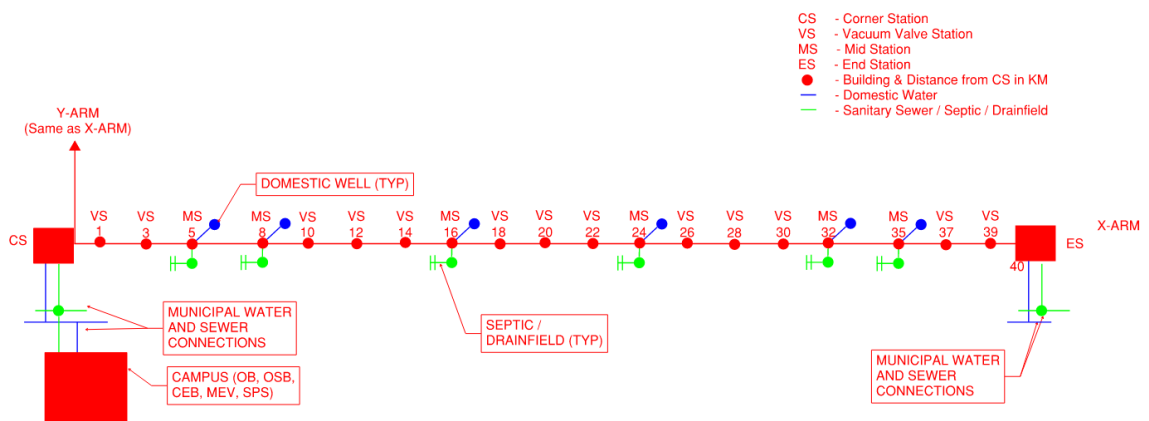
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ELECTRICAL ROUTING CONT.

- 13kV Routing & Communications
 - Underground or Above Grade on Poles
 - Underground is significantly more expensive. 2X to 4X
- PV/Renewable Needs/Preferences
- Diesel Generators
 - Operations (OSB)
 - Office Building (OB)
 - Station Prep & Storage (SPS)
 - Do Mid Stations (MD), Vacuum Valve Stations (VS), or End Stations (ES) require backup generation?
- BESS – Shown with PV.
 - Should some buildings have BESS? If so,
 - Which buildings?
 - Backup duration? 2-hr, 4-hr, 24hr?

DOMESTIC WATER / SANITARY SEWER ROUTING



DOMESTIC WATER / SANITARY SEWER ROUTING

- Municipal Water and Sewer connections
 - Campus Facilities (OSB, OB, SPS, CEB, MEV)
 - Corner Station
 - End Stations
- Domestic water wellpoints / filtration
 - Mid Stations
- Septic / Drainfield Systems
 - Mid Stations

CIVIL ENGINEERING

OUR UNDERSTANDING

SITE FACTORS

ARUP

Science requirements

- Must host 40 km or 20 km L-shaped interferometers with near-90° opening angles.
- Low seismic noise, minimal tilt, favorable geology, long-term climate resilience.
- Locations optimized for the *global detector network*, not in isolation.

Cost and feasibility

- Civil engineering costs dominated by terrain flatness and Earth curvature.
- Even small arm-length reductions can significantly reduce excavation volume and cost.
- Land ownership, infrastructure access, and permitting are decisive constraints.

Social and ethical framework

- Explicit commitment to early, ongoing partnership with local and Indigenous communities.
- Workforce inclusion, quality of life, and community compatibility are treated as performance factors.

Cosmic Explorer Location Criteria (Daniel et al., 2024)

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COSMIC EXPLORER FEASIBILITY STUDY

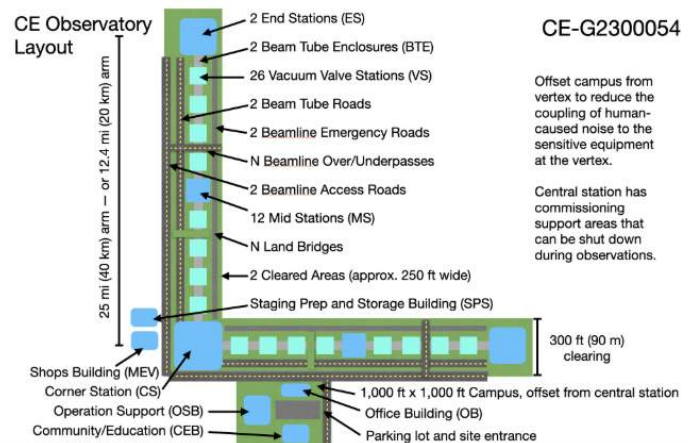
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OUR UNDERSTANDING

SITE PROGRAM & CIRCULATION (DEPENDENT ON BTE)

ARUP

- 300 foot-wide cleared zone
- Circulation
 - Two (2) access roads - 1 lane in each direction (4 lanes total)
 - One (1) maintenance road
 - Land bridges or underpass access where beam tube enclosure is at grade
- Operational Requirements
 - Paving
 - Shoulders
 - Mid-station parking/lay by



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CIVIL WET UTILITY STRATEGIES

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SEWER/ WATER/ STORMWATER

Strategies depend on availability of existing infrastructure and site conditions

- SEWER
 - Onsite wastewater treatment
 - Utility connection to municipal system (if available)
- WATER
 - Onsite supply (groundwater well with onsite storage and treatment)
 - Utility connection to municipal water grid (if available)
- STORMWATER (avoid conveyance)
 - Preserve Natural Drainage
 - Infiltrate
 - Detain

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COSMIC EXPLORER FEASIBILITY STUDY

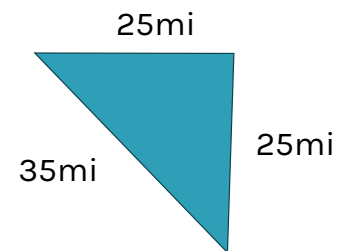
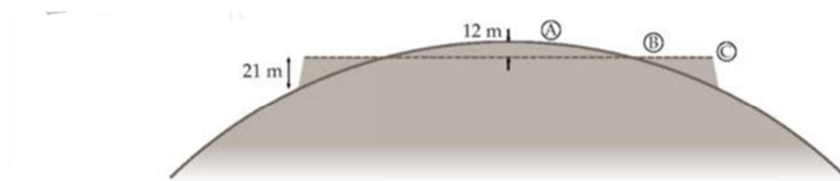
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CIVIL EARTHWORK

ARUP

BASELINE DESIGN

- Assume project is effectively 50 miles long for construction logistics
- Assume soil volume can be balanced on site
- Net Soil volume to be moved based on simplified volume calc (300 ft wide)
= 36,666,666 cy (equal to 26 Empire State Bldgs or 26M dump trucks)
Quantity presented for scale only, does not consider slopes, earth curvature, etc.
- Assume corner station to be near or below grade



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COSMIC EXPLORER FEASIBILITY STUDY

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OUR UNDERSTANDING

CIVIL STRUCTURE TYPE CONSIDERATIONS

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Geology
Induced vibrations
Seismic/fracking
Temp/humidity control
Wind / hurricane
Structural Joints
Surface Drainage
Groundwater
Settlement / tolerance
Crossings
Maintenance Access
Construction Complexity
Construction Logistics
Schedule
Durability / maintenance
Security / tumbleweeds



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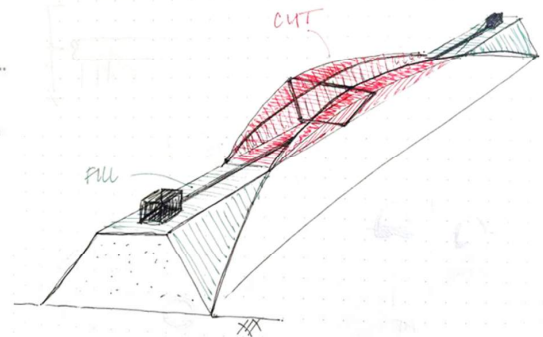
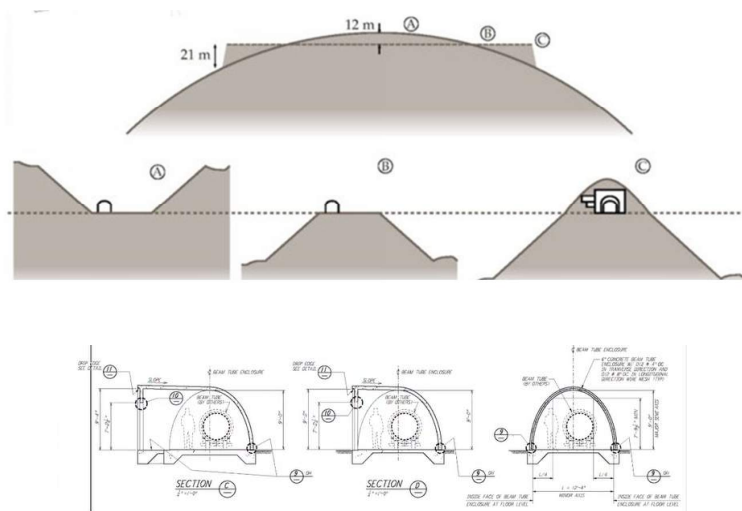
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BEAM TUBE ENCLOSURE (BTE)

REFERENCE DESIGN

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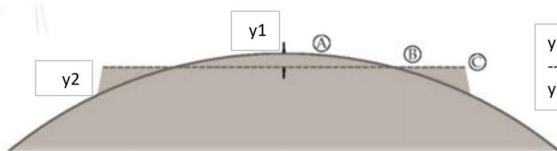
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BEAM TUBE ENCLOSURE (BTE)

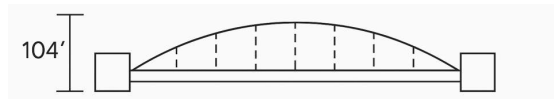
ELEVATION & TYPE SELECTION CONSIDERATIONS

ARUP

			LIGO				LIGO		
Civil Structure Type	Elevated Viaduct	MSE Wall	Embankment	At-Grade	Emersed	U-Wall/SOE	Open Cut Trench	Cut & Cover Tunnel	Bored Tunnel
y2 max	100	50	50						
y2 min	20	5	0	0					
y1 min					0	4	12	12	20
y1 max					8	14	50	20	100
Relative Quantities									
Cut Fill		X	XX	X	XX	XX	XXX	XXX	
Additional RC / MSE	XXX	XX			X			XXX	
Piles	X					XXX		X	X
TBM									XXX



y1
--- = 104' = 35m
y2



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COSMIC EXPLORER FEASIBILITY STUDY

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BEAM TUBE ENCLOSURE (BTE)

ELEVATION & TYPE SELECTION CONSIDERATIONS

ARUP

			LIGO				LIGO		
Civil Structure Type	Elevated Viaduct	MSE Wall	Embankment	At-Grade	Emersed	U-Wall/SOE	Open Cut Trench	Cut & Cover Tunnel	Bored Tunnel
y2 max	100	50	50						
y2 min	20	5	0	0					
y1 min					0	4	12	12	20
y1 max					8	14	50	20	100
Sensitivity to Engineering Risks									
Geology/Geotechnical	●	●	●	●	●	●	●	●	●
Vibrations	●	●	●	●	●	●	●	●	●
Seismic/ground motions	●	●	●	●	●	●	●	●	●
Temperature	●	●	●	●	●	●	●	●	●
Wind	●	●	●	●	●	●	●	●	●
Joints	●	●	●	●	●	●	●	●	●
Surface Drainage	●	●	●	●	●	●	●	●	●
Groundwater	●	●	●	●	●	●	●	●	●
Settlement	●	●	●	●	●	●	●	●	●
Crossings	●	●	●	●	●	●	●	●	●
Maintenance Access	●	●	●	●	●	●	●	●	●
Construction Complexity	●	●	●	●	●	●	●	●	●
Construction Logistics	●	●	●	●	●	●	●	●	●
Operability	●	●	●	●	●	●	●	●	●

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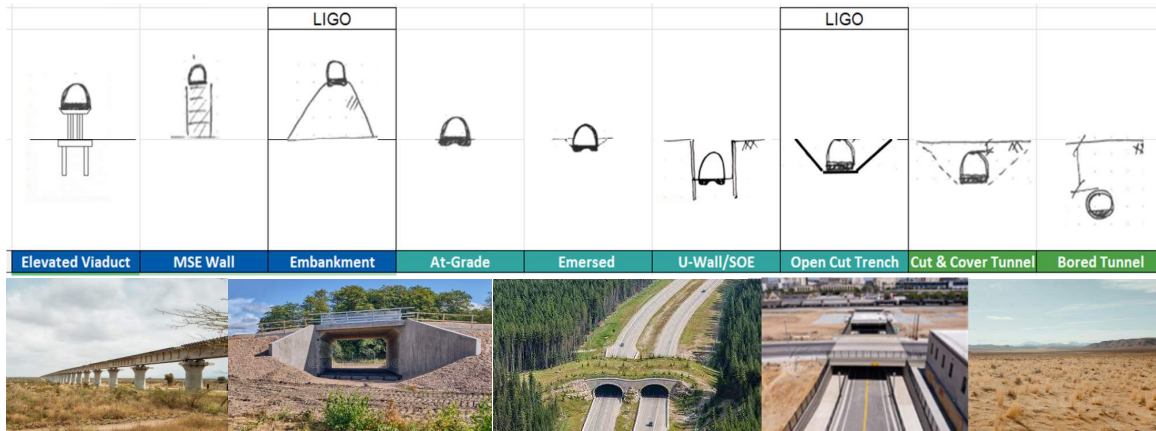
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BEAM TUBE ENCLOSURE (BTE)

CROSSINGS & ACCESS

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CIVIL ENGINEERING

Q & A

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- Confirmation on BTE structure types for cost estimate
- Seismic assumptions (site location parameters)
- Flood Hazard assumptions (site location parameters)
- Access doors/shaft program requirements (evenly spaced?)
- Requirement for air-tight vs water-tight

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COSMIC EXPLORER FEASIBILITY STUDY

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~ONWARDS AND UPWARDS TO WS-3!

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COSMIC EXPLORER FEASIBILITY STUDY WS-3

COSMIC EXPLORER FEASIBILITY STUDY

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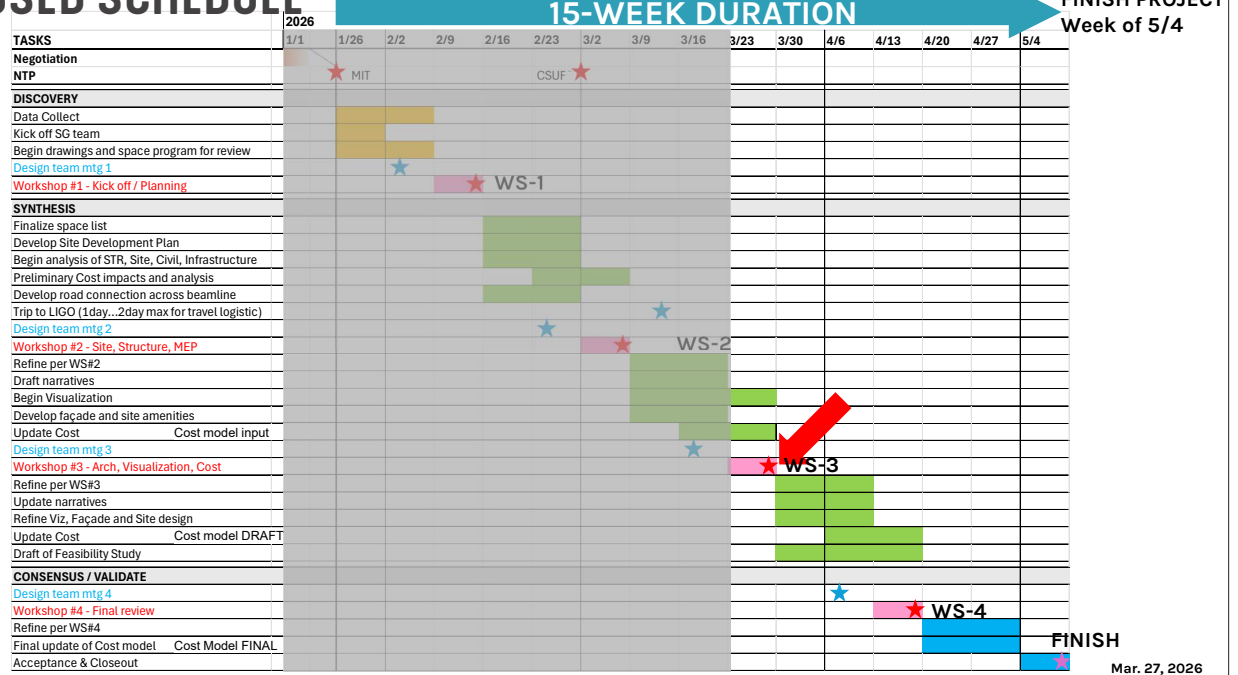


SCHEDULE AND GOALS

COSMIC EXPLORER FEASIBILITY STUDY

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PROPOSED SCHEDULE



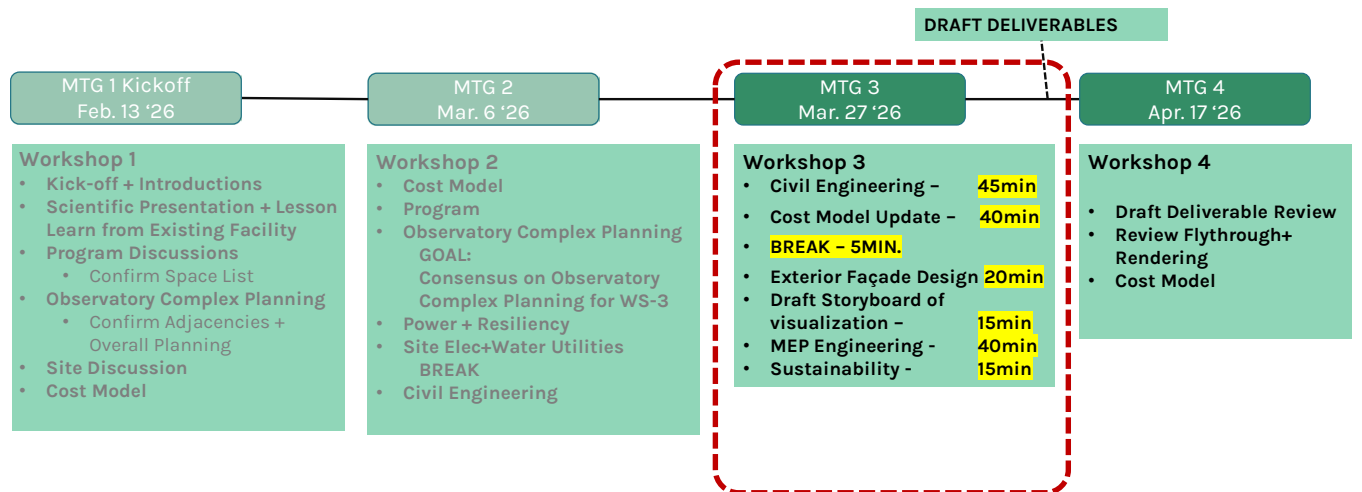
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WORKSHOPS

Fridays = Workshops
Start at 9am (West) / 12 noon (East)



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CIVIL ENGINEERING

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ASSUMPTION AND PROCEDURE

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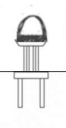
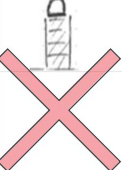
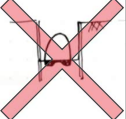
1. Here we summarize information and assumptions we provided to Cumming required to initiate their costing exercise.
2. We provide simplified typologies and unit sections, and Cumming prices them accordingly. Arup did not perform any costing or quantity estimation, or focus on utilities.
3. Our process is site-agnostic, so any percentages provided in this exercise are not set in stone.



BEAM TUBE ENCLOSURE (BTE)

CROSSING AND ACCESS

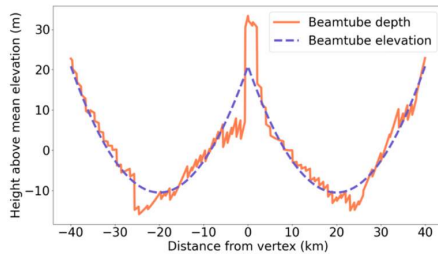
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		LIGO				LIGO		
								
Elevated Viaduct	MSE Wall	Embankment	At-Grade	Emersed	U-Wall/SOE	Open Cut Trench	Cut & Cover Tunnel	Bored Tunnel
								

EARTHWORK APPROXIMATION

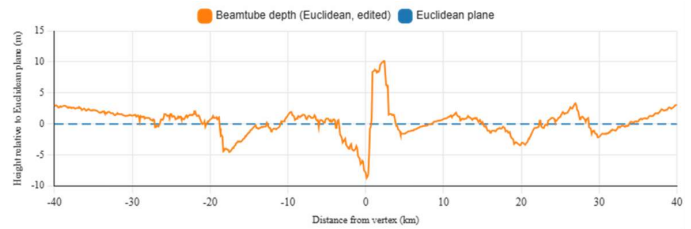
UTILIZING INDICATIVE BEAMTUBE-ELEVATION PROFILE

ARUP



Example “bowl shaped” beamtube elevation over indicative surface

(Referenced from white paper: Datrier, L, et al. “Site Evaluation and Cost Estimation for Cosmic Explorer” (2025))



Indicative projection

****Note:** This is not an exact projection and is merely provided as an indicative representation.

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COSMIC EXPLORER FEASIBILITY STUDY

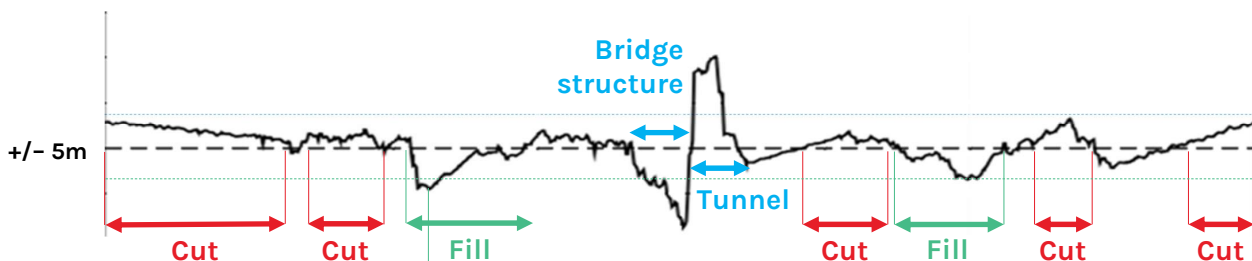
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EARTHWORK APPROXIMATION

UTILIZING INDICATIVE BEAMTUBE-ELEVATION PROFILE

ARUP



Est. percentage of alignment	
Fill	10% at 10ft uniform fill
Cut	10% at 10ft uniform cut
Special structures	20% viaduct or tunnel
At-grade	60% (**transitions not accounted)

***NOTE:** values are meant for costing exercise.

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COSMIC EXPLORER FEASIBILITY STUDY

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BRIDGE ASSUMPTIONS

UTILIZING INDICATIVE BEAMTUBE-ELEVATION PROFILE

ARUP

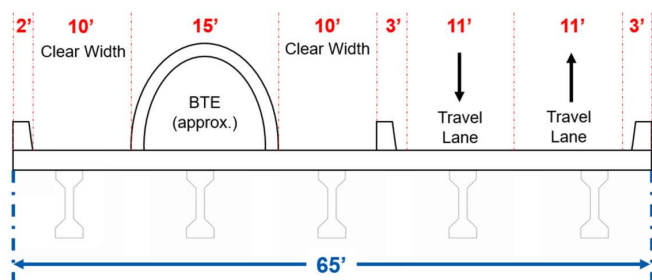
- The percent proportion of fill, cut or special structure may modify after the next workshop
- Arizona DOT Bridge Design Guidelines for quantity approximation for bridge
- FHWA Bridge Replacement Cost Database by year and state to give a ROM

BTE Bridge Summary – Approximate Concrete per 100-ft Span

Component	Approx. CY per Span
Deck	~180 CY
Superstructure	~130 CY
Pier columns	~70 CY
Pier cap + footing	~250 CY
Total	~630 CY / span

Assumptions:

- Deck width: 65 ft
- Span length: 100 ft (on center)
- Average column height: 35 ft
- Typical overpass: multi-span, concrete superstructure, concrete piers
- Cast-in-place concrete deck on concrete girders or box
- One pier line per span (two columns per pier)
- Typical Arizona DOT / AASHTO proportions (conceptual level)



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COSMIC EXPLORER FEASIBILITY STUDY

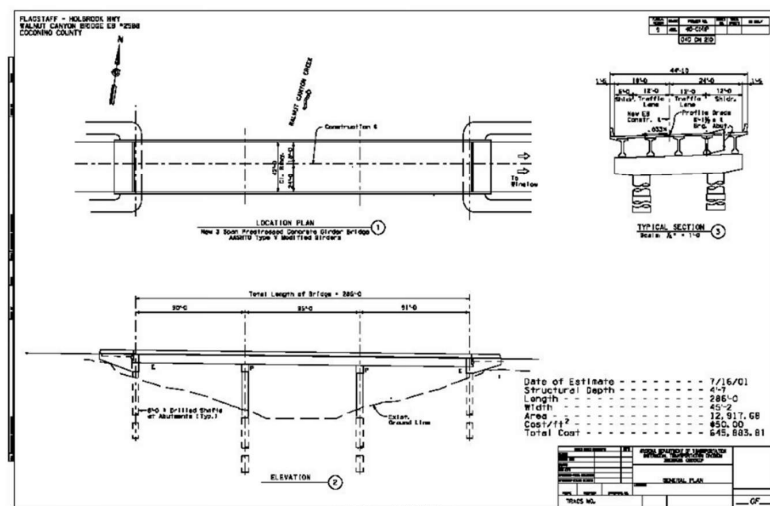
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BRIDGE ASSUMPTIONS

AZDOT STANDARD BRIDGE PLANS

ARUP

- Arizona DOT Bridge Design Guidelines for quantity approximation for bridge



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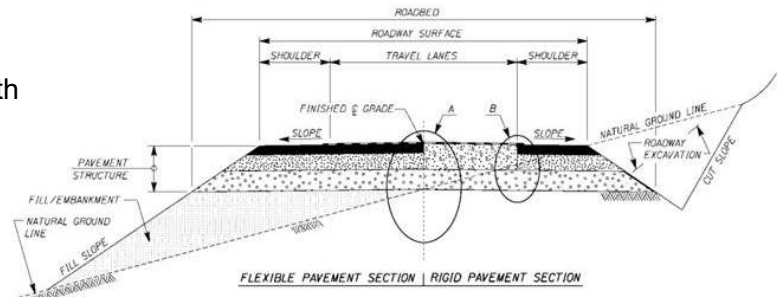
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ROADWAY ASSUMPTIONS

ARUP

UTILIZING INDICATIVE BEAMTUBE-ELEVATION PROFILE

- Circulation roadway and access roadway is a 26-foot paved width (two 12-foot lanes), pavement is flexible with the following buildup:
 - 2" AC surface course
 - 2" AC binder course
 - 6" aggregate base
 - 12" subbase
- Maintenance roadway adjacent to beamline is gravel with 26 foot width and the following buildup:
 - 6" gravel surface course
 - 12" of granular base



Source: ADOT Pavement Design Manual 2017

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STORMWATER MANAGEMENT ASSUMPTIONS

ARUP

- One retention pond at each campus area (building/parking area)
 - 6 foot deep and the area of the basin will equal 12% of impervious area created by building/parking
- Roadway is superelevated to drain in one direction
 - 6 foot wide, 2-foot-deep gravel swale for the entire length (x2)
 - Applies to the two paved roads only
- Gravel road will infiltrate, no additional water management required

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EARTHWORK ASSUMPTIONS FOR CAMPUS DEVELOPMENTS (BUILDINGS WITH PARKING)

ARUP

- Top 6" is topsoil and needs to be removed, can be reused onsite for landscaped areas (if any)
- For a 2-story building on a remote site with good soil, assume over excavation of 2 feet and compact material to ready the site for improvements

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MINED TUNNELS IN ROCK

ARUP



Flexible Geometry



Shotcrete Lining



Cast-in-Place Lining

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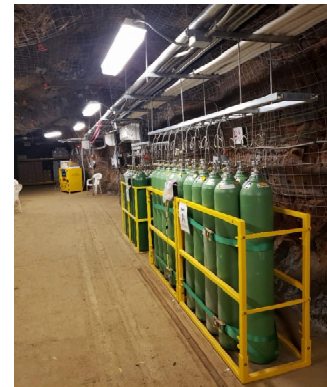
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LBNF – LONG BASELINE NEUTRINO FACILITY

ARUP

Hard rock mined tunnels / caverns
Use of alcoves / refuge chambers for safety



[Read more: Long Baseline Neutrino Facility \(LBNF\) - Arup](#)

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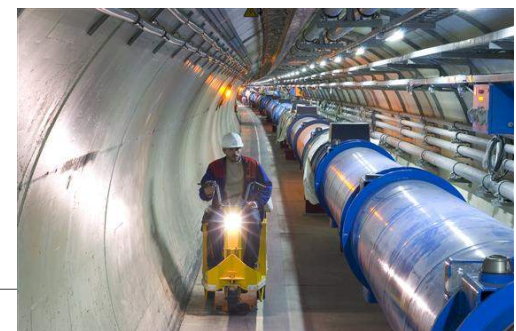
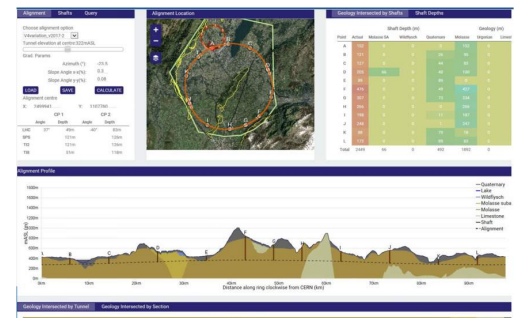
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CERN

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN tunnels do not follow rail or road tunnel codes (e.g., NFPA 130 / 502). Instead, they use a bespoke, performance-based safety concept that is fundamentally different from public-occupancy tunnels. Strategy is heavily influenced by:

- Low occupancy during operation
- Controlled access (trained personnel only)
- Strict operational procedures
- Compartmentalization and ventilation control
- Refuge-in-place strategies
- Fire compartment lengths typically ~400 m
- Alcoves / safety features used for refuge and intervention
- Major access points (shafts, caverns) spaced at 00s of meters to ~1 km+



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COSMIC EXPLORER FEASIBILITY STUDY

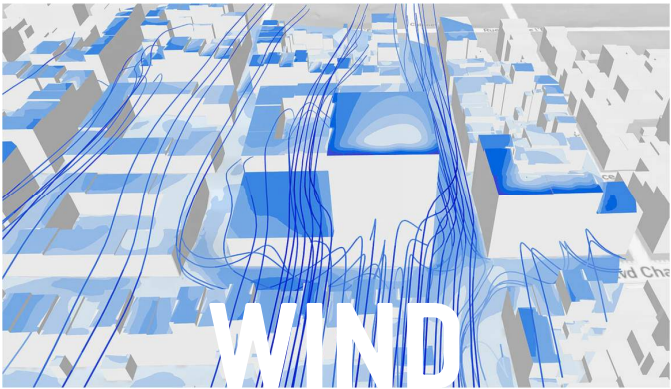




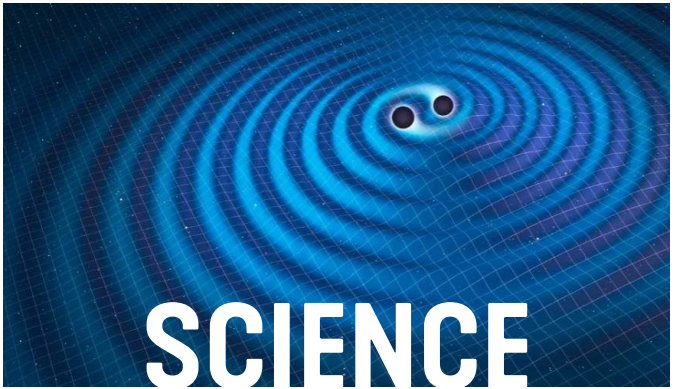
INFLUENCES



INFLUENCES

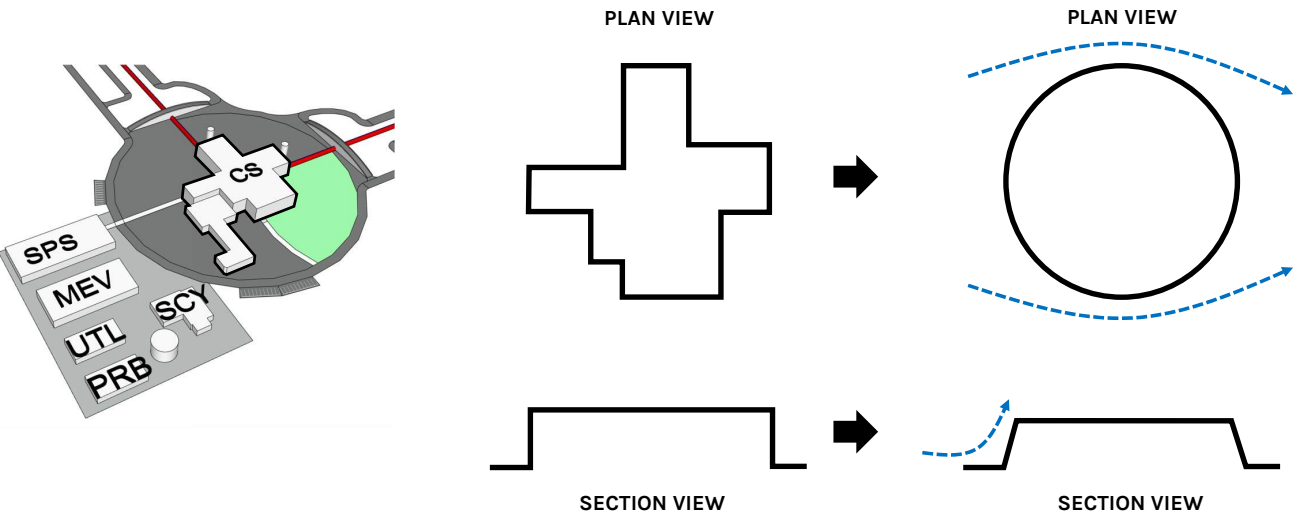


WIND

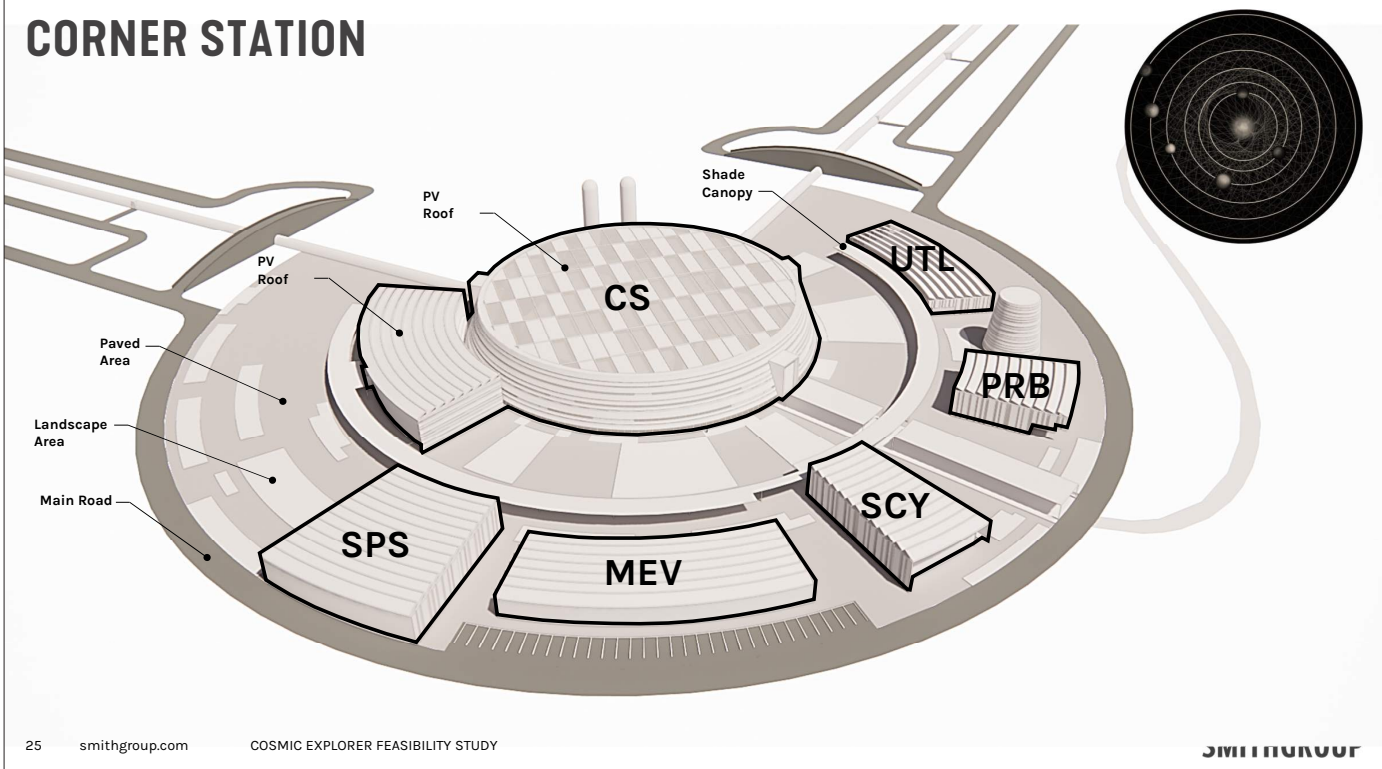


SCIENCE

CONCEPT



CORNER STATION

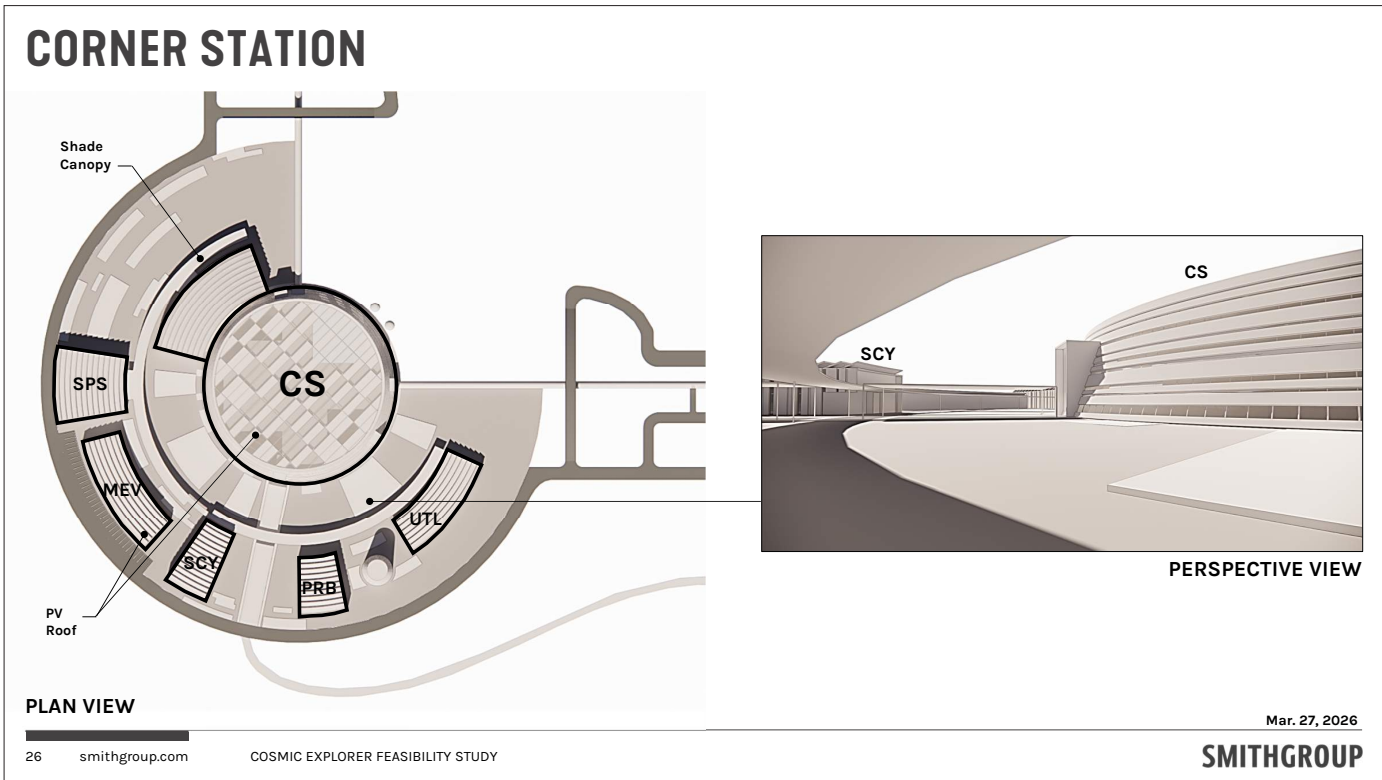


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CORNER STATION



PLAN VIEW

PERSPECTIVE VIEW

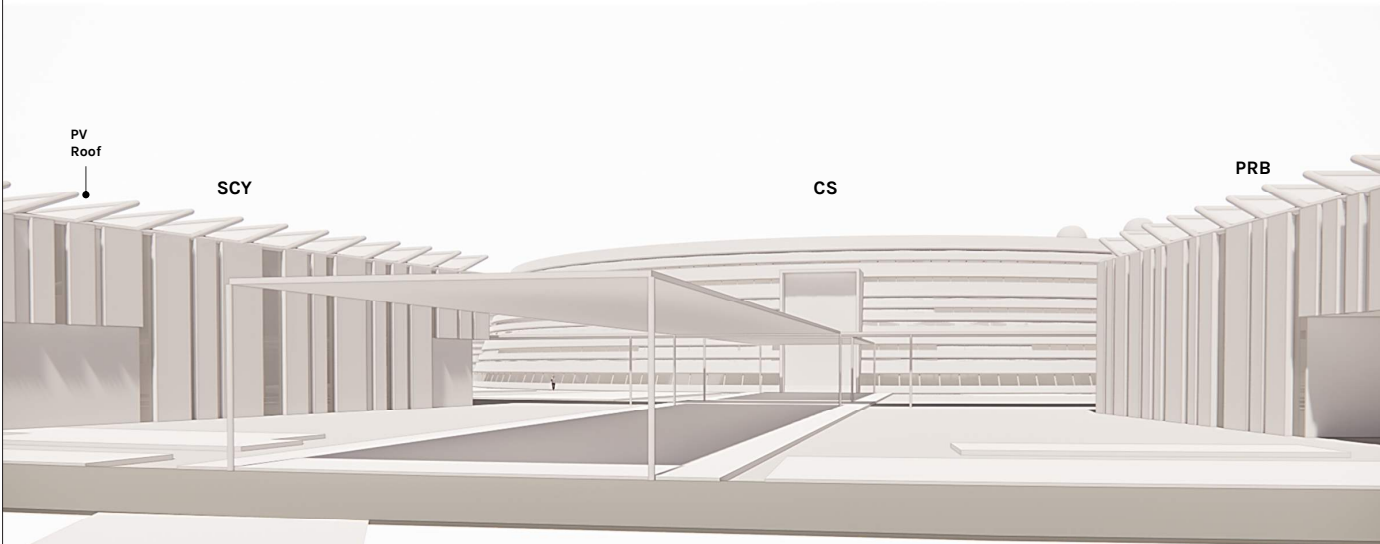
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COSMIC EXPLORER FEASIBILITY STUDY

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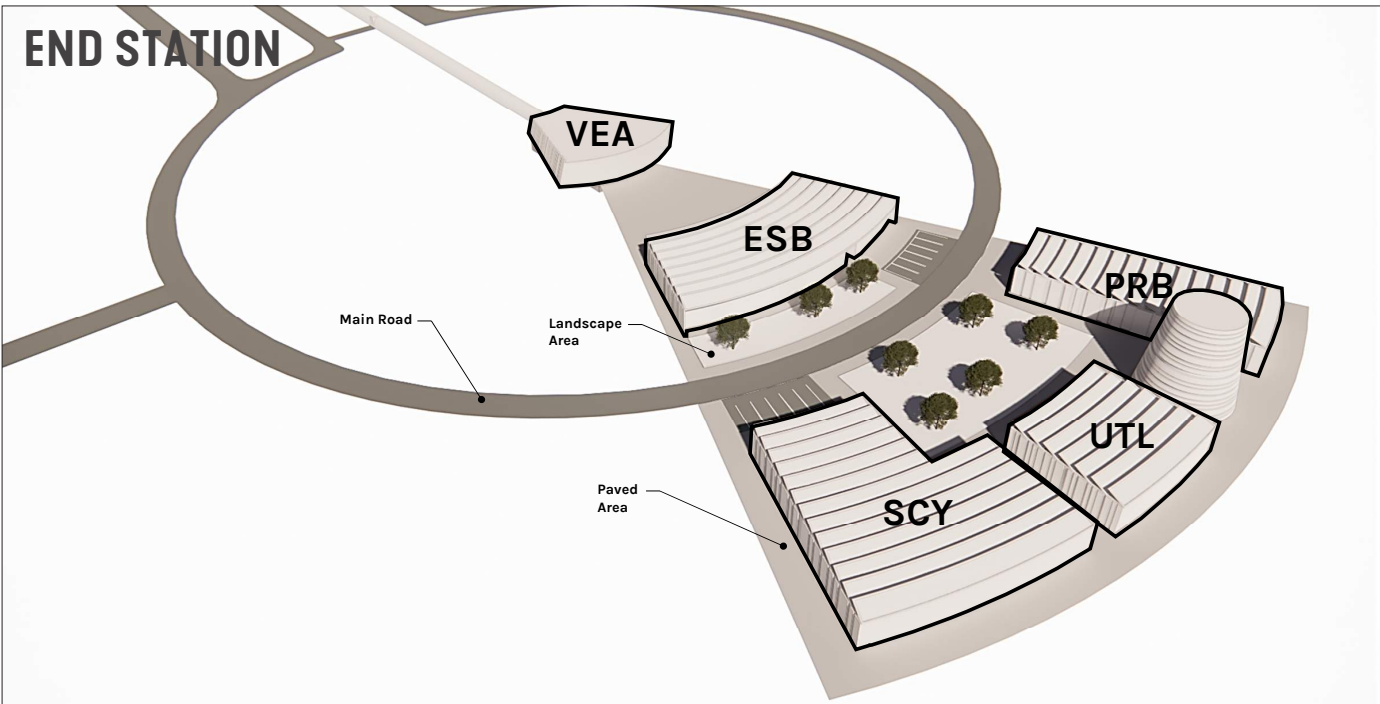
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CORNER STATION

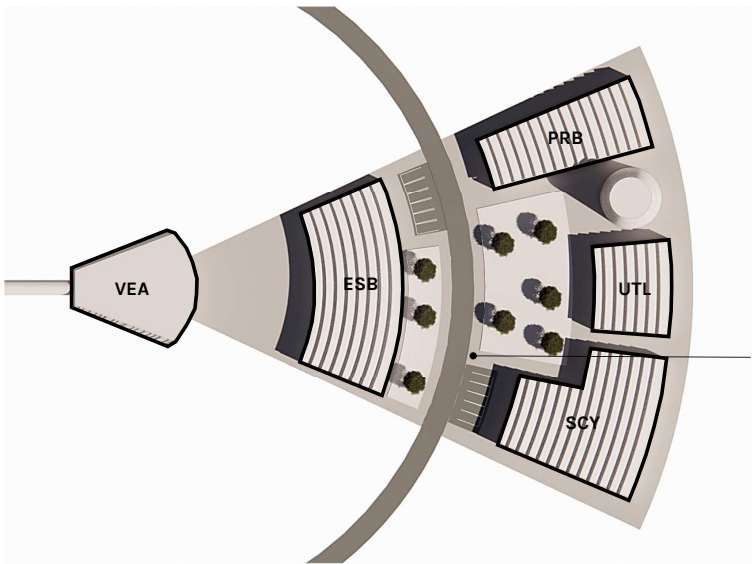


PERSPECTIVE VIEW

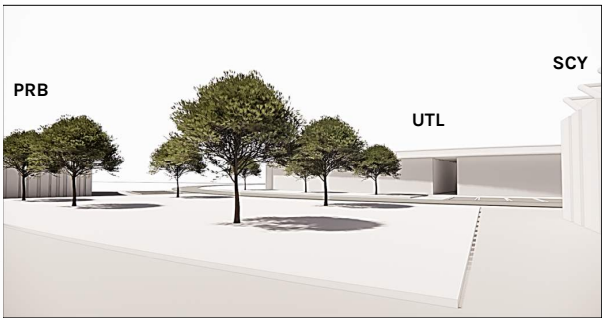
END STATION



END STATION



PLAN VIEW

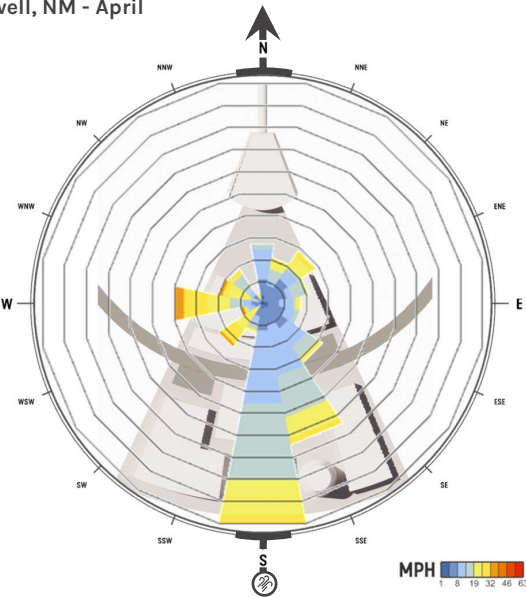


PERSPECTIVE VIEW

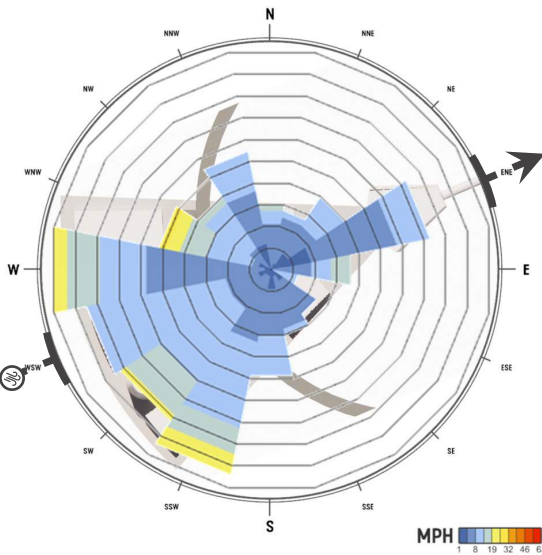
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END STATION – WIND INFORMED

Roswell, NM - April

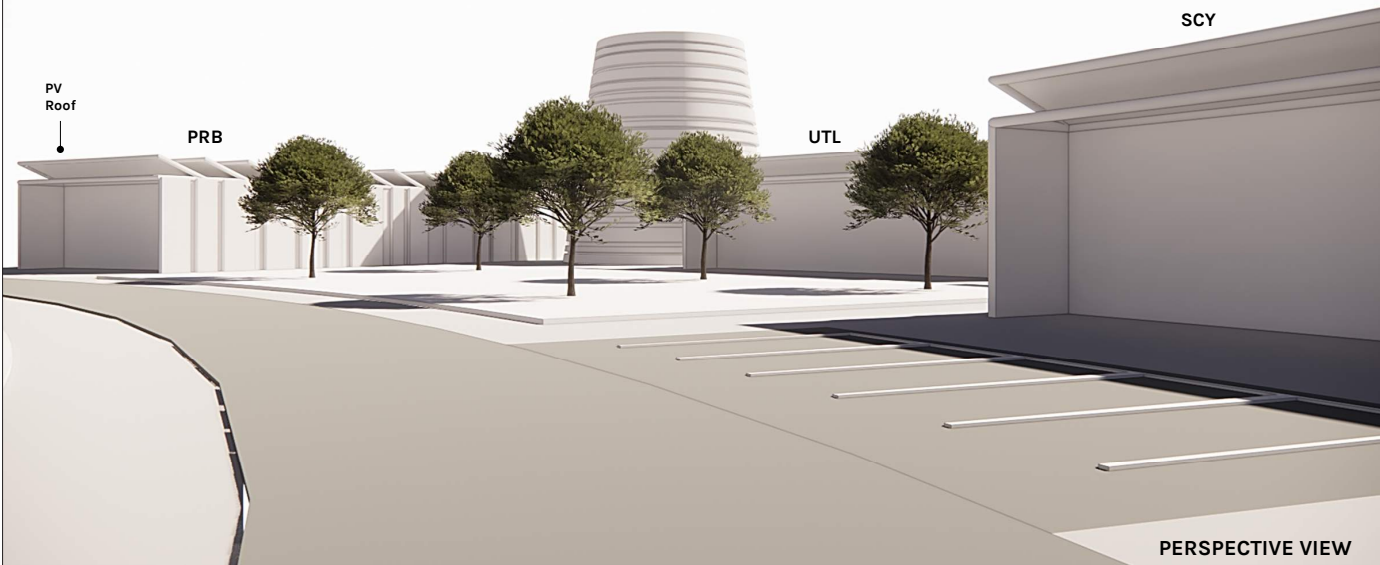


Denver, CO - November



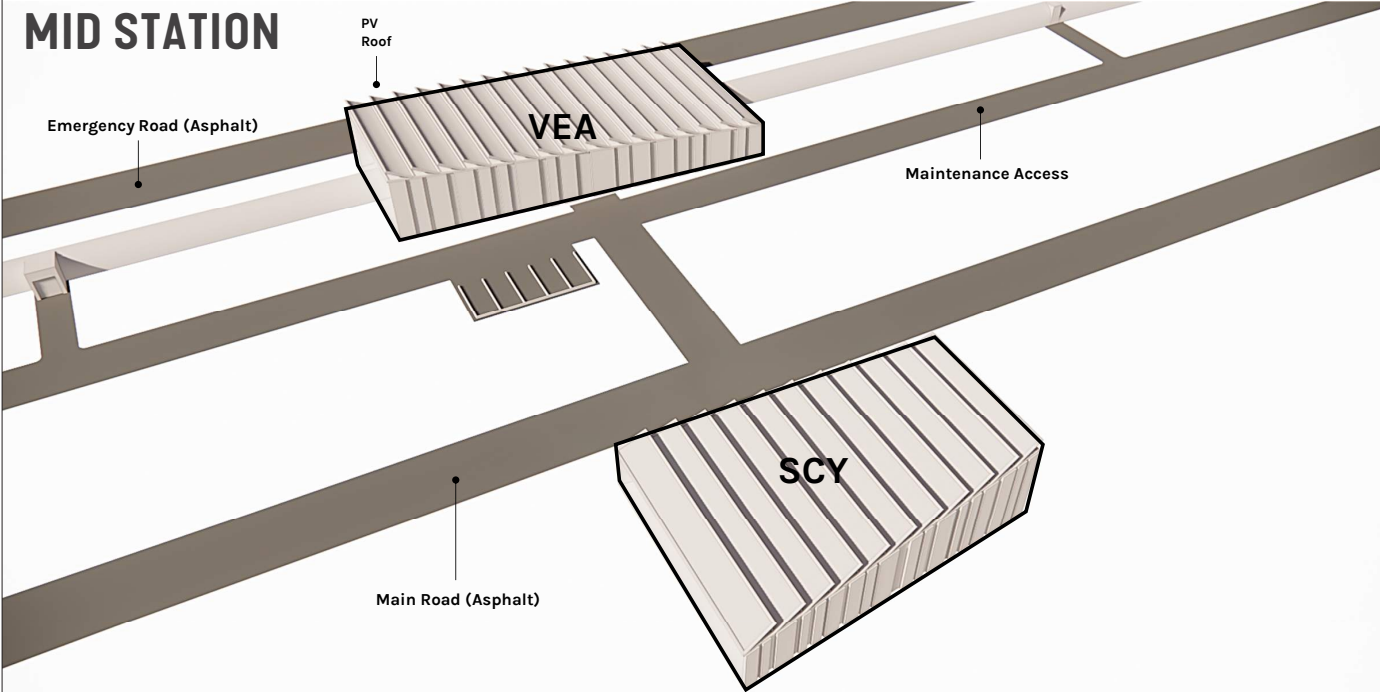
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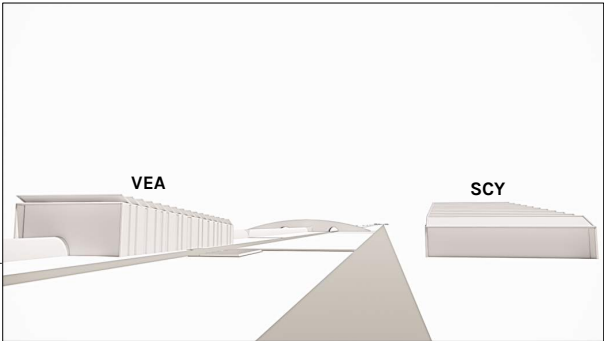
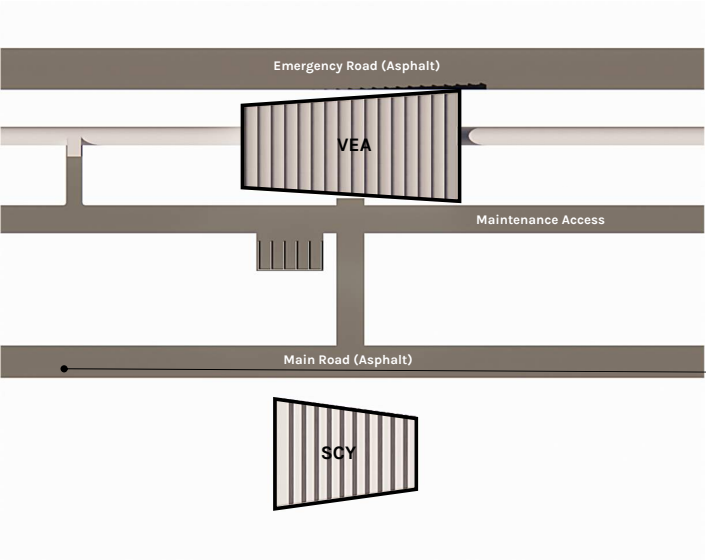


PERSPECTIVE VIEW

MID STATION



MID STATION

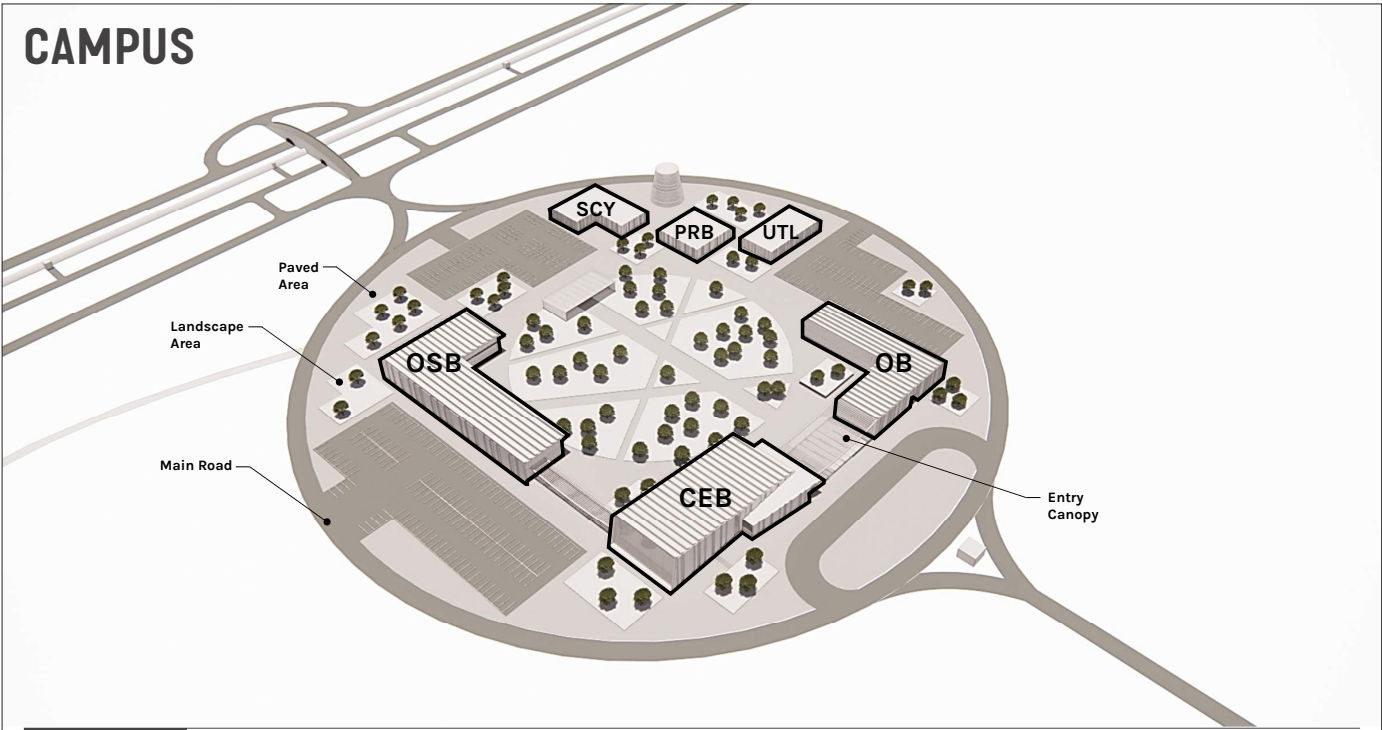


PERSPECTIVE VIEW

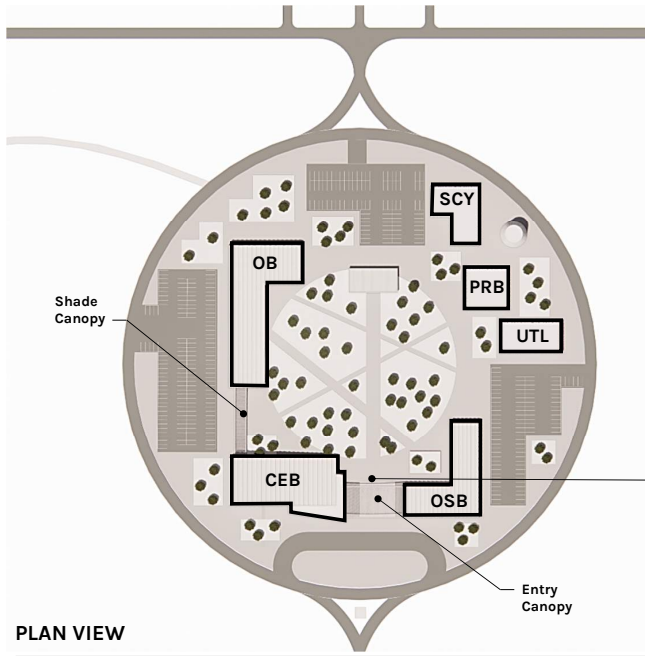
PLAN VIEW

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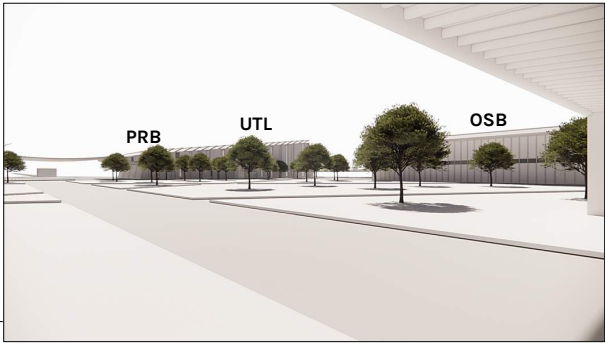
CAMPUS



CAMPUS



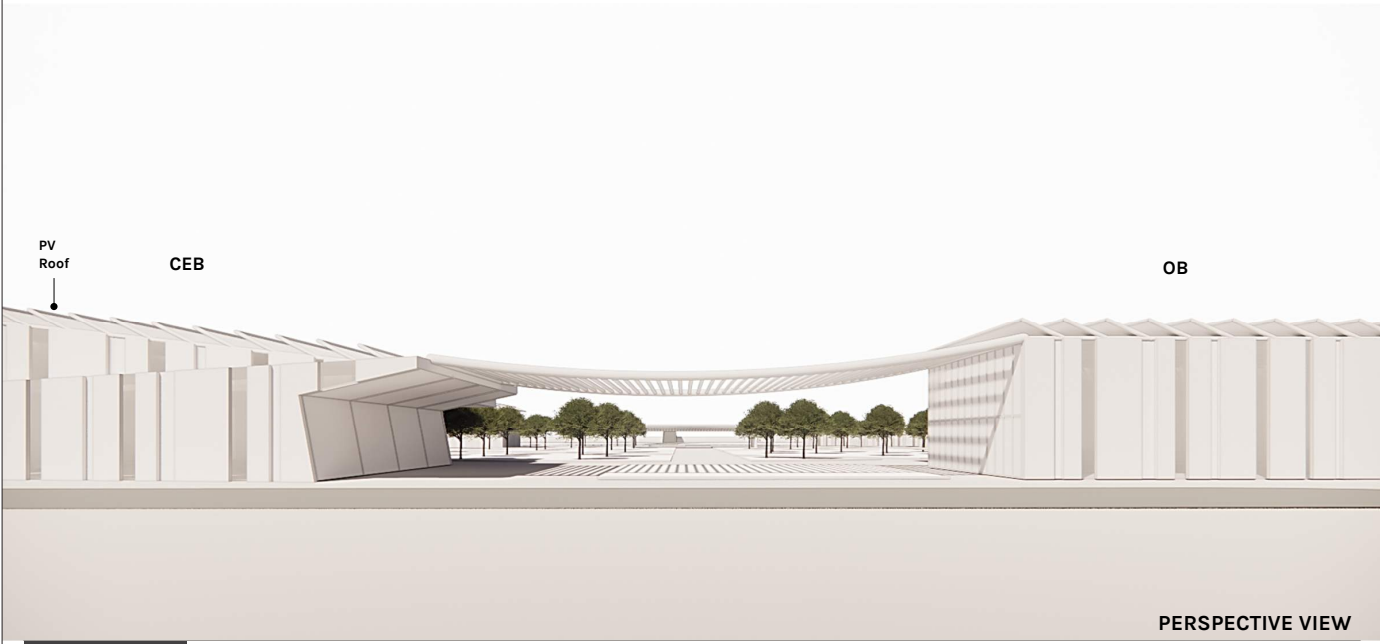
PLAN VIEW



PERSPECTIVE VIEW

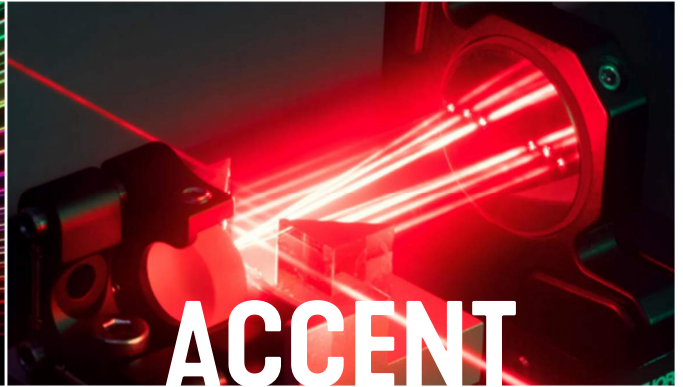
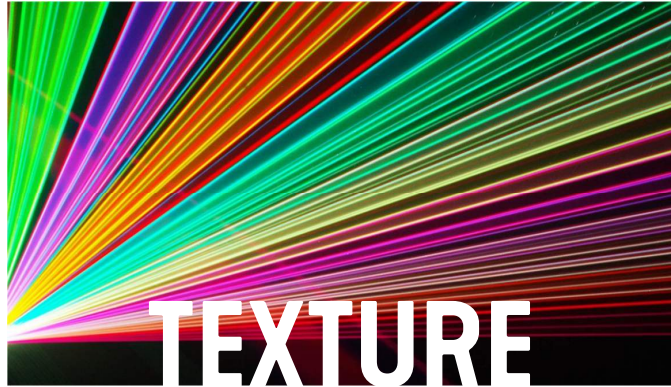
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CAMPUS



PERSPECTIVE VIEW

ARTICULATION



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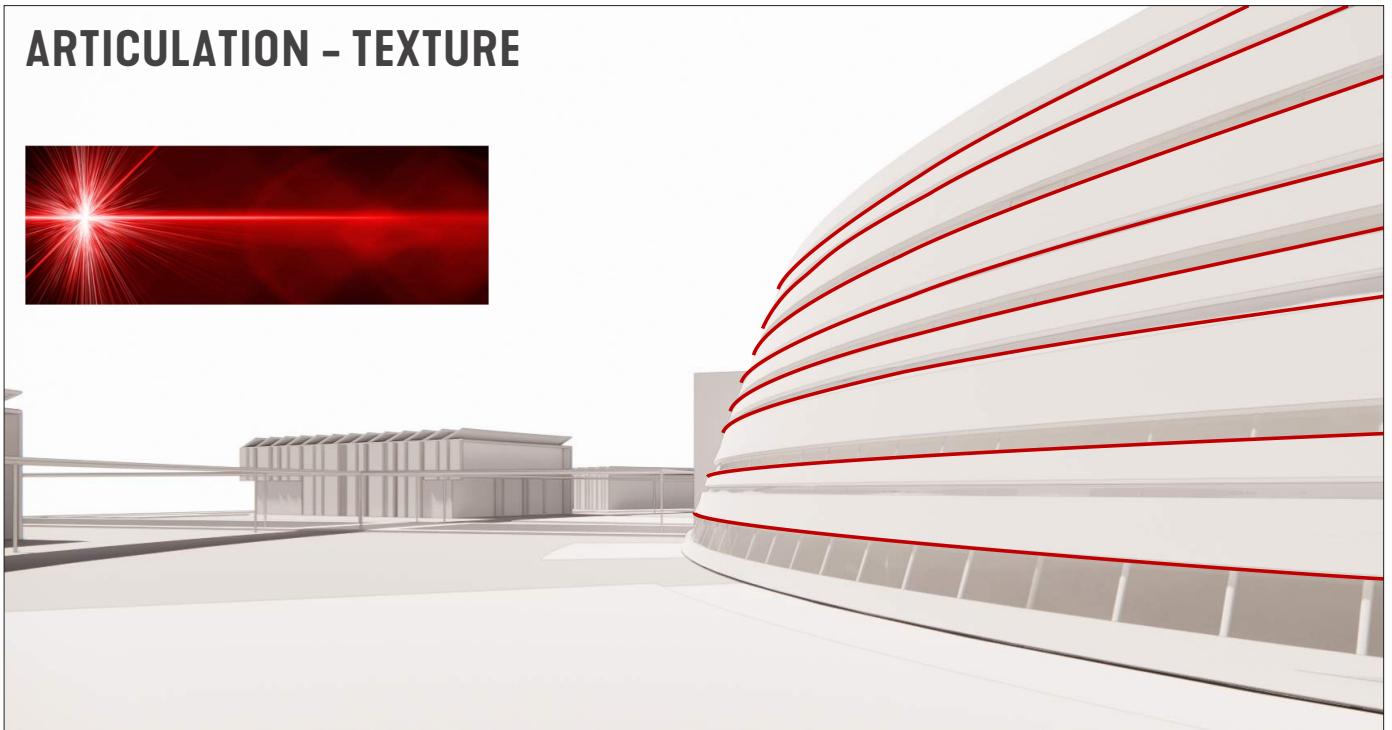
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ARTICULATION - TEXTURE



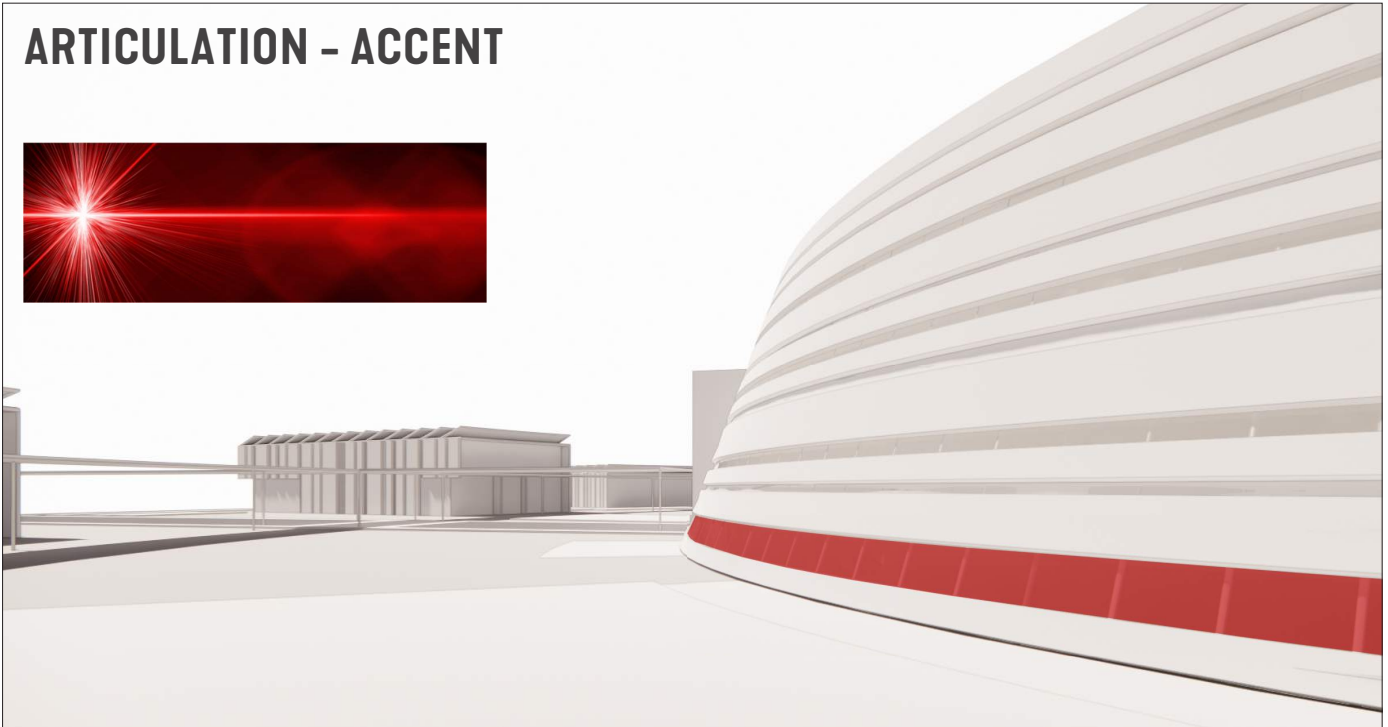
38

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ARTICULATION - ACCENT

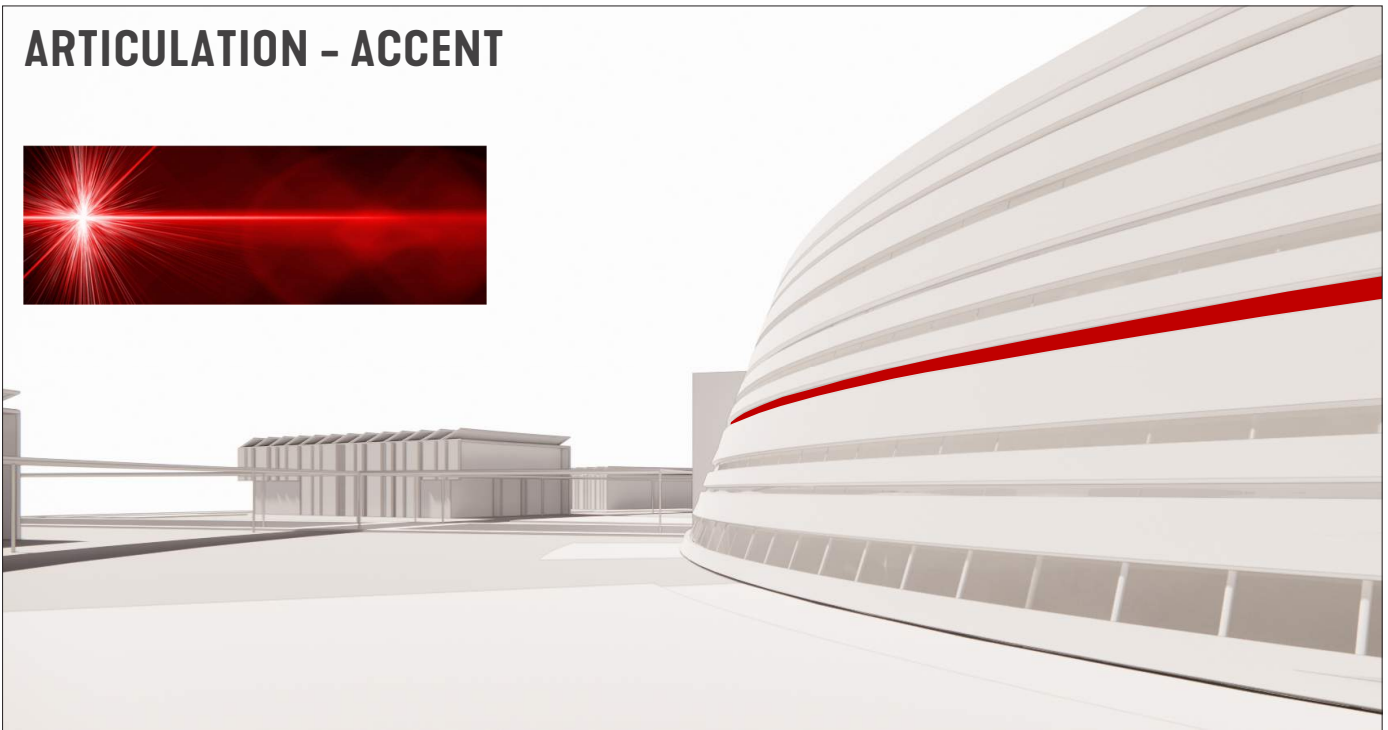


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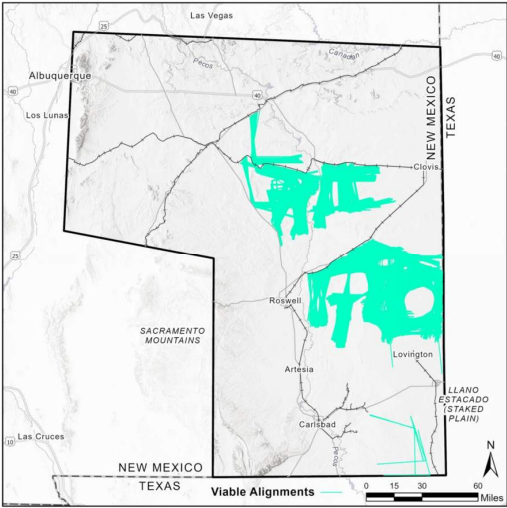


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SITE ADAPTATION



SITE ADAPTATION - TEXTURE

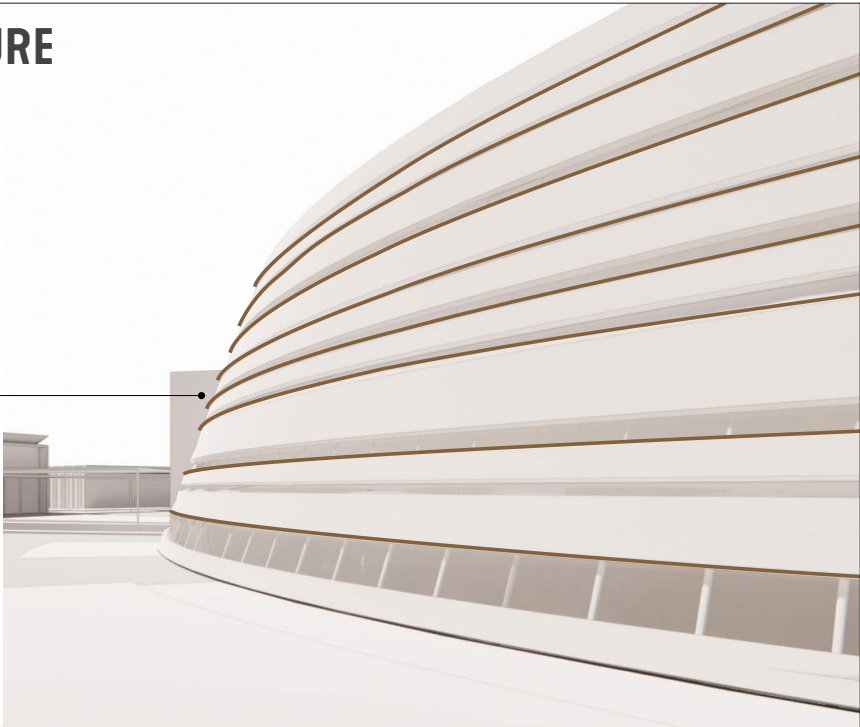


CAPROCK ESCARPMENT

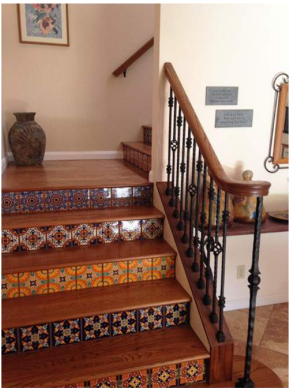


EARTH WALLS

SITE ADAPTATION - TEXTURE



SITE ADAPTATION - ACCENT

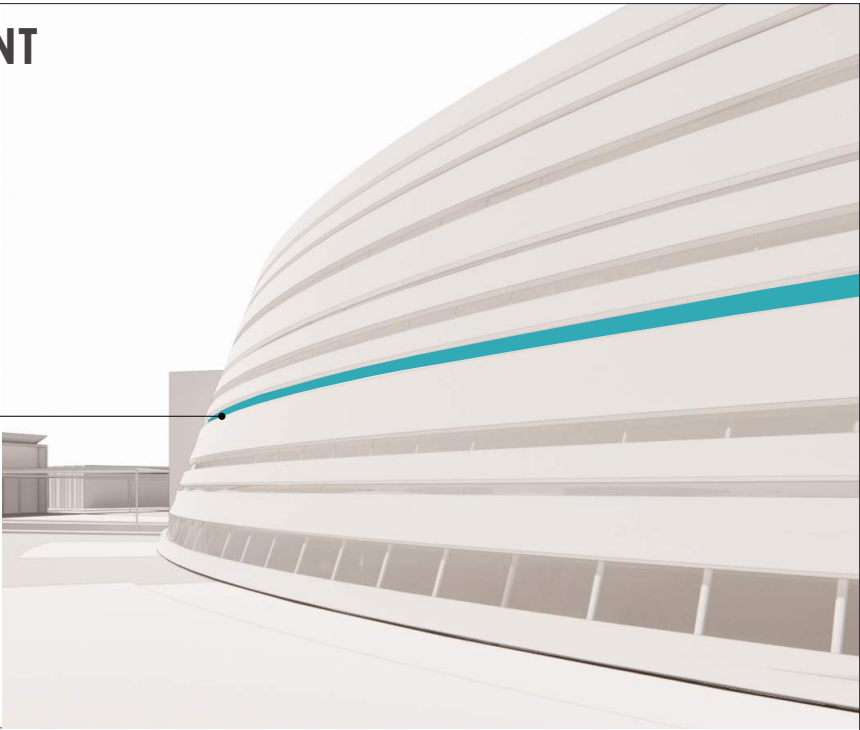


SOUTHWEST DECORATIVE TILE TRADITIONS

SITE ADAPTATION - ACCENT



SITE ADAPTATION - ACCENT



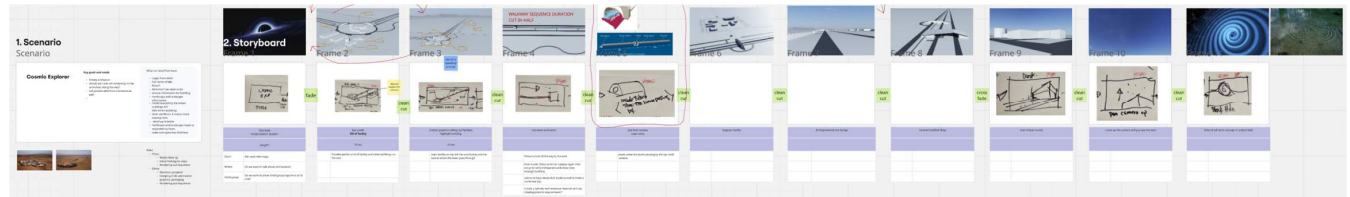
OVERALL



VISUALIZATION



STORYBOARD



CONSIDERATIONS

1. PURPOSE AND AUDIENCE

Understanding this is for fundraising purposes; is this directed to NSF only, or made available to public?

A. Mission Goal Brief needed?

2. FLOW OF STORYTELLING

A. Start with Mission Goals first? Or dive right into CE fly-through?

B. Should this include narration?

C. Highlight any particular areas or features?

3. CONCLUSION

A. What message should Viewers get? Should they contact CE team?

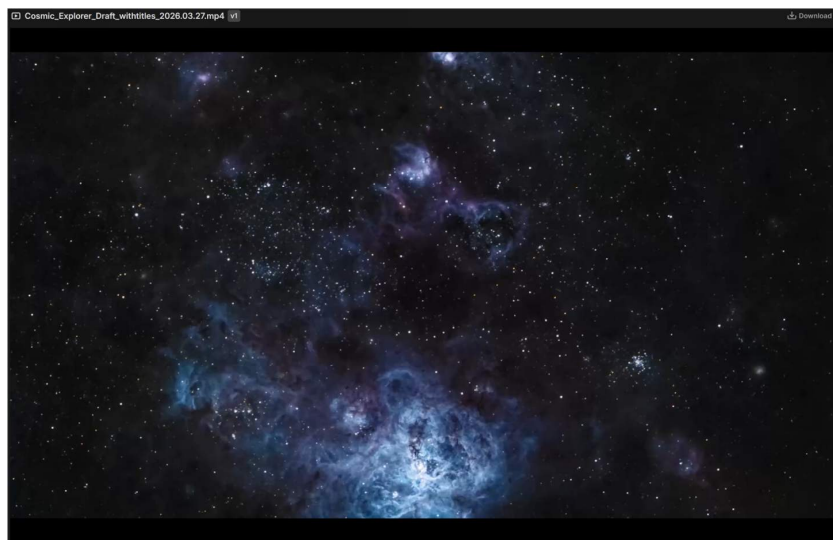
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ANIMATION



<https://app.iconik.io/review/share/assets/>

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MEP ENGINEERING

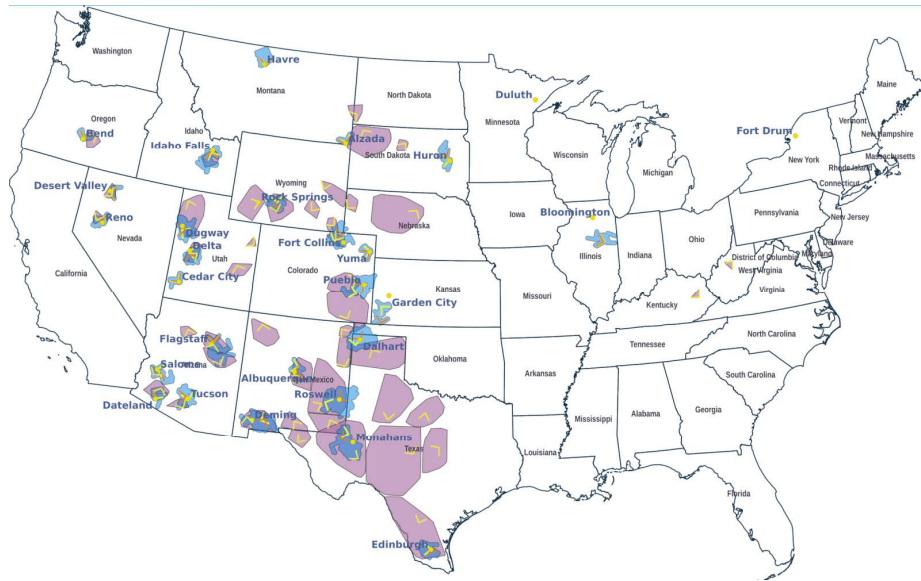
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MEP ENGINEERING TOPICS

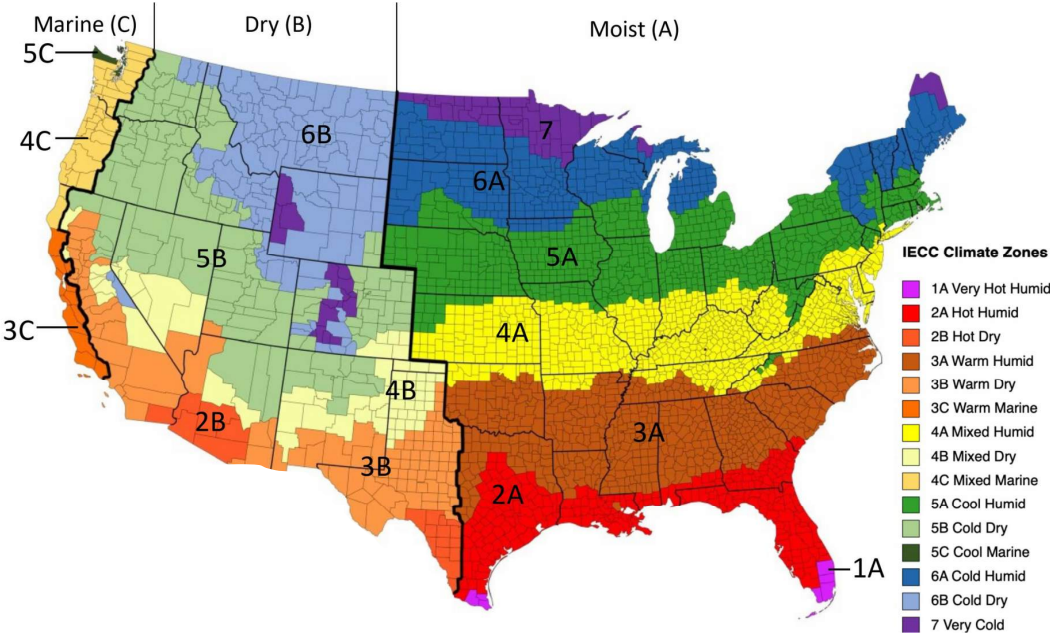
- 1 **CLIMATE ZONE OVERVIEW**
- 2 **CORNER STATION COMPLEX**
- 3 **MAIN CAMPUS COMPLEX**
- 4 **MID STATIONS & BEAM TUBE ENCLOSURE**

DRAFT SITE LOCATIONS



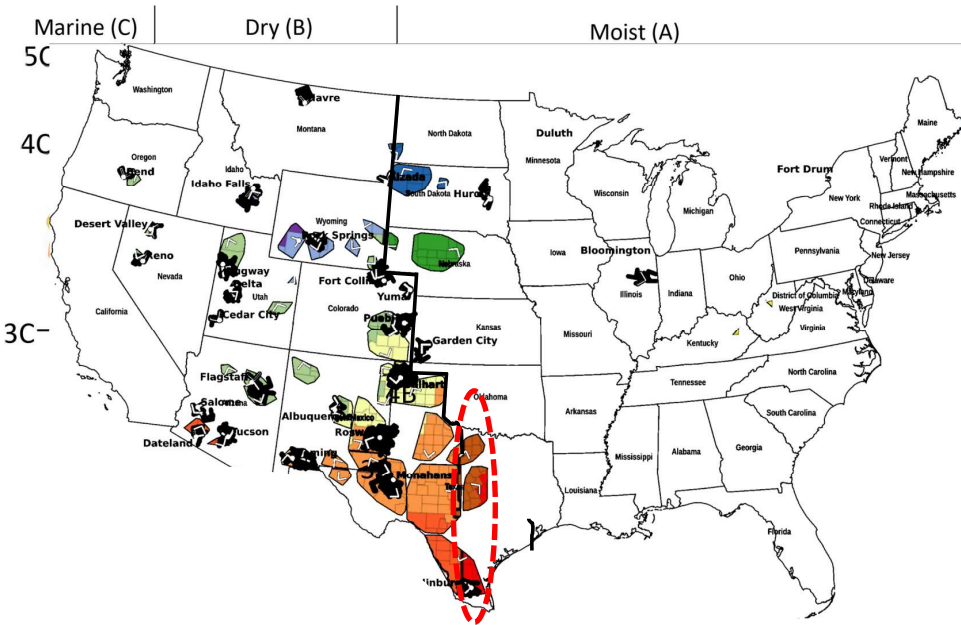
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ASHRAE CLIMATE ZONES



Mar. 27, 2026

ASHRAE CLIMATE ZONES



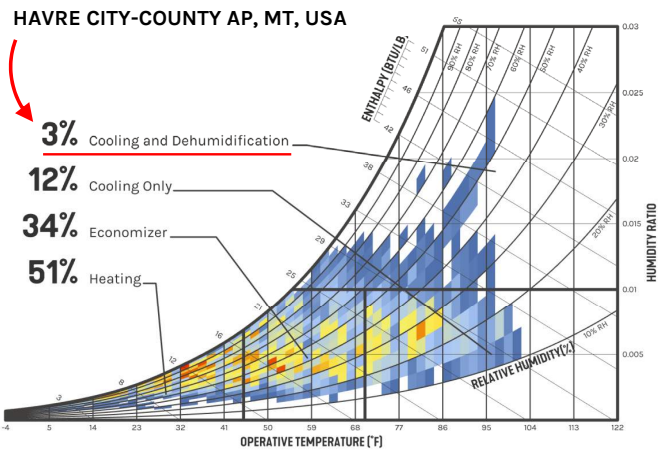
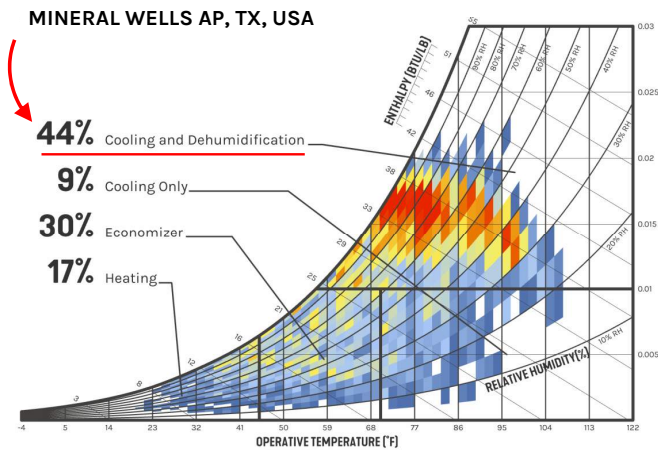
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CLIMATE ZONE IMPLICATIONS



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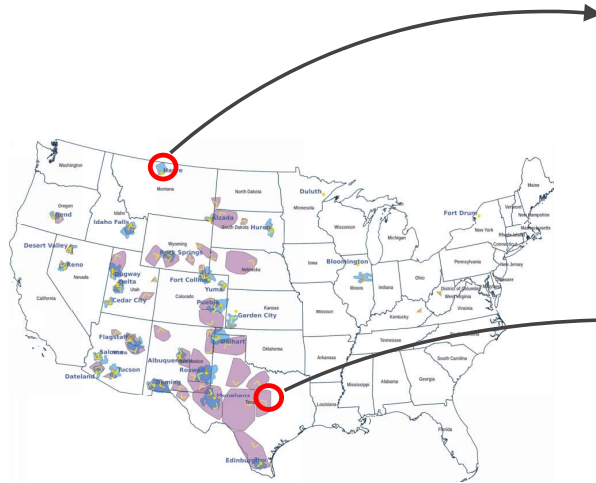
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COSMIC EXPLORER FEASIBILITY STUDY

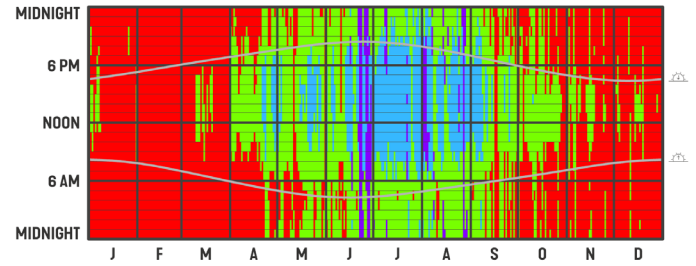
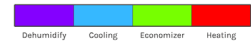
SMITHGROUP

CLIMATE ZONE IMPLICATIONS

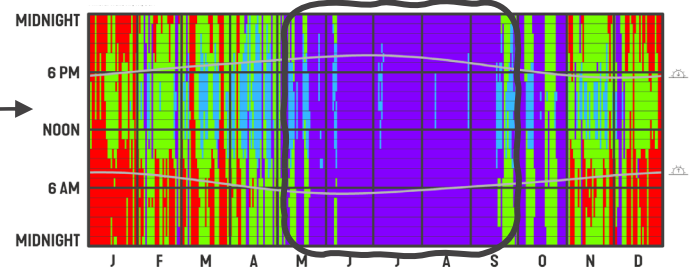
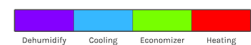
PREDICTED HVAC



HAVRE CITY-COUNTY AP, MT, USA



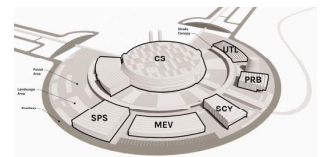
MINERAL WELLS AP, TX, USA



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CORNER STATION COMPLEX

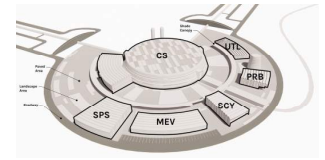
HVAC OVERVIEW



	BUILDINGS	ABBR.	SPACE	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
CORNER STATION COMPLEX	MAIN CORNER STATION BUILDING	CS	VEA EXPERIMENTAL HALL	LABORATORY	2	73 ±2°F 55 ±5% RH	73 ±2°F 55 ±5% RH	ISO 8
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F	65°F	None
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2			
	STAGING, PREP, AND STORAGE BUILDING	SPS	CLEAN AND BAKE OPERATIONS	LABORATORY	2	73 ±2°F 55 ±5% RH	73 ±2°F 55 ±5% RH	ISO 7
			STAGING					
			OPTICAL LABORATORY					
			CLEAN STORAGE					
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1			
	MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2					
	MACHINE, ELECTRONICS, AND VACUUM SHOPS	MEV	MACHINE SHOP	SHOP	2	75°F <50% RH	72°F	None
			ELECTRONICS SHOP					
			VACUUM HARDWARE SHOP					
			SHIPPING/RECEIVING	SHIPPING/RECEIVING	2	75°F <50% RH	72°F	None
			STORAGE	OCCUPIABLE STORAGE ROOMS FOR DRY MATERIALS	1	75°F <50% RH	72°F	None
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F	65°F	n/a
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2			
	SUBSTATION AND CHILLER YARD	SCY	SUBSTATION ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F ±15°F	65°F ±15°F	None
			CHILLER ROOM	MACHINERY ROOM	4	80°F ±15°F	65°F ±15°F	None
	WATER TANK AND PUMP ROOM BUILDING	PRB	PUMP ROOM	EQUIPMENT ROOM (MECHANICAL)	1	80°F ±15°F	65°F ±15°F	None

CORNER STATION COMPLEX

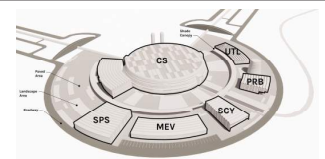
CS AND SPS HUMIDIFICATION



	BUILDINGS	ABBR.	SPACE	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
CORNER STATION COMPLEX	MAIN CORNER STATION BUILDING	CS	VEA EXPERIMENTAL HALL	LABORATORY	2	73 ±2°F 55 ±5% RH	73 ±2°F 55 ±5% RH	ISO 8
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F	65°F	None
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2			
	STAGING, PREP, AND STORAGE BUILDING	SPS	CLEAN AND BAKE OPERATIONS	TRIGGERS REQUIREMENT FOR HUMIDIFIED BUILDING CONSTRUCTION		73 ±2°F 55 ±5% RH	73 ±2°F 55 ±5% RH	ISO 7
			STAGING					
			OPTICAL LABORATORY					
			CLEAN STORAGE					
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F	65°F	n/a
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2			

CORNER STATION COMPLEX

SPACE HAZARD CLASSIFICATION



	BUILDINGS	ABBR.	SPACE	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS
CORNER STATION COMPLEX	MAIN CORNER STATION BUILDING	CS	VEA EXPERIMENTAL HALL	LABORATORY	2?
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2
	STAGING, PREP, AND STORAGE BUILDING	SPS	CLEAN AND BAKE OPERATIONS	LABORATORY	2?
			STAGING		
			OPTICAL LABORATORY		
			CLEAN STORAGE		
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1
			MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2
	MACHINE, ELECTRONICS, AND VACUUM SHOPS	MEV	MACHINE SHOP	SHOP	2?
			ELECTRONICS SHOP		
			VACUUM HARDWARE SHOP		
			SHIPPING/RECEIVING	SHIPPING/RECEIVING	2
			STORAGE	OCCUPIABLE STORAGE ROOMS FOR DRY MATERIALS	1
			ELECTRICAL ROOM	EQUIPMENT ROOM (ELECTRICAL)	1
	SUBSTATION AND CHILLER YARD	SCY	MECHANICAL ROOM	EQUIPMENT ROOM (MECHANICAL)	2
			SUBSTATION ROOM	EQUIPMENT ROOM (ELECTRICAL)	1
			CHILLER ROOM	MACHINERY ROOM	4
	WATER TANK AND PUMP ROOM BUILDING	PRB	PUMP ROOM	EQUIPMENT ROOM (MECHANICAL)	1

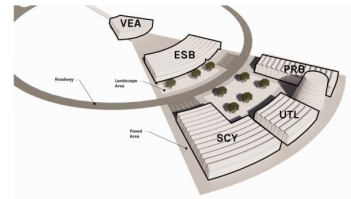
Determined from factors such as chemical quantity and material flammability

Informs code permissibility of recirculation to reduce HVAC energy use

Informs type and size of hazardous exhaust systems

END STATION COMPLEX

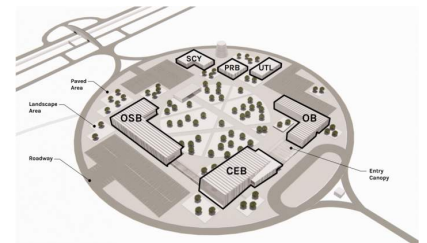
HVAC OVERVIEW



	BUILDINGS	ABBR.	SPACE	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
END STATION COMPLEX	VACUUM EQUIPMENT AREA BUILDING	VEA	VEA EXPERIMENTAL HALL	LABORATORY	2?	73±2°F 55 ±5% RH	73±2°F 55 ±5% RH	ISO 8
	END STATION SUPPORT BUILDING	ESB	OFFICE	OFFICE	1	75°F <50% RH	72°F	None
			CONTROL ROOM	COMPUTER	1	75°F <50% RH	72°F	None
			ELECTRONIC SHOP	LABORATORY	2?	75°F <50% RH	73 ±2°F 55 ±5% RH	None
			OPTICS LAB					
	SUBSTATION AND CHILLER YARD	SCY	SUBSTATION ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F ±15°F	65°F ±15°F	None
			CHILLER ROOM	MACHINERY ROOM	4	80°F ±15°F	65°F ±15°F	None
	WATER TANK AND PUMP ROOM BUILDING	PRB	PUMP ROOM	EQUIPMENT ROOM (MECHANICAL)	1	80°F ±15°F	65°F ±15°F	None

MAIN CAMPUS

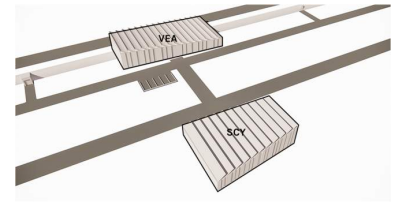
HVAC OVERVIEW



	BUILDINGS	ABBR.	SPACE
MAIN CAMPUS	OPERATIONS SUPPORT BUILDING	OSB	OFFICES, MEETING ROOMS, LOUNGE PANTRY, TOILETS, STORAGE CONTROL ROOM ELECTRONIC SHOP MACHINE SHOP GENERAL WORKSHOP CLEAN LABS OPTICS LABORATORY VACUUM PREPARATION LAB DATA STORAGE AREA
			OFFICE SERVER ROOM CONFERENCE ROOM DINING HALL PANTRY LOBBY/DISPLAY
	OFFICE BUILDING	OB	AUDITORIUM (200-PERSON CAPACITY) EXHIBIT HALL CLASSROOM OFFICE
	COMMUNITY EDUCATION BUILDING	CEB	

MID STATION COMPLEX

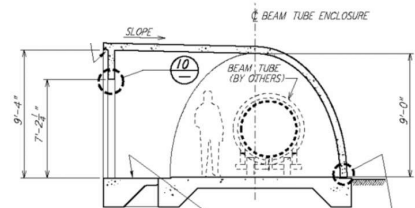
HVAC OVERVIEW



	BUILDINGS	ABBR.	SPACE	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
MID STATION COMPLEX	VACUUM EQUIPMENT AREA BUILDING	VEA	VEA EXPERIMENTAL HALL	SCIENCE LABORATORIES	2?	73 ±2°F 55 ±5% RH	73 ±2°F 55 ±5% RH	ISO 8
	SUBSTATION AND CHILLER YARD	SCY	SUBSTATION ROOM	EQUIPMENT ROOM (ELECTRICAL)	1	80°F ±15°F	65°F ±15°F	None
			CHILLER ROOM	MACHINERY ROOM	4	80°F ±15°F	65°F ±15°F	None

VACUUM VALVE STATION

HVAC OVERVIEW



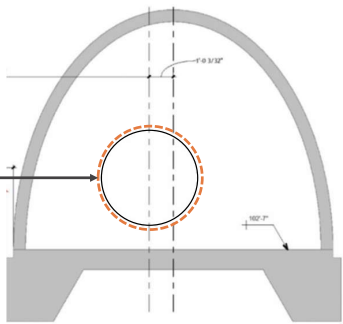
	ABBR.	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
VACUUM VALVE STATION	VS	EQUIPMENT ROOM (MECHANICAL)	2	73 ±10°F 55 ±15%	73 ±10°F 55 ±15%	None

Airtight construction of VS required to maintain setpoint

BEAM TUBE ENCLOSURE

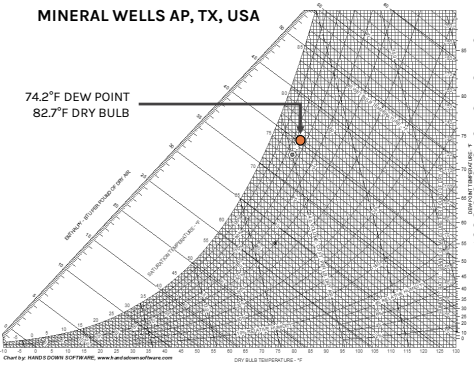
HVAC OVERVIEW

TARGET SURFACE TEMPERATURE
ABOVE 74.2°F



MINERAL WELLS AP, TX, USA

74.2°F DEW POINT
82.7°F DRY BULB



	ABBR.	ASHRAE VENTILATION OCCUPANCY CATEGORY	AIR CLASS	COOLING SETPOINT	HEATING SETPOINT	CLEANROOM CLASS
BEAM TUBE ENCLOSURE	BTE	EQUIPMENT ROOM (MECHANICAL)	2	NON-CONDENSING ENVIRONMENT		None

SUSTAINABILITY

SUSTAINABILITY

- 1

EMBODIED CARBON
- 2

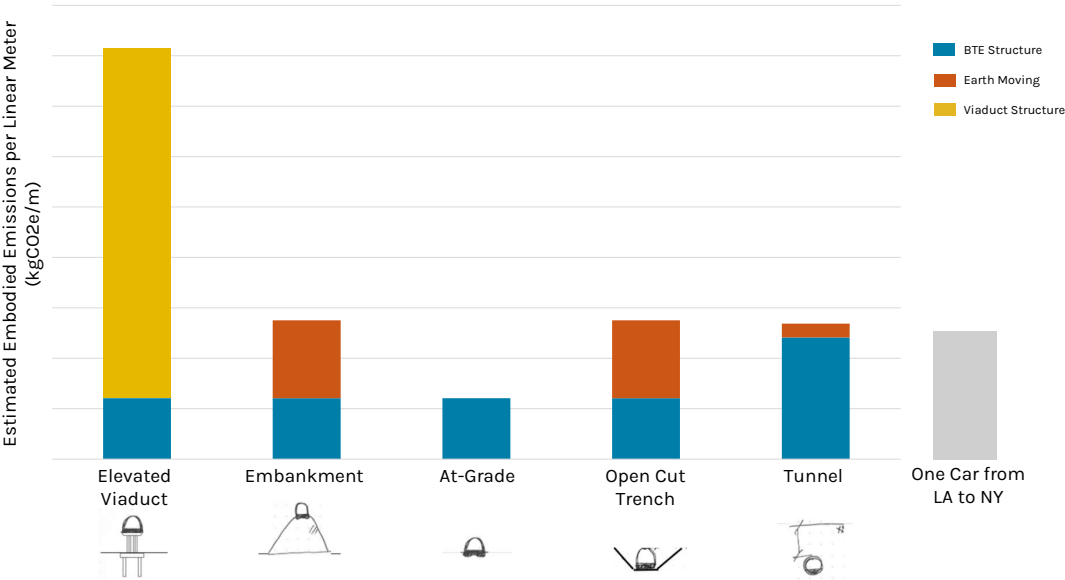
ENERGY AND OPERATINAL EMISSIONS
- 3

BUILDING v. SITE CERTIFICATION SYSTEMS
- 4

GOALS AND INVERSTMENT CLARITY

BTE EMBODIED CARBON EMISSIONS

BTE TYPE COMPARISON

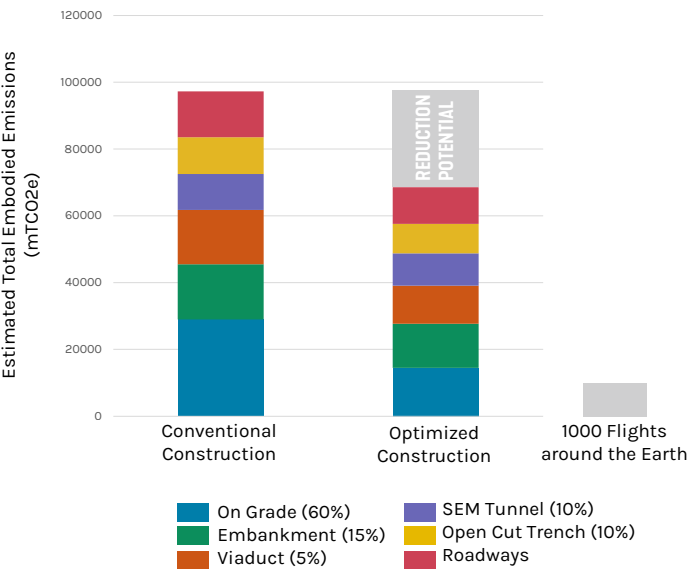


BTE EMBODIED CARBON EMISSIONS

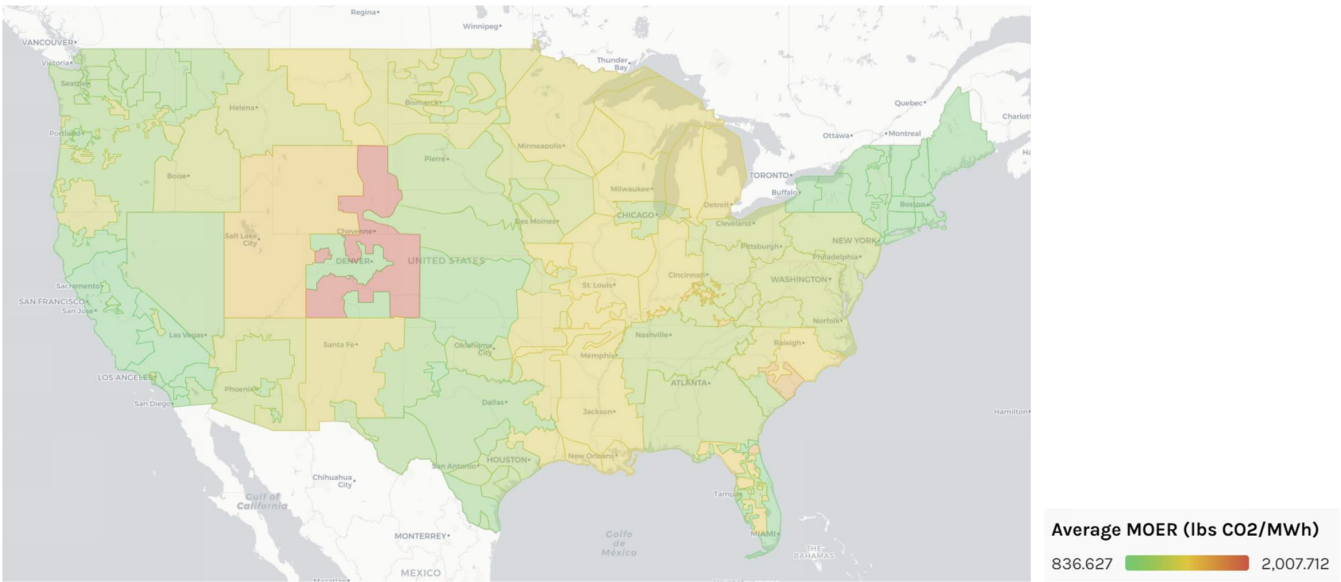
ESTIMATED TOTALS AND REDUCTION OPPORTUNITIES

REDUCTION STRATEGIES

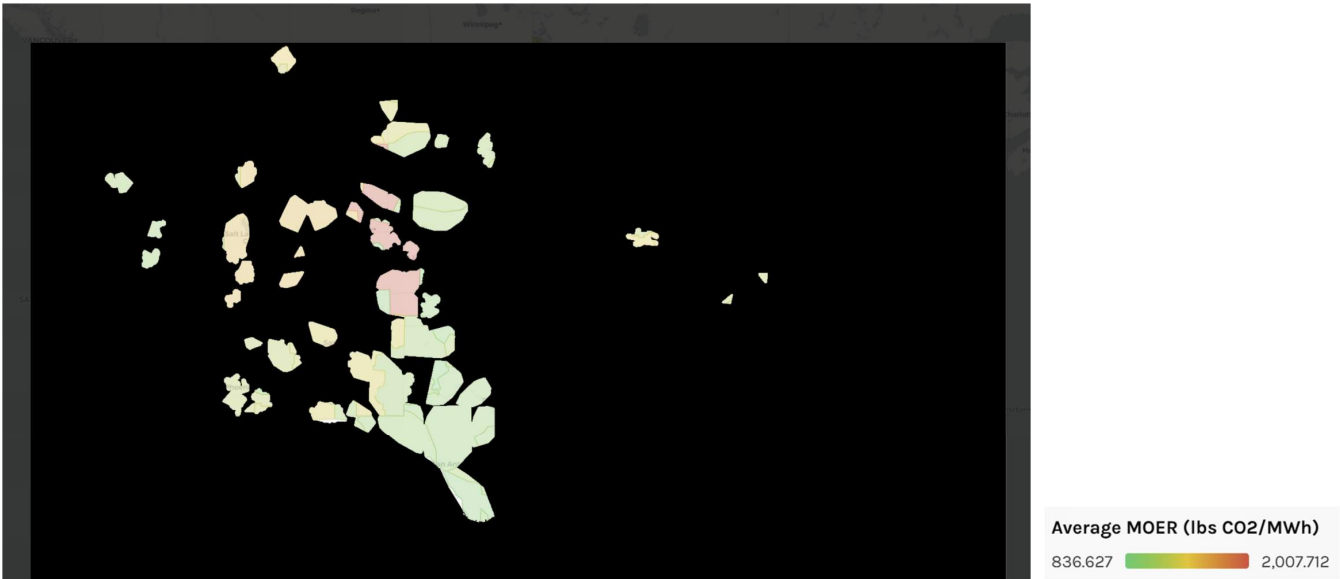
- 1. LOW-CARBON CONCRETE**
Current best-practices can reduce the carbon impact of concrete by 20-30%. Emerging technologies can achieve closer to 50-80% reduction and are worth considering for a project of this scale.
- 2. OPTIMIZED AND BALANCED CUT/FILL**
Disposal or importing of soil can double emissions associated with earthwork. Optimizing construction sequencing to reduce the handling of soil can reduce emissions.
- 3. ALL-ELECTRIC CONSTRUCTION VEHICLES**
Tailpipe emissions could be eliminated with all-electric vehicles, significantly reducing emissions associated with earthwork and material transport to site. Grid emissions for vehicle charging should be considered.



US GRID MARGINAL CARBON EMISSIONS



US GRID MARGINAL CARBON EMISSIONS



Mar. 27, 2026

ENERGY CONSUMPTION – EXISTING LIGOs

EUI = Energy Use Intensity
(total energy / program area)

Hanford: 8.4mm kWh

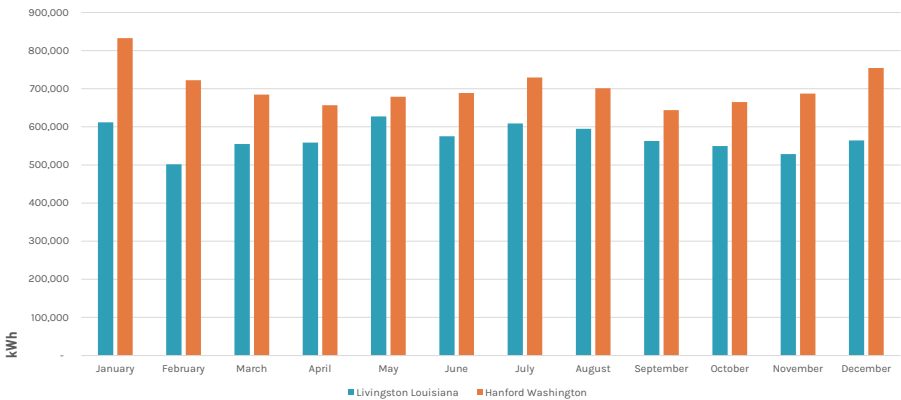
EUI = 485 kBtu/ft²/yr

EUI = 95 kBtu/ft²/yr (with BTE area)

Livingston: 6.8mm kWh

EUI = 393 kBtu/ft²/yr

EUI = 77 kBtu/ft²/yr (with BTE area)



Mar. 27, 2026

ENERGY CONSUMPTION – ROM CE CONSUMPTION

EUI = Energy Use Intensity
(total energy / program area)

Hanford: 8.4mm kWh

EUI = 485 kBtu/ft²/yr

EUI = 95 kBtu/ft²/yr (with BTE area)

Livingston: 6.8mm kWh

EUI = 393 kBtu/ft²/yr

EUI = 77 kBtu/ft²/yr (with BTE area)

Cosmic Explorer:

Name	electrical max total (kW)
Baseline Buildings	
Corner Station Complex	1500
East Station Complex	400
Mid Station Complex	1000
Western Station Complex	500
Beam Tube Enclosures	200 (1500*)
Shipping, Prep and Storage Building	
Main Campus Buildings	
Operation Support Building	400
Community Education Building	500
Office Building	500

Total Connected Load

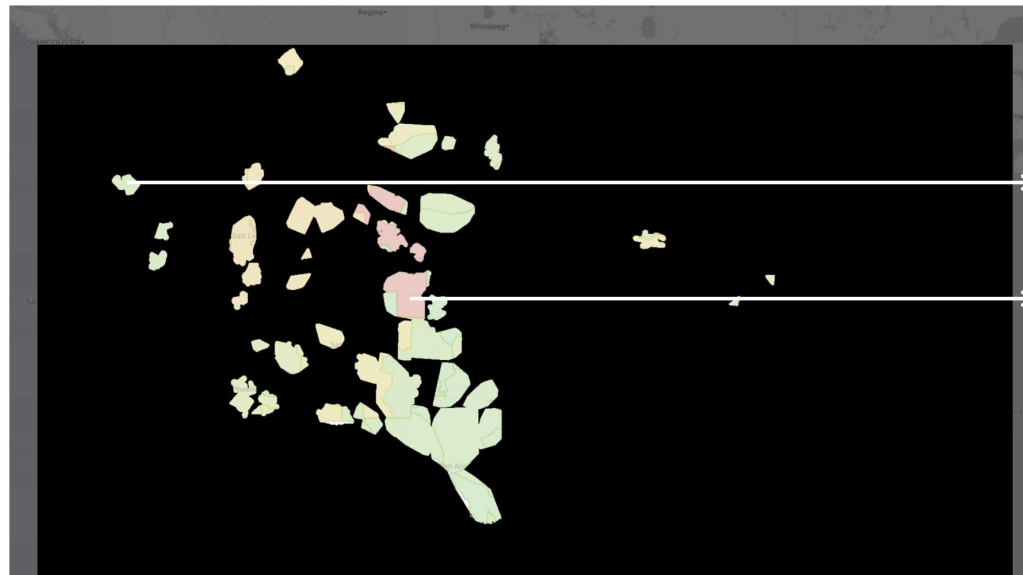
X 24 hrs/day
X 365 days/yr
X Energy professional factor

= Cosmic Explorer: 50mm kWh

EUI = 480 kBtu/ft²/yr

EUI = 61 kBtu/ft²/yr (with BTE area)

50,000 MWh IN DIFFERENT GRID REGIONS...



Operating CE in Eastern Oregon for year:

18,900 MT CO₂

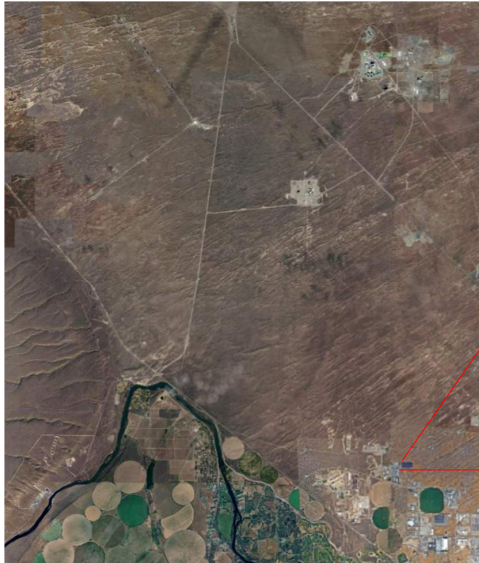
Operating CE in Eastern Colorado for year:

45,400 MT CO₂

Average MOER (lbs CO₂/MWh)

836.627 2,007.712

50,000 MWh FROM PV?



Example 4 MW PV Installation near Hanford
~1100' x 585'

Produces ~5.2mm kWh/yr



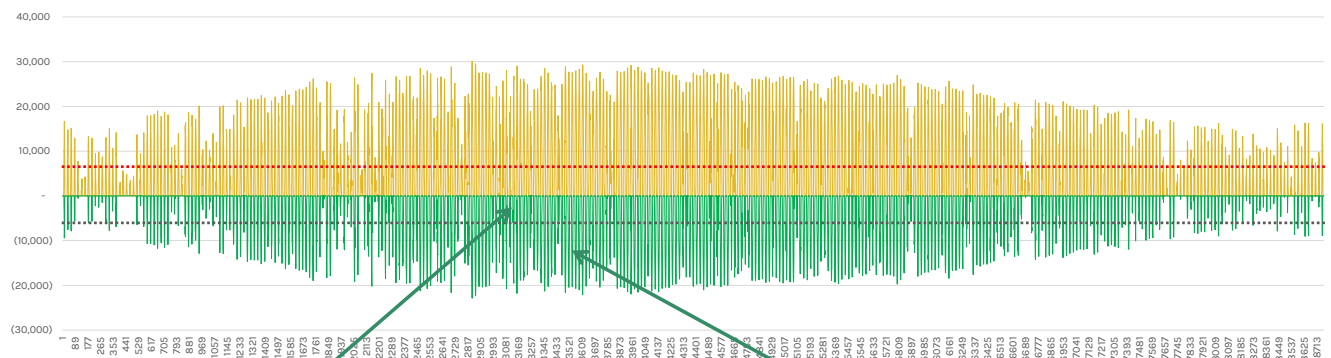
**x10 of these
to produce
annual net
consumption
of CE...**

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PRODUCTION FROM A 40 MW ARRAY?



**Sufficient 24hr
BESS capacity for
much of the year...**

**Massive daily overproduction back to
grid to annually net out 50,000 kWh
of consumption from solar
production...**

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SOLAR + BESS

Choosing a site with good grid emissions, stability, and capacity is critical, even with generous amounts of on-site solar.

At \$2.50/watt installed for solar...

- 1MW array = \$2,500,000
- 4MW array = \$10,000,000
- 40MW array = \$100,000,000

SUSTAINABILITY FRAMEWORKS

DESIGN GUIDELINES

SITE INFRASTRUCTURE



REGIONAL GOALS

SUSTAINABLE DEVELOPMENT GOALS



CAMPUS DESIGN

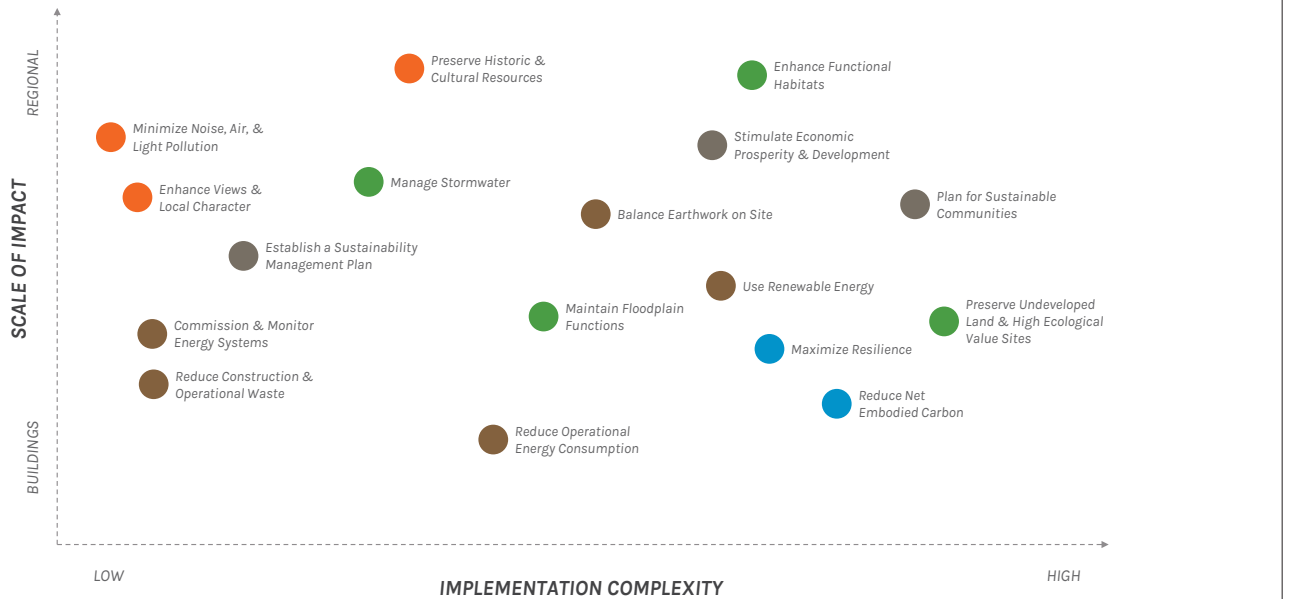


INFRASTRUCTURE SUSTAINABILITY FRAMEWORK

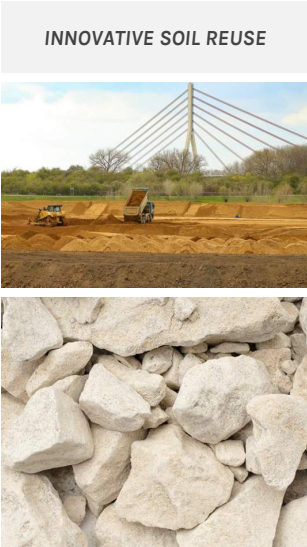
ENVISION



SUSTAINABILITY DESIGN PRIORITIES



WHAT ELSE IS POSSIBLE?



SUSTAINABILITY INTENTIONS

SUSTAINABILITY ATTITUDES

- Agnostic
- Do our best, but can't dedicate any funds to Sustainability
- 1% of Construction Budget to Sustainability
- Specific Sustainability Aspiration

PROPOSED ASPIRATION: ILFI ZERO CARBON CERTIFICATION



1. 25% Energy Reduction + **procure 100% clean electricity.** Zero fossil fuel combustion once operating.
2. 20% Minimum embodied carbon reduction + **full accounting of embodied emissions and one-time offsets purchased.**

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PROPOSED ASPIRATION: ILFI ZERO CARBON CERTIFICATION



1. 25% Energy Reduction + procure 100% clean electricity. Zero fossil fuel combustion once operating.
2. 20% Minimum embodied carbon reduction + full accounting of embodied emissions and one-time offsets purchased.

Future grid decarbonization and some on-site solar under consideration could get us there.

Offsets are critiqueable. But intentional purchase of offset projects in CE's immediate region would be genuinely impactful – perhaps more than 40MW of solar...

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SUSTAINABILITY INTENTIONS

Agnostic

Do our best, but can't dedicate any funds to Sustainability

SUSTAINABILITY EXPECTATION

1% of Construction Budget to Sustainability, to achieve ILFI Zero Carbon Certification.

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COSMIC EXPLORER FEASIBILITY STUDY

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COMMENTS

Smith, Joshua 11:40 AM

JS [https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Nighttime_Visualization_\(CloseUp...\)](https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Nighttime_Visualization_(CloseUp...))
[https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Daytime_Visualization_\(CloseUp...\)](https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Daytime_Visualization_(CloseUp...))
[https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Nighttime_Visualization_\(CloseUp...\)](https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Nighttime_Visualization_(CloseUp...))
[https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Daytime_Visualization_\(CloseUp...\)](https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Daytime_Visualization_(CloseUp...))
https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_End_Station_Nighttime_Visualization.jpg
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https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Nighttime_Visualization.jpg
https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Off_Campus_Daytime_Visualization.jpg
https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Nighttime_Visualization.jpg
https://commons.wikimedia.org/wiki/File:Cosmic_Explorer_-_Corner_Station_Daytime_Visualization.jpg

File:Cosmic Explorer - Off Campus Nighttime Vi...
commons.wikimedia.org

Here are all of the renders on Wikimedia, some are day, some are night

Sean Ahdi 10:34 AM

SA Smith, Joshua in your rough check of material movement, you said 3M cubic yards, correct? (just taking accurate notes)

Smith, Joshua 10:36 AM

JS Ah, no, I converted the number given in cubic yards into cubic meters and it is about 3M cubic meters, so I think the number given (3910000 cy) is reasonable.

For ARUP, we have had some discussions about how much subsidence is too much, i.e., would make building unfeasible or greatly increase the costs, might you be aware of a rule of thumb threshold we could use to raise a risk flag for locations in the US at the national scale?

FHWA - Center for Local Aid Support - Publications

Table 1. Estimated capacity for each of the proposed stations, assuming a single standard 12' x 12' x 12' ft. train.

Station	Capacity (trains/hr)	Capacity (trains/day)
17	1.0	24
24	1.0	24
25	1.0	24
26	1.0	24
27	1.0	24
28	1.0	24
29	1.0	24
30	1.0	24
31	1.0	24
32	1.0	24
33	1.0	24
34	1.0	24
35	1.0	24
36	1.0	24
37	1.0	24
38	1.0	24
39	1.0	24
40	1.0	24
41	1.0	24
42	1.0	24
43	1.0	24
44	1.0	24
45	1.0	24
46	1.0	24
47	1.0	24
48	1.0	24
49	1.0	24
50	1.0	24
51	1.0	24
52	1.0	24
53	1.0	24
54	1.0	24
55	1.0	24
56	1.0	24
57	1.0	24
58	1.0	24
59	1.0	24
60	1.0	24
61	1.0	24
62	1.0	24
63	1.0	24
64	1.0	24
65	1.0	24
66	1.0	24
67	1.0	24
68	1.0	24
69	1.0	24
70	1.0	24
71	1.0	24
72	1.0	24
73	1.0	24
74	1.0	24
75	1.0	24
76	1.0	24
77	1.0	24
78	1.0	24
79	1.0	24
80	1.0	24
81	1.0	24
82	1.0	24
83	1.0	24
84	1.0	24
85	1.0	24
86	1.0	24
87	1.0	24
88	1.0	24
89	1.0	24
90	1.0	24
91	1.0	24
92	1.0	24
93	1.0	24
94	1.0	24
95	1.0	24
96	1.0	24
97	1.0	24
98	1.0	24
99	1.0	24
100	1.0	24

Matthew J Evans 10:44 AM

ME To keep the laser beam well centered in the beamtubes, they should not move up/down/left/right by more than ~2 inch. We can correct with the beamtube support structure, so somewhat more subsidence may be acceptable.

Sean Ahdi 10:44 AM

SA Thanks Joshua, we will look into that and get an answer for you regarding subsidence & settlement.

As Nik Sokol mentioned, performance-based design criteria may be more appropriate for this project, as it is in, say, modern practice of seismic design for buildings & infrastructure, a step beyond code-based design. In such a framework, your team would specify the performance criteria (e.g., a limit in vertical deflection in cm), and design and construction methods would aim to achieve this target.

Thanks Matt for the approximate ~2 inch estimate.

Matthew J Evans 12:19 PM

ME I haven't managed to connect the math quickly, but the number we have using for expected energy use is 1.5 - 2MW average. This is not the sum of the capacity numbers listed in table 1.

Smith, Joshua 11:33 AM

JS Some comments:

- I really like the driving scene, very reminiscent of drives in Hanford
- When panning up at the end, I would pan from the central station rather than the thimble-type building.
- I think it will look more visually pleasing when the buildings are more connected with the landscape and less white
- Maybe there's something that can connect with the local landscape in addition to the black holes

Landry, Michael R. 11:36 AM

ML Same for the walking path, a little jarring against the uniform landscape - will prompt queries as to what its purpose is.

Suzanne Napier 11:37 AM

SN we can simplify the walking path so it blends in more

Landry, Michael R. 11:13 AM

ML We work with local tribes on viewshed issues with each change we make to the observatory

Matthew J Evans 11:21 AM

ME Audience: general scientific, and science-interested public. We will use this video, and stills from it, in our scientific and public talks. It will also be used when speaking with policymakers and NSF representatives.



NEXT STEPS

~ONWARDS AND UPWARDS TO WS-4!

COSMIC EXPLORER FEASIBILITY STUDY

SMITHGROUP



COSMIC EXPLORER FEASIBILITY STUDY WS-4

COSMIC EXPLORER FEASIBILITY STUDY

SMITHGROUP



SCHEDULE AND GOALS

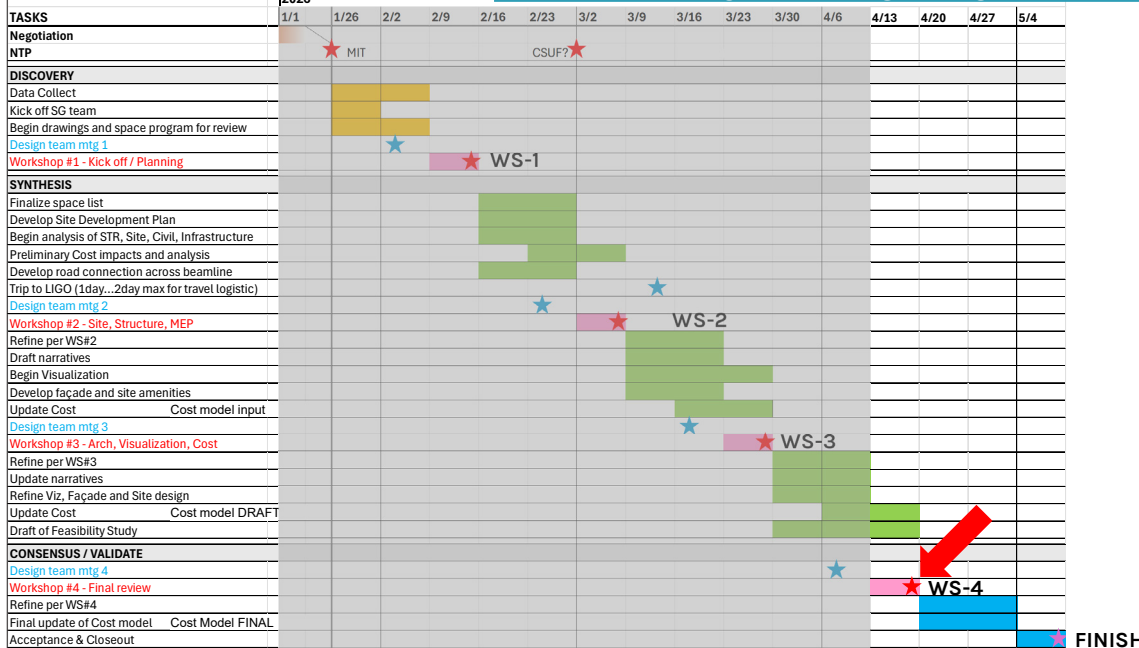
COSMIC EXPLORER FEASIBILITY STUDY

SMITHGROUP

PROPOSED SCHEDULE

15-WEEK DURATION

FINISH PROJECT
Week of 5/4



Apr. 17, 2026

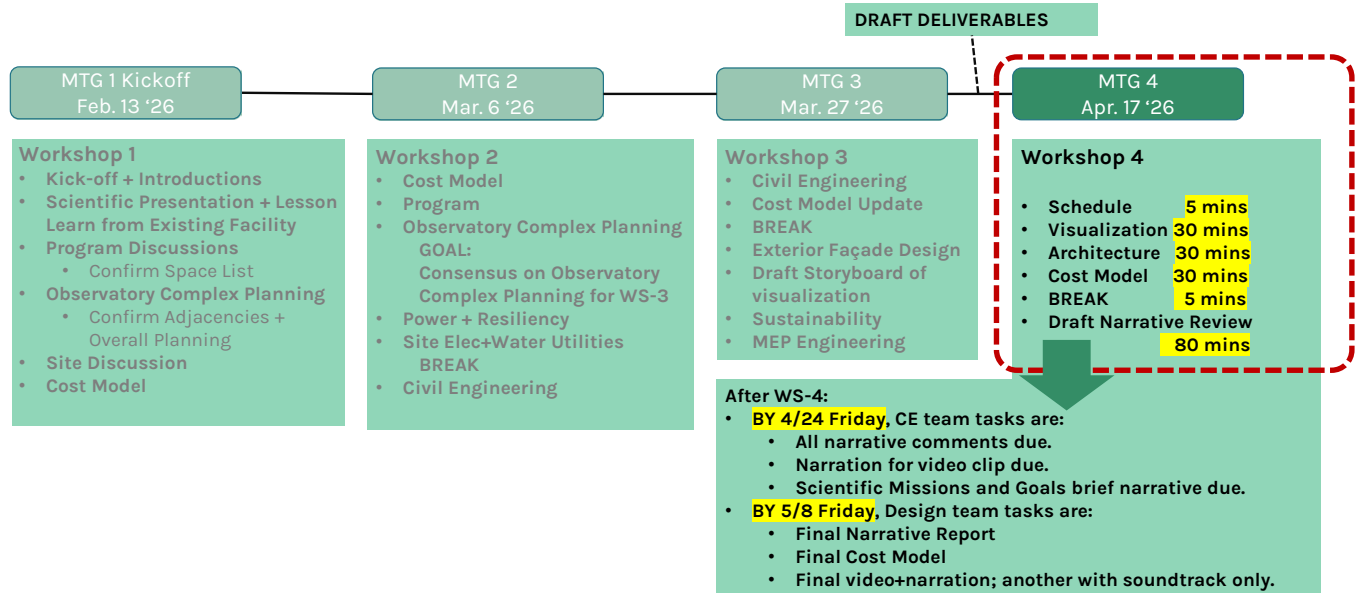
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COSMIC EXPLORER FEASIBILITY STUDY

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WORKSHOPS

Fridays = Workshops
Start at 9am (West) / 12 noon (East)



Apr. 17, 2026

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COSMIC EXPLORER FEASIBILITY STUDY

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VISUALIZATION UPDATE

1. RUN THRU VID, NARRATE KEY PTS MISSING OR CLARIFY. WIP. KEY CHANGES PER COMMENT FROM WS3

2. TWO VERSIONS OF VID

- ONE VID WITH SOUND+NARRATION. FOR YOUTUBE

- ONE VID WITH SOUND ONLY. FOR CONFERENCES. SPEAKER WILL NARRATE OVER IT LIVE.

4/24 : NEED SCRIPT.

COSMIC EXPLORER FEASIBILITY STUDY

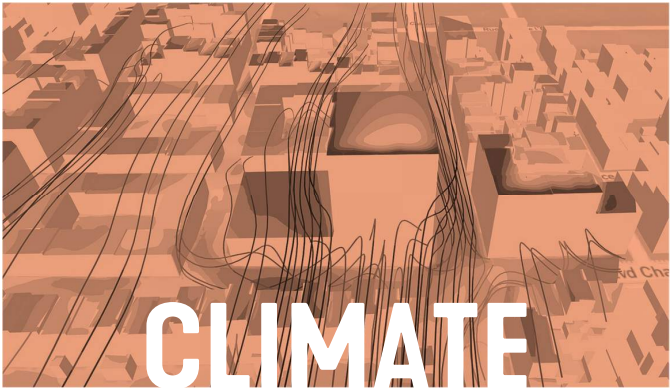
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ARCHITECTURAL DEVELOPMENT

COSMIC EXPLORER FEASIBILITY STUDY

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INFLUENCES



7

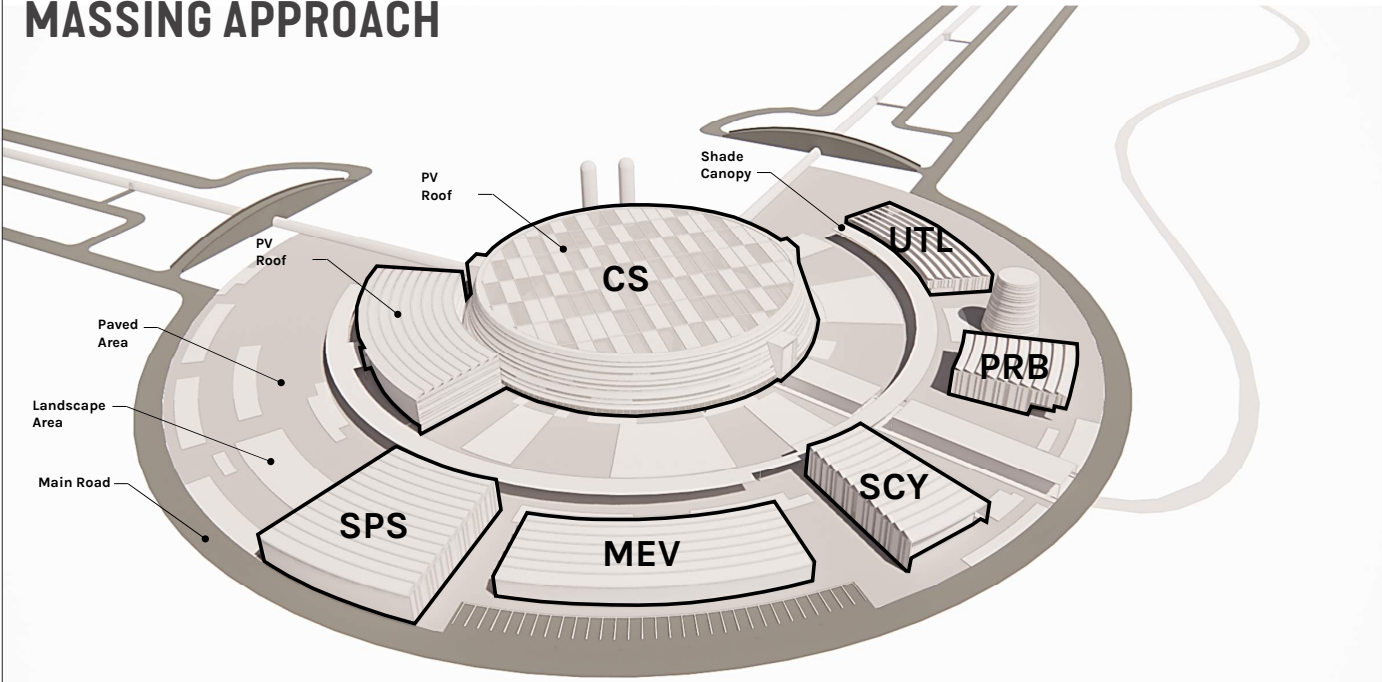
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COSMIC EXPLORER FEASIBILITY STUDY

Apr. 17, 2026

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MASSING APPROACH



8

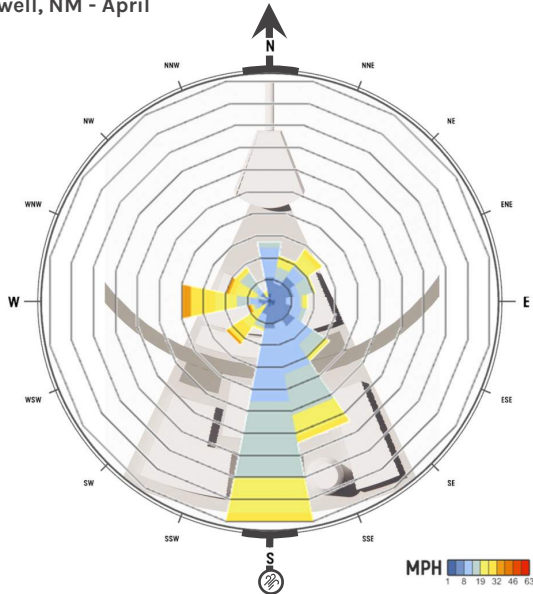
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COSMIC EXPLORER FEASIBILITY STUDY

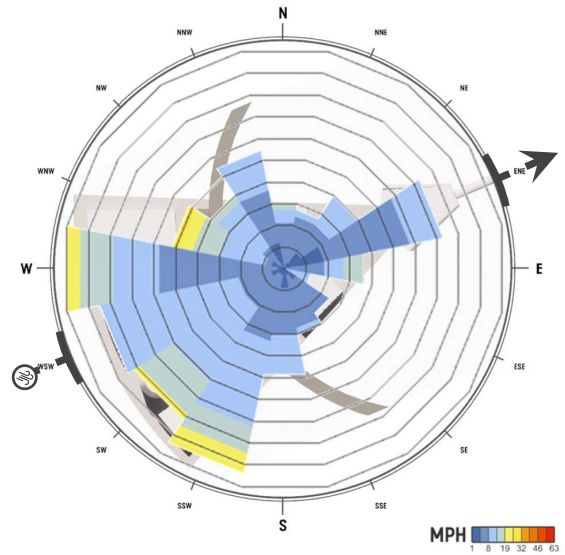
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WIND INFORMED

Roswell, NM - April



Denver, CO - November



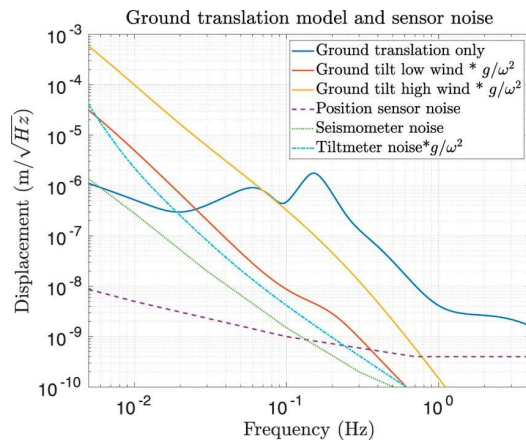
Apr. 17, 2026

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COSMIC EXPLORER FEASIBILITY STUDY

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WIND ANALYSIS



Building sway (structural vibration) → 0.5-15 Hz
•Speeds higher than 10-20 MPH

Building tilt → lower frequencies (<0.1 Hz)
•15 MPH with ground tilt
•33 – 45 MPH with sensor correction

These tilts arise from **deformations of the observatory's floor due to wind-driven pressure fluctuations on the walls of the building.**

Apr. 17, 2026

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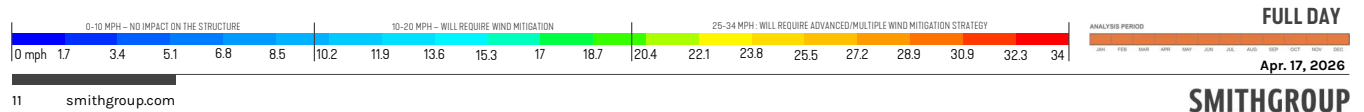
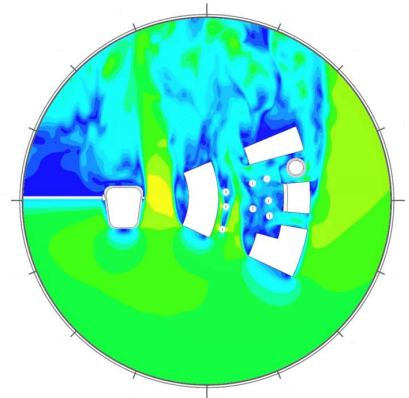
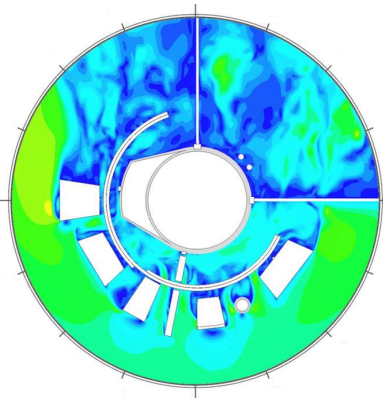
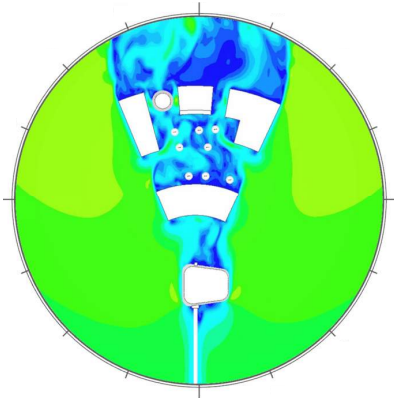
WIND ANALYSIS



TOP END STATION

CORNER STATION

SIDE END STATION



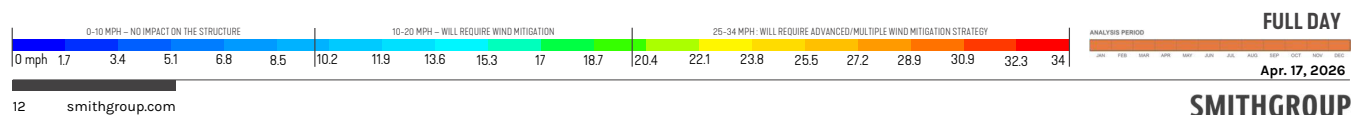
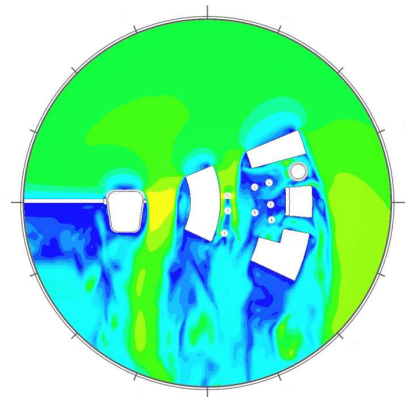
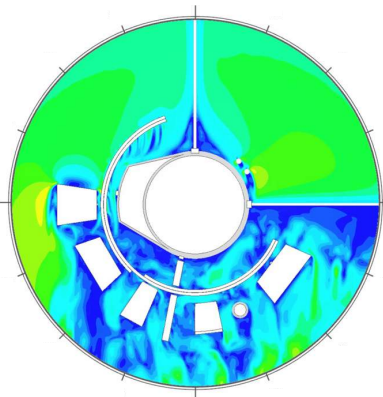
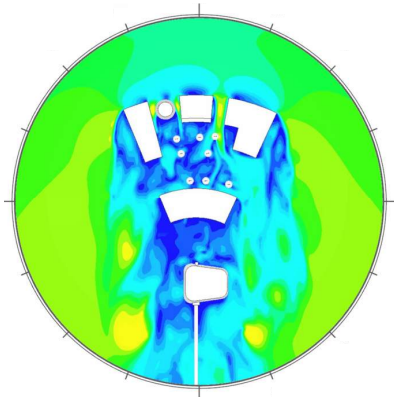
WIND ANALYSIS



TOP END STATION

CORNER STATION

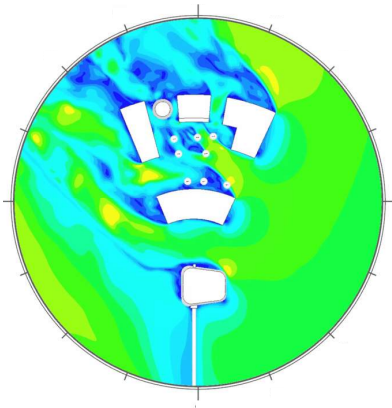
SIDE END STATION



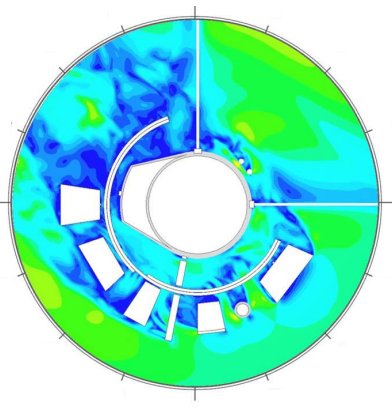
WIND ANALYSIS



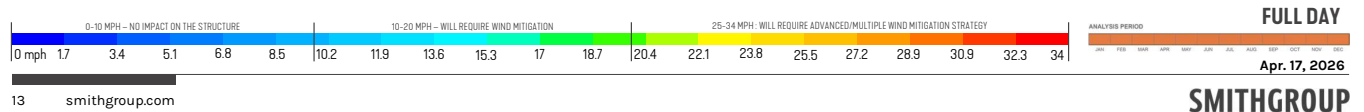
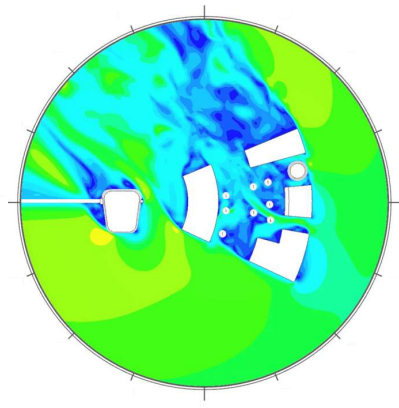
TOP END STATION



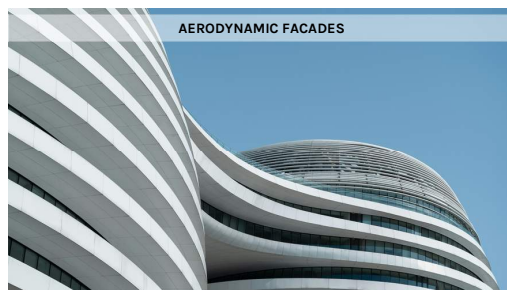
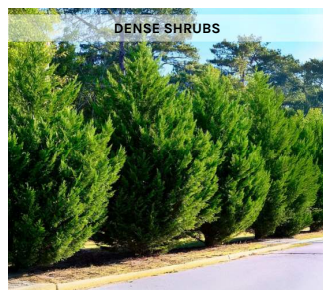
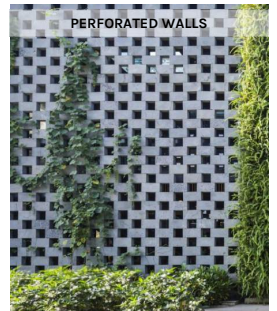
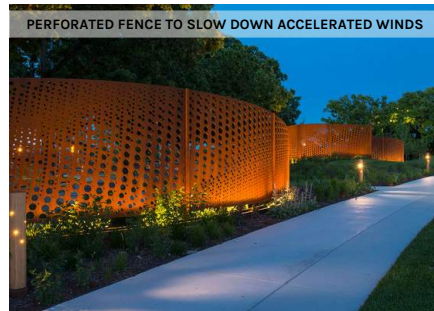
CORNER STATION



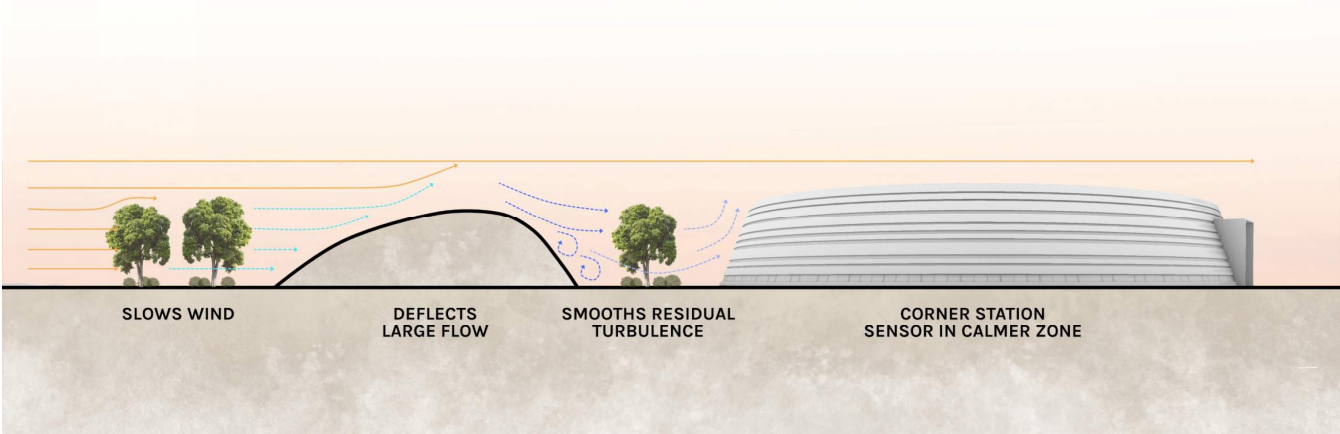
SIDE END STATION



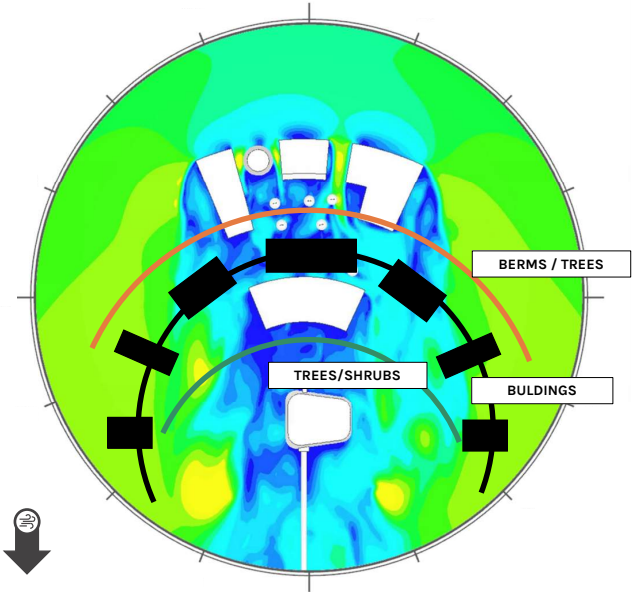
DESIGN STRATEGIES



DESIGN STRATEGIES

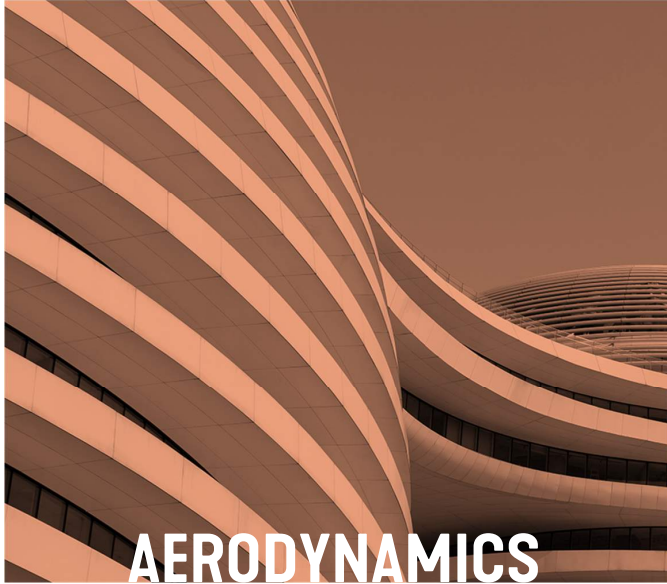


DESIGN STRATEGIES



- SITE LAYOUT AND ORIENTATION
- BUILDING DESIGN
- VEGETATION / BERMS

ARCHITECTURAL RESPONSE



Apr. 17, 2026

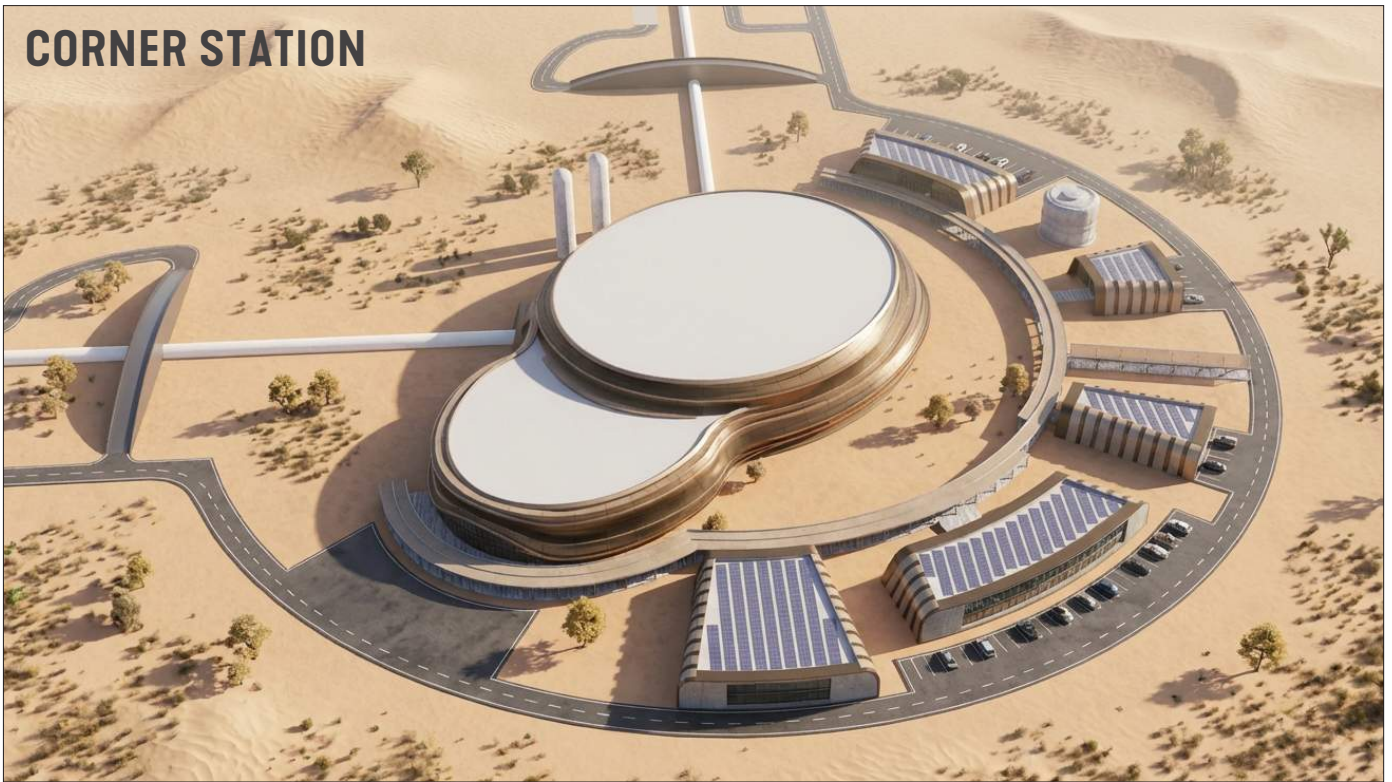
17

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COSMIC EXPLORER FEASIBILITY STUDY

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CORNER STATION



CORNER STATION



CORNER STATION



END STATION



END STATION



CAMPUS



CAMPUS



CAMPUS



COST MODEL



COSMIC EXPLORER FEASIBILITY STUDY

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COMMENTS

Landry, Michael R. 9:22 AM

ML Vince, Brian, another artist's example:
<https://www.ligo.caltech.edu/image/ligo20170601b>



Image | Dancing Duo...
Dancing Duo of Black Holes
www.ligo.caltech.edu

Smith, Joshua 9:24 AM

JS <https://www.ligo.caltech.edu/video/ligo20160211v3>

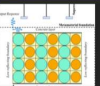


Two Black Holes Mer...
A computer simulation shows the collision of two...
www.ligo.caltech.edu

^ This is another one based on scientific simulations (Mike's is artistic, and also really cool, maybe better)

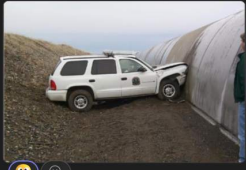
Smith, Joshua 9:29 AM

JS <https://www.nature.com/articles/s41598-023-27678-1>



Metamaterial foundation for ...
Scientific Reports - Metamaterial foundation for seismic wave...
www.nature.com

Landry, Michael R. 9:40 AM



Landry, Michael R. 9:46 AM

ML Agree with Josh strongly, the natural landscape and minimization of irrigation water use is excellent.

Smith, Joshua 9:48 AM

JS It's authentic. I love it, thanks!

Sean Ahdi 11:18 AM

SA microseism*

Landry, Michael R. 11:20 AM

ML +/- 100microns over 12h

Nick Mata 11:22 AM

NMA we also included an additional 1% for sustainability, behind the 10% design contingency, based on the narrative direction

Landry, Michael R. 10:46 AM

ML Vince, regarding the mp4 video linked at the top of the chat, and traffic that should be slowed: at 40s at the corner station, at 1:08 near the Support building, and at 1:30 at an end station. Vac building at 1:25 or so is less of an issue.

Landry, Michael R. 10:51 AM

ML Other minor suggestions: the laser originating point at about 10s is offset from it's circular "pad"; could the laser origin coincide. And, midstations shown at 32s could be replicated (pads only) on the Y-arm, for clarity.

Smith, Joshua 11:08 AM

JS Ironically, "the model that Josh Smith put together" was actually put together by Matt Evans, and I inherited it! But yes, these numbers are very helpful.

Sean Ahdi 11:13 AM

SA Smith, Joshua 4/17/2026 11:08 AM
 Ironically, "the model that Josh Smith put together" was actually put together by Matt Evans, and I...
 that's a "go team" mentality 😊

Landry, Michael R. 11:18 AM

ML Mainly from storms off the coast of Alaska, Labrador, and the Gulf

Vince Jaramillo 12:06 PM

Landry, Michael R. 4/17/2026 10:46 AM
 Vince, regarding the mp4 video linked at the top of the chat, and traffic that should be slowed: at 40s...
 Did you want to set specific speed limits for these areas?

Landry, Michael R. 12:07 PM

ML Say 15mph? Just as long as it doesn't look like they are zooming by pedestrians!

Smith, Joshua 12:14 PM

JS Really helpful risks layout, thanks!

Landry, Michael R. 12:14 PM

ML Thanks Rachel

Smith, Joshua 12:16 PM

JS <https://www.nsf.gov/updates-on-priorities>



Updates on NSF Priorities
www.nsf.gov

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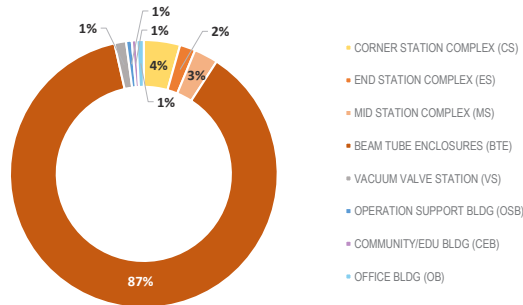
NEXT STEPS

~THANK YOU FOR YOUR INPUTS AND COLLABORATION!

SMITHGROUP

A^{.5} PROGRAM LIST

COSMIC EXPLORER RESEARCH FACILITY
ASSIGNABLE SPACE SUMMARY BY BLDG TYPE



PROGRAM SUMMARY / BREAKDOWN

(N) COSMIC EXPLORER RESEARCH FACILITY	Program Summary (ASF)
---------------------------------------	-----------------------

BEAMLINE BUILDINGS:

1.0 CORNER STATION COMPLEX (CS)	121,725
2.0 END STATION COMPLEX (ES)	52,400
3.0 MID STATION COMPLEX (MS)	80,400
4.0 BEAM TUBE ENCLOSURES (BTE)	2,428,000
5.0 VACUUM VALVE STATION (VS)	39,000

MAIN CAMPUS BUILDINGS:

6.0 OPERATION SUPPORT BLDG (OSB)	19,050
7.0 COMMUNITY/EDU BLDG (CEB)	15,568
8.0 OFFICE BLDG (OB)	24,530

Total ASF	2,780,673
60% Building Efficiency Gross Sq. Foot	1,853,782
Total GSF	4,634,454

ASF = Assignable Square Feet

Building Efficiency = Area for mechanical, toilets, circulation, walls, structure,

GSF = Gross Square Feet

COSMIC EXPLORER FEASIBILITY STUDY

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

1.0 CORNER STATION COMPLEX (CS)

		NEW RESEARCH FACILITY								Planning Module = 10'-0" x 10'-0"	
Category	Space	# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF	Notes	
1.1	CORNER STATION (CS)*	BLDG HEIGHT:		65 FT	1-STORY + BASEMENT				80,550	*Based on RFP Sketch Plan per 13 Feb 26 WSH1	
1.1.10	CS EXPERIMENTAL HALL								80,550		
1.1.11	Experimental Hall (Laser Vacuum Experiment Area, LVEA)				70.0	10.0	70,000	1	70,000	- Houses interferometer of VEA - Crane Hook Height of 14m w/ 10t Load Capacity - Close proximity to SPS Bldg & MEV Bldg (See 6. SPS) - Equipment housed are sensitive to vibration and ground tilt caused by wind impacting exterior - wind-mitigating architecture (e.g. buried design, aerodynamics/wind-design, etc) should be studied.	
1.1.12	Commissioning Control Room	2**			5.5	5.0	2,750	1	2,750		
1.1.13	Class 10,000 ISO 7 Cleanroom & Storage				7.0	6.5	4,550	1	4,550		
1.1.14	Electronics Shop & Storage				5.0	6.5	3,250	1	3,250		
1.2	SHARED/SUPPORT FUNCTIONS								23,500		
1.2.10	COMMON/SUPPORT FUNCTIONS								23,500		
1.2.11	Switch Gear Rooms (HT & LT)						-	2	-		
1.2.12	Mechanical Equipment Room (AHU)						-	2	-		
1.2.13	FC & MER Ducting Room						-	1	-		
1.2.14	Plumbing / Fire-Riser						-	1	-		
1.2.15	Battery Rooms						-	2	-		
1.2.16	Lobby / Entry						-	1	-		
1.2.17	Restrooms						-	4	-		
1.2.18	Janitor Closet						-	1	-		
1.2.19	Basement				23.5	10.0	23,500	1	23,500	15' Ceiling Height	
1.3	STAGING, PREP & STORAGE BLDG (SPS)	BLDG HEIGHT:		30 FT	1-STORY				13,175		
1.3.10	STAGING, PREP & STORAGE (SPS)								13,175		
1.3.11	Staging Facility	2			9.5	5.0	4,750	1	4,750	- Located approx. 100' from VEA Bldg of CS - Crane w/ Hook Height of 7.5m w/ 10t Load Capacity - Align finished floor level w/ VEA. - Contains Staging, Clean & Bake Operations, Optical Lab, Clean Storage Area, and Shipping/Receiving Area.	
1.3.12	Clean Storage				5.0	3.25	1,625	1	1,625		
1.3.13	Clean & Bake Facility				8.0	5.0	4,000	1	4,000		
1.3.14	Optical Lab				4.0	2.0	800	1	800		
1.3.15	Shipping & Receiving				4.0	5.0	2,000	1	2,000		
1.3.16	Restrooms						-	2	-		
1.4	MACHINE, ELEC & VACUUM SHOP (MEV)	BLDG HEIGHT:		30 FT	1-STORY				4,500		
1.4.10	MACHINE, ELEC & VACUUM SHOP (MEV)								4,500		
1.4.11	Machine Shop (Lathe Machines)				3.00	2.5	750	1	750		
1.4.12	Mechanical Instruments Room				3.00	2.5	750	1	750		
1.4.13	Storage Facility				6.00	5.0	3,000	1	3,000		
1.4.14	Electrical Panel Room						-	1	-		
1.4.15	Mechanical Equipment Room (AHU)						-	1	-	- Located approx. 100' from VEA Bldg of CS - Also includes Shipping/Receiving Area. - No cleanroom storage requirement w/in MEV	
1.4.16	Plumbing / Fire-Riser						-	1	-		
1.5	UTILITY/SERVICES								-		
1.5.10	SUBSTATION & CHILLER-YARD (SCY)								-		
1.5.11	Substation & Chiller-Yard (SCY)						-	1	-		
1.5.20	PUMP & WATER TANK BUILDING (PRB)								-		
1.5.21	Pump Room						-	1	-		
1.5.22	Water Tank						-	1	-		

CS TOTAL 104,050
SPS & MEV TOTAL 17,675
GRAND TOTAL 121,725

** (2) during normal operation, staff access needed; (30) during equipment installation

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

2.0 END STATION COMPLEX (ES)

NEW RESEARCH FACILITY										Planning Module = 10'-0" x 10'-0"	
Category	Space	# People	SF per Person	BLDG Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF		Notes
2.1	MAIN END STATION BLDG*	BLDG HEIGHT:			65 FT	1-STORY + BASEMENT				31,400	*Based on LIGO India Plan per 13 Feb 26 WS#1
2.1.10	VACUUM EQUIPMENT AREA (VEA)								31,400		
2.1.11	Vacuum Equipment Area (VEA)			0	9.0	10.0	9,000	2	18,000		- Require vibration mitigation design. - Cleanroom access personnel & equipment. - Require vibration mitigation design. - Crane w/ Hook Height = 14m
2.1.12	VEA Experimental Equipment Room			0	2.3	2.0	450	2	900		
2.1.13	Clean Room			0	2.3	2.0	450	2	900		- Access to Computer Room & VEA Exp Eqp Room (2.1.12)
2.1.14	Computer Room			0	2.0	1.0	200	2	400		
2.1.15	Inspection, Shipping & Receiving			0	2.5	2.0	500	2	1,000		
2.1.16	Vacuum Support Room			0	3.0	2.0	600	2	1,200		
2.1.17	Basement			0	9.0	5.0	4,500	2	9,000		- Require vibration mitigation design. - 15' Ceiling Height - Runs entire length of VEA & width centered on beamline.
2.1.18	Electrical Panel Room						-	2	-		
2.1.19	Mechanical Equipment Room (AHU)						-	2	-		
2.2	END STATION SUPPORT BLDG	BLDG HEIGHT:			25 FT	(SIMILAR TO OSB)				21,000	
2.2.10	END STATION SUPPORT BLDG (ESB)								21,000		
2.2.11	Control Room (Small)	2		0	2.5	2.0	500	2	1,000		
2.2.12	Office			0	1.0	1.0	100	20	2,000		
2.2.13	Electronic Shop			0	10.0	5.0	5,000	2	10,000		- Facilitate local monitoring, data analysis, and coordination during maintenance & operational activities.
2.2.14	Optics Lab			0	10.0	4.0	4,000	2	8,000		
2.2.15	Restrooms						-	4	-		
2.3	UTILITY/SERVICE YARD									-	
2.3.10	SUBSTATION & CHILLER-YARD (SCY)								-		
2.3.11	Substation & Chiller Yatd (SCY)			0			-	2	-		Locate minimum 100' away from the VEAs to minimize vibration transmissions.
2.4	PUMP RM & WATER TANK BLDG	BLDG HEIGHT:			25 FT					-	
2.4.10	PUMP RM & WATER TANK BLDG (PRB)								-		
2.4.11	Water Tank & Pump Room			0			-	2	-		For domestic and firefighting purposes, each end station is expected to include a water tank and PRB within a designated service area.
GRAND TOTAL									52,400		

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

3.0 MID STATION COMPLEX (MS)

NEW RESEARCH FACILITY										Planning Module = 10'-0" x 10'-0"	
Category	Space	# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF		Notes
3.1	MID STATION COMPLEX*	BLDG HEIGHT:		40 FT	1-STORY					80,400	*Located @ Beamline KM Markers 5, 8, 16, 24, 32 & 35 - based on LIG
3.1.10	MID STATION								80,400		
3.1.11	Vacuum Equipment Area (VEA)	0		0	9.0	5.0	4,500	12	54,000		- Require vibration mitigation design. - Crane Hook @ 30' (9m) in the Experimental Hall - Will house sensitive optical & vacuum equipment (e.g. large chambers w/ suspended baffles)
3.1.12	VEA Experimental Equipment Room	0		0	2.3	2.0	450	12	5,400		- Cleanroom access personnel & equipment. - Require vibration mitigation design. - Crane w/ Hook Height = 14m
3.1.13	Clean Room	0		0	2.3	2.0	450	12	5,400		Access to Computer Room & VEA Exp Eqp Room (3.1.12)
3.1.14	Computer Room	0		0	2.0	1.0	200	12	2,400		
3.1.15	Inspection, Shipping & Receiving	0		0	2.5	2.0	500	12	6,000		
3.1.16	Vacuum Support Room	0		0	3.0	2.0	600	12	7,200		
3.1.17	Electrical Panel Room	0					-	12	-		
3.1.18	Mechanical Equipment Room (AHU)	0					-	12	-		
3.1.19	Plumbing	0					-	12	-		
3.1.20	All-Gender Restrooms	0					-	12	-		
3.2	UTILITY/SERVICE YARD									-	
3.2.10	SUBSTATION & CHILLER-YARD (SCY)								-		
3.2.12	Substation & Chiller-Yard (SCY)	0		0			-	12	-		
GRAND TOTAL									80,400		

**(0) during normal operation, staff access needed; (10) during equipment installation

***Functionally similar to ES but w/o basement or Support Bldg

****ES plan used as a basis of programming for MS, as WS#1 indicated MS is similar to ES without support building.

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

4.0 BEAM TUBE ENCLOSURE (BTE)

NEW RESEARCH FACILITY										Planning Module = 10'-0" x 10'-0"	
Category	Space	# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF		Notes
4.1	BEAM TUBE ENCLOSURE	BLDG HEIGHT:		10 FT						2,428,000	
4.1.10	BEAM TUBE ENCLOSURE								2,428,000		
4.1.11	Beam Tube Enclosure	0*			1.0	12,000.0	1,200,000	2	2,400,000		- MIN 9' Interior Height (RFP Doc shows 10' MAX in chart) - House 48" Beam Tube - Allow passage on (1) side of the tube the entire span of the beamline - SEE SECTIONS BELOW:
4.1.12	Pump Support / Access	0*			1.0	1.0	100	280	28,000		- Located (1) every 820' of BTE to access interior, aligned w/ pump ports. - Pump-Ports Access cross-section to match BTE dimensions, w/ access door that provide 9' x 9' x 15' (HxWxL) - SEE SECTIONS BELOW:
GRAND TOTAL									2,428,000		
*(0) during normal operation, staff access needed; (???) during equipment installation											

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

5.0 VACUUM VALVE STATION (VS)

NEW RESEARCH FACILITY										Planning Module = 10'-0" x 10'-0"		
Category	Space	# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF		Notes	
5.1	VACUUM VALVE STATIONS (VS)	BLDG HEIGHT:		21 FT	1-STORY					39,000		
5.1.10	VACUUM VALVE STATIONS (VS)								39,000			
5.1.11	Vacuum Valve Stations (VS)	0		0	5.0	3.0	1,500	26	39,000		- Located along Beamline KM Markers 1, 3, 10, 12, 14, 18, 20, 22, 26, 28, 30, 37, 39 - Crane Hook height of 30'	
GRAND TOTAL									39,000			
*(0) during normal operation, staff access needed; (5) during equipment installation												

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

6.0 OPERATIONS SUPPORT BUILDING (OSB)

		NEW RESEARCH FACILITY								Planning Module = 10'-0" x 10'-0"	
Category	Space	# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity	Total ASF		Notes
6.1	CORE OPERATIONS*	BLDG HEIGHT:		25 FT	2-STORIES					12,475	
6.1.10	OPERATIONS SUPPORT BUILDING (OSB)								12,475		*Based on LIGO India Plan per 13 Feb 26 WS#1
6.1.11	Office	20			1.0	0.5	50	20	1,000		- Ceiling Heights @ 15' (offices & communal spaces) & 25' (technical spaces)
6.1.12	Conference Rooms	20			3.0	2.0	600	2	1,200		
6.1.13	Paper Library				2.5	1.5	375	1	375		
6.1.14	Computer Library				4.0	3.5	1,400	1	1,400		
6.1.15	Faculty Control Room				5.0	4.5	2,250	1	2,250		
6.1.16	Electronics Test & Maintenance Room				4.0	3.5	1,400	1	1,400		
6.1.17	Optics Lab				3.5	3.0	1,050	1	1,050		
6.1.18	Vacuum Prep & Assembly				4.0	3.0	1,200	1	1,200		
6.1.19	Mechanical Shop				3.0	2.5	750	1	750		
6.1.20	Electronics Room (CER)				4.0	3.5	1,400	1	1,400		
6.2.21	DC Power Room				2.25	2.0	450	1	450		
6.2	SHARED FUNCTIONS*									5,975	*Based on LIGO India Plan per 13 Feb 26 WS#1
6.2.10	COMMON FUNCTIONS								5,975		
6.2.11	Lobby / Entry / Security				5.00	3.5	1,750	1	1,750		
6.2.12	Restrooms						-	2	-		
6.2.13	Janitor Closet						-	1	-		
6.2.14	Pantry						-	1	-		
6.2.15	Air Lock Room / Cleaning Room				3.0	2.25	675	1	675		
6.2.16	Change Room				2.0	2.0	400	1	400		
6.2.17	Mass/Bulk Storage				5.0	3.5	1,750	1	1,750		
6.2.18	Long-Term Storage				4.00	3.5	1,400	1	1,400		
6.3	BUILDING SUPPORT*									600	*Based on LIGO India Plan per 13 Feb 26 WS#1
6.3.10	SUPPORT FUNCTIONS								600		
6.3.11	HVAC (AHU) Room						-	1	-		
6.3.12	Electrical Panel Room						-	1	-		
6.3.13	Inspection, Shipping & Receiving				3.0	2.0	600	1	600		
6.3.14	Server / MDF						-	1	-		
6.3.15	RMS Room						-	1	-		
6.3.16	Plumbing / Fire-Riser						-	1	-		
GRAND TOTAL									19,050		

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

7.0 COMMUNITY/EDUCATION BUILDING (CEB)

Category	Space	NEW RESEARCH FACILITY							Total ASF	Notes
		# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity		
7.1	COMMUNITY/EDUCATION	BLDG HEIGHT:	25 FT	1-STORY					14,888	
7.1.10	COMMUNITY & EDUCATION PROGRAMS								14,888	
7.1.11	Auditorium	200			10.0	6.0	6,000	1	6,000	
7.1.12	Classroom				3.5	2.75	962.5	3	2,888	
7.1.13	Exhibition Hall				10.0	5.0	5,000	1	5,000	
7.1.14	Offices	10			1.0	1.0	100	10	1,000	
7.2	SHARED FUNCTIONS								80	
7.2.10	COMMON FUNCTIONS								80	
7.2.11	Lobby / Entry						-	1	-	
7.2.12	Restrooms						-	2	-	
7.2.13	Janitor Closet						-	1	-	
7.2.14	Storage						-	1	-	
7.2.15	Wellness				0.8	1.0	80	1	80	
7.3	BUILDING SUPPORT								600	
7.3.10	SUPPORT FUNCTIONS								600	
7.3.11	HVAC (AHU) Room						-	1	-	
7.3.12	Electrical Panel Room						-	1	-	
7.3.13	Inspection, Shipping & Receiving				3.0	2.0	600	1	600	
7.3.14	Electrical Room						-	1	-	
7.3.15	Server / MDF						-	1	-	
7.3.16	Plumbing						-	1	-	
GRAND TOTAL									15,568	

Planning Module = 10'-0" x 10'-0"

COSMIC EXPLORER BASE PROGRAM STUDY (40km / 25 mi)

Space Program

8.0 OFFICE BUILDING (OB)

Category	Space	NEW RESEARCH FACILITY							Total ASF	Notes
		# People	SF per Person	Room Size	# Modules (Width)	# Modules (Length)	Modular Rm Size	Quantity		
8.1	WORKSTATIONS & OFFICES	BLDG HEIGHT:	20 FT	1-STORY					20,970	
8.1.10	WORKSTATIONS & OFFICES								20,970	
8.1.11	Open Office / Workstations	120			1.0	0.5	50	120	6,000	- Located near CEB - Central administrative hub during construction, transitions to main admin facility to support observatory operations. - Include open-air courtyard for natural light and ventilation.
8.1.12	Open Office / Workstations - Visitors	4			1.0	0.5	50	4	200	
8.1.13	Private Office	80			1.0	1.2	120	80	9,600	For lead engineers (civil, electrical, mechanical disciplines) & senior staff members.
8.1.14	Private Office - Director	1			1.0	1.5	150	1	150	
8.1.15	Private Office - Visitor / Multipurpose	4			1.0	1.2	120	4	480	
8.1.16	Conference Room - Large				2.0	3.75	750	2	1,500	
8.1.17	Conference Room - Medium				1.25	2.0	250	8	2,000	
8.1.18	Conference Room - Small (Huddle)				1.0	1.2	120	6	720	
8.1.19	Phone Room				0.8	0.5	40	8	320	
8.2	SHARED FUNCTIONS								2,960	
8.2.10	COMMON FUNCTIONS								2,960	
8.2.11	Lobby / Entry				2.0	1.0	200	1	200	
8.2.12	Multipurpose Room				1.25	2.0	250	2	500	
8.2.13	Break Room				1.00	2.0	200	4	800	
8.2.14	Pantry				1.0	1.0	100	2	200	
8.2.15	Office Storage				1.0	1.5	150	4	600	
8.2.16	Shower / Locker / Restrooms				1.0	2.0	200	2	400	
8.2.17	Janitor Closet						-	2	-	
8.2.18	Café				1.5	2.0	300	1	300	
8.2.19	Wellness				0.8	1.0	80	2	160	
8.3	BUILDING SUPPORT								600	
8.3.10	SUPPORT FUNCTIONS								600	
8.3.11	HVAC (AHU) Room						-	1	-	
8.3.12	Electrical Panel Room						-	1	-	
8.3.13	Inspection, Shipping & Receiving				3.0	2.0	600	1	600	
8.3.14	Electrical Room						-	1	-	
8.3.15	Server / MDF						-	1	-	
8.3.16	Plumbing / Fire-Riser						-	1	-	
GRAND TOTAL									24,530	

Planning Module = 10'-0" x 10'-0"

A^{.6} FHWA Wildlife Crossing Structure Handbook

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WILDLIFE CROSSING STRUCTURE HANDBOOK Design and Evaluation in North America

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INTRODUCTION

Just as important as the correct location of wildlife crossings is to have them properly designed to meet the performance objectives. Questions arise as to the size of the crossing and how species-specific behaviors should be incorporated into the crossing structure design. These concerns are offset by the logistics of the project, which include costs of the structure, available material and expertise, and physical limitations of the site, e.g., soil, terrain, hydrology. Stakeholders involved in the crossing structure design process can then find themselves searching through published and grey literature regarding the design, performance and cost of the project. As project managers attempt to incorporate the designs and lessons from other experiences, several general questions arise:

- What do wildlife crossings look like?
- Where were they built?
- For what species were they designed?
- For what types of roads and highways were they built?
- In what environmental settings were they built (national park/forest, wildland - urban interface, urban, rural agricultural, etc.)?
- Were they successful?

The general questions are followed by many specific questions:

- What documentation is there regarding specific design and construction cost?
- What are the practicalities of each design?
 - Were they over-designed? (They were successful but could have been built more cheaply.)
 - Were they under-designed? (Wildlife used them less than expected and they performed poorly.)

This chapter provides examples of what tools and practical applications are available today for designing wildlife crossings in transportation projects. It is not meant to be a complete list of technical designs or methods used, but describe the most common wildlife crossing structure design types that are currently in use.

FUNCTION OF WILDLIFE CROSSINGS AND ASSOCIATED MEASURES

Wildlife crossing mitigation has two main objectives: 1) to connect habitats and wildlife populations and 2) reduce mortality of wildlife on roads as the Figure 18 chart shows.

Objective			Objective	
Facilitate connections between habitats and wildlife populations			improve motorist safety and reduce wildlife-vehicle collisions ¹	
Wildlife Overpasses	Wildlife Underpasses	Specific Measures	Habitat Adaptation	Infrastructure Adaptation
	Viaduct or flyover (Sheet 5)	Fencing - Large mammals (Sheet 12)		
Landscape bridge (Sheet 1)	Large mammal underpass (Sheet 6)	Fencing - small and medium vertebrates (Sheet 13)		
	Multi-use underpass (Sheet 7)			
Wildlife overpass (Sheet 2)	Underpass with Waterflow (Sheet 8)	Gates and escape ramps (Sheet 14)	Managing habitat and right-of-ways	Adapting road infrastructure (curbs, drainage, grates Jersey barriers) for wildlife movement
Multi-use overpass (Sheet 3)	Small to medium-sized mammal underpass (Sheet 9)	Signage	Intercept feeding	Increasing width of road median
Canopy crossing (Sheet 4)	Modified culvert (Sheet 10)	Animal - vehicle detection systems		
		Speed reduction		
	Herpetile tunnel (Sheet 11)	Lighting		
		Reflectors		

¹ See Huijser et al. (2008).

Figure 18. Chart. Types of measures used to reduce the impacts of roads on wildlife (adapted from Luell 2005).

Objective 1: Facilitate connections between habitats and wildlife populations

To achieve this goal, wildlife crossing structures are designed to allow movement of wildlife above or below road, either exclusively for wildlife use, mixed wildlife - human use, or as part of other infrastructure, e.g., creeks, canals. Wildlife crossing structures come in a variety of shapes and sizes, depending on their specific objective, and can be divided into 11 different design types (see Appendix C, Hot Sheets 1-11).

- Four wildlife crossings are above-grade (over-the-road); seven are designed for below-grade (under-the-road) wildlife movement
- Two of the 11 crossings are designed for both wildlife and human use (multi-use); nine are exclusively for wildlife use
- Unique wildlife crossings include:
 - Canopy crossings for arboreal wildlife
 - Underpasses that accommodate movement of water and wildlife
 - Adapted walkways at canal and creek bridges, and
 - Below-grade tunnels designed for movement of amphibians and reptiles

Objective 2: Improve motorist safety and reduce wildlife - vehicle collisions

Traffic-related mortality of wildlife can significantly impact some wildlife populations; particularly those that are found in low densities, slow reproducing, and need to travel over large areas. Common and abundant species like Deer, Elk and Moose can present serious problems for motorist safety. Many mitigation measures have been designed over the years to reduce collisions with wildlife; but few actually perform well or have been rigorously tested. Mitigation measures can be categorized as three types:

1. Specific mitigation measures designed to improve motorist safety and reduce collisions with wildlife
2. Mitigation measures that require habitat alterations near roads, and
3. Mitigation measures that require modifications to the road infrastructure

Objectives 1 and 2 should work together and can be integrated to provide for safe movements of wildlife across road corridors, by reducing motor vehicle accidents with wildlife. Wildlife crossings generally require one or more types of specific measures designed to improve motorist safety and reduce wildlife - vehicle collisions, e.g., fencing, escape gates and ramps (see Appendix C, Hot Sheets 12-14). Other techniques used to increase motorist safety and reduce collisions with wildlife, such as specific measures (signage and animal detection system) and the adaptation of habitats and road infrastructure, are not within the scope of this work. Detailed descriptions and guidelines for using these types of mitigation measures for wildlife can be found in Huijser et al. (2007a,b) and Iuell (2005).

SPACING OF WILDLIFE CROSSINGS

Landscape connectivity is the degree to which the landscape facilitates wildlife movement and other ecological flows. However, no two landscapes are the same. Terrain, habitat type, levels of human activity and climate are some factors that influence wildlife movements and ecological flows. Therefore the spacing of wildlife crossings on a given section of roadway will depend largely on the variability of landscape, terrain, population densities, the juxtaposition of critical wildlife habitat that intersects the roadway and the connectivity requirements for different species. In landscapes that are highly fragmented with little natural habitat bisected by roadways shown in Figure 19, generally fewer wildlife crossings will be required compared to relatively intact, less fragmented landscapes as Figure 20 shows.



Figure 19. Photo. Benavente, Spain. Highly fragmented landscape (high contrast; adapted from Google Earth).

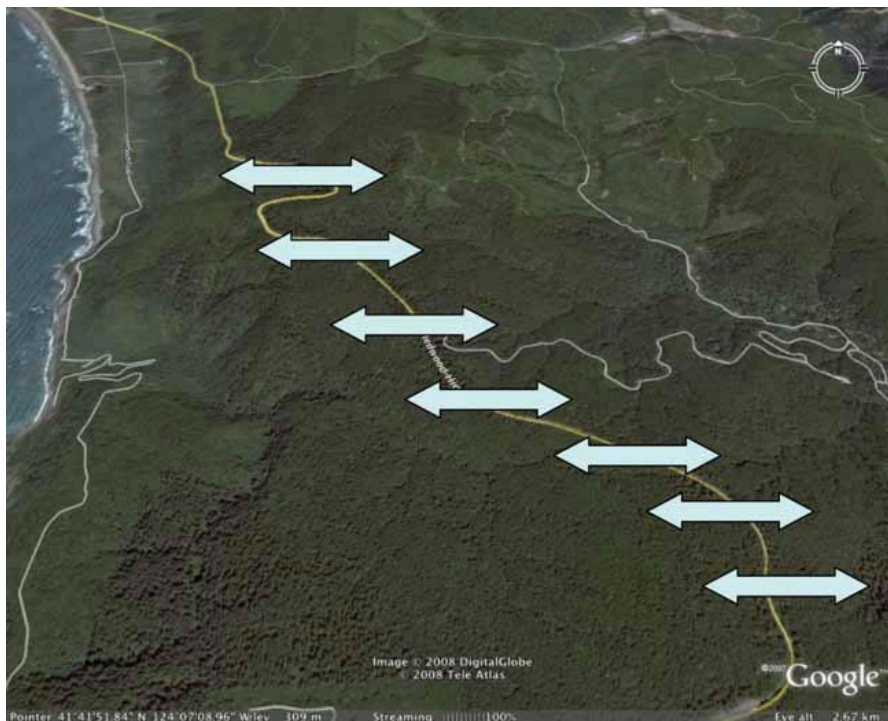


Figure 20. Photo. Hwy 101, Redwood highway, California. Low contrast landscape with low level of habitat fragmentation (adapted from Google Earth).

Wildlife crossings are permanent structures embedded within a dynamic landscape. With the lifespan of wildlife crossing structures around 70 - 80 years, the location and design of the crossings need to accommodate the changing dynamics of habitat and climatic conditions and their wildlife populations over time. How can we reconcile the dynamic environmental processes of nature with static physical structures on roadways? Environmental change is inevitable and will occur during the lifespan of the crossing structures. Some basic principles that management needs to consider:

- *Topographic features:* Wildlife crossings should be placed where movement corridors for the focal species are associated with dominant topographic features (riparian areas, ridgelines, etc). Sections of roadway can be ignored where terrain (steep slopes) and land cover (built areas) are unsuitable for wildlife and their movement.
- *Multiple species:* Crossings should be designed and managed to accommodate multiple species and variable home range sizes. A range of wildlife crossing types and sizes should be provided at frequent intervals along with necessary microhabitat elements that enhance movement, e.g., root crowns for cover. Unlike the physical structure of wildlife crossings, microhabitat elements are movable and can be modified over time as conditions and species distributions change.
- *Adjacent land management:* How well a wildlife crossing structure performs is partly dependent upon the land management that surrounds them. Transportation and land management agencies need to coordinate in the short and long term to ensure that tracts of suitable habitat adjacent to the crossings facilitate movement to designated wildlife crossings.
- *Larger corridor network:* Wildlife crossings must connect to, and form an integral part of, a larger regional corridor network. They should not lead to "ecological dead-ends." The integrity and persistence of the larger corridor network is not the responsibility of the transportation agency, but that of neighboring land management agencies and municipalities.

These basic principles will help guide the determination of how many wildlife crossings may be necessary and how to locate them in order to get the greatest long-term conservation value. There is no simple formula to determine the recommended distance between wildlife crossings, as mentioned earlier each site is different. Planning will largely be landscape- and species- specific.

The spacing interval of some wildlife crossing projects designed for large mammals are found in Table 2. Listed are several large-scale mitigation projects in North America (existing and planned). The spacing interval varies from one wildlife crossing per 0.9 mi (1.5 km) to one crossing per 3.8 miles (6.0 km). The projects listed indicate that wildlife crossings are variably spaced but on average about 1.2 mi (1.9 km) apart.

Table 2. Average spacing interval per mile between wildlife crossings designed for large mammals at existing and planned transportation projects.

Number of crossings	Road length (km)	Average Spacing/mile (km)	Location (Reference)
17	17 (27)	1 / 1.0 (1 / 1.6)	SR 260, Arizona USA (Dodd et al. 2007)
24	27 (45)	1 / 1.2 (1 / 1.9)	Trans-Canada Highway,a Banff, Alberta Canada (Clevenger et al. 2002)
8	7.5 (12)	1 / 0.9 (1 / 1.5)	Trans-Canada Highway,b Banff, Alberta Canada (Parks Canada, unpubl. data)
32	32 (51)	1 / 1.0 (1 / 1.6)	Interstate 75, Florida USA (Foster and Humphries 1995)
42	56 (90)	1 / 1.3c (1 / 2.14)	US 93, Montana USA (Marshik et al. 2001)
16	15 (24)	1 / 0.9 (1 / 1.5)	Interstate 90, Washington USA (Wagner 2005)
4	15 (24)	1 / 3.8 (1 / 6.0)	US 93 Arizona USA (McKinney and Smith 2007)
82	45 (72)	1 / 0.5 c (1 / 0.9)	A-52, Zamora Spain (Mata et al. 2005)

^a Phase 1, 2 and 3A reconstruction.

^b Phase 3B reconstruction.

^c Includes crossings for small and large mammals.

GUIDELINES FOR THE SELECTION OF WILDLIFE CROSSINGS

Earlier, the 11 different wildlife crossing design types were introduced. Their intended use and function are each described below.

Wildlife Crossing Design Types (Appendix C, Hot Sheets 1-11)**Overpass Design**

1. *Landscape bridge* - Designed exclusively for wildlife use. Due to their large size they are used by the greatest diversity of wildlife and can be adapted for amphibian and reptile passage.
2. *Wildlife overpass* - Smaller than landscape bridges, these overpass structures are designed exclusively to meet needs of a wide range of wildlife from small to large.
3. *Multi-use overpass* - Generally the smallest of the wildlife overpasses. Designed for mixed wildlife - human use. This wildlife crossing type is best adapted in human disturbed environments and will benefit generalist type species adapted to regular amounts of human activity and disturbance.
4. *Canopy crossing* - Designed exclusively for semi-arboreal and arboreal species that commonly use canopy cover for travel. Meets the needs of species not built for terrestrial travel and generally have difficulties crossing open, non-forested areas.

Underpass Design

5. *Viaduct or flyover* - The largest of underpass structures for wildlife use, but usually not built exclusively for wildlife movement. The large span and vertical clearance of viaducts allow for use by a wide range of wildlife. Structures can be adapted for amphibian and reptiles, semi-aquatic and semi-arboreal species.
6. *Large mammal underpass* - Not as large as most viaducts, but the largest of underpass structures designed specifically for wildlife use. Designed for large mammals but small- and medium-sized mammals use readily as well.
7. *Multi-use underpass* - Design similar to large mammal underpass, however management objective is co-use between wildlife and humans. Design is generally smaller than a large mammal underpass because of type of wildlife using the structures along with human use. These structures may not be adequate for all wildlife, but usually results in use by generalist species common in human-dominated environments (e.g., urban or peri-urban habitats). Large structures may be constructed to accommodate the need for more physical space for humans and habitat generalist species.
8. *Underpass with waterflow* - An underpass structure designed to accommodate the needs of moving water and wildlife. These underpass structures are frequently used by some large mammal species, but their use depends largely on how it is adapted for their specific crossing needs. Small- and medium-sized mammals generally utilize these structures, particularly if riparian habitat or cover is retained within the underpass.
9. *Small- to medium-sized mammal underpass* - One of the smaller wildlife crossing structures. Primarily designed for small- and medium-sized mammals, but species use will depend largely on how it may be adapted for their specific crossing needs.
10. *Modified culvert* - Crossing that is adaptively designed for use by small- and medium- sized wildlife associated with riparian habitats or irrigation canals. Adapted dry platforms or walkways can vary in design and typically constructed on the lateral interior walls of the culvert and above the high-water mark.
11. *Amphibian and reptile tunnels* - Crossing designed specifically for passage by amphibians and reptiles, although other small- and medium-sized vertebrates may use as well. Many different amphibian and reptile designs have been used to meet the specific requirements of each species or taxonomic group.

Determining the type of wildlife crossing structure most suitable for a given location will depend on several criteria. Selection begins by identifying a general wildlife crossing type that conforms to the wildlife habitat connectivity potential for the target species and topography of the site chosen. Figures 21, 22 and 23 can be used to guide the selection of wildlife crossing type based on the two main criteria - quality of wildlife habitat and topographical constraints.

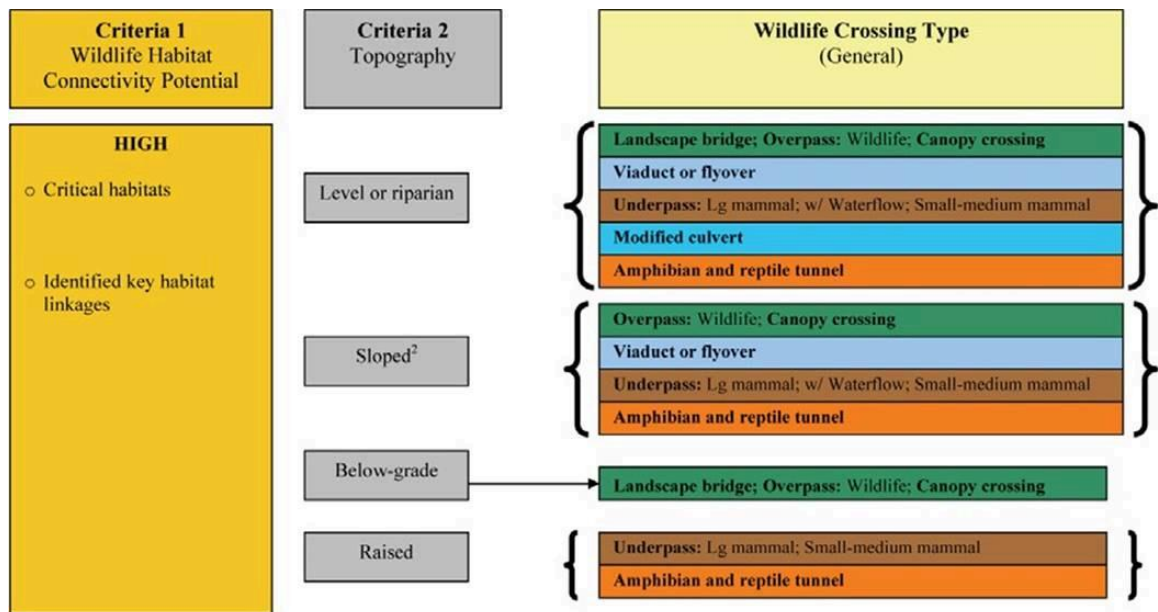


Figure 21. Chart. Criteria for selecting general wildlife crossing type where roads bisect habitats of high conservation value.

[View larger version of Figure 21.](#)

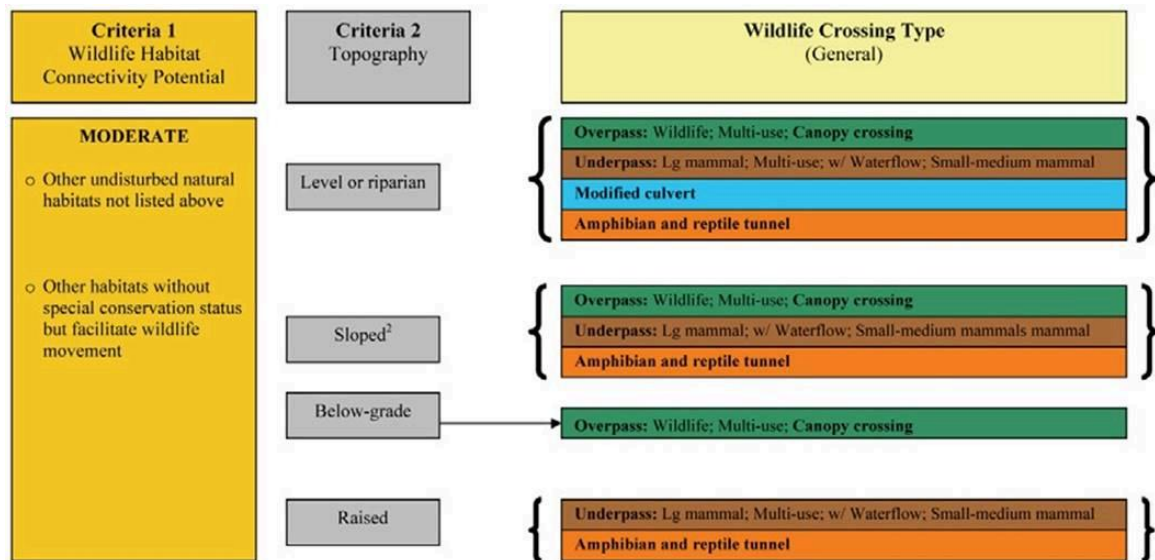


Figure 22. Chart. Criteria for selecting general wildlife crossing type where roads bisect habitats of moderate conservation value.

[View larger version of Figure 22.](#)

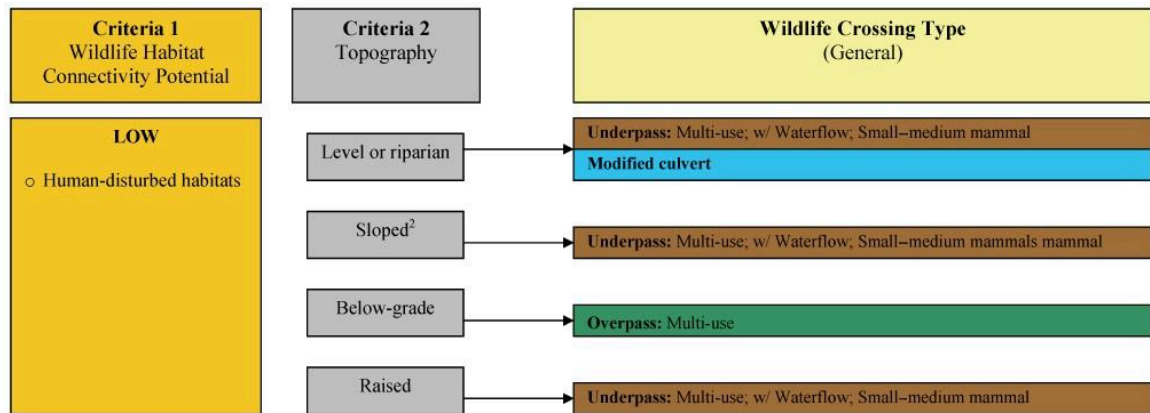


Figure 23. Chart. Criteria for selecting general wildlife crossing type where roads bisect habitats of low conservation value.

[View larger version of Figure 23.](#)

Wildlife Habitat Connectivity Potential

Wildlife habitat connectivity potential can be grouped into three categories:

- *High potential* - Sites that occupy high quality or critical habitats for wildlife and/or are identified as key habitat linkages to facilitate movement of wildlife at a local or regional scale.
 - **Associated wildlife crossing types:** These are prime areas for wildlife habitat connectivity. Mixed-used (multi-use with humans) wildlife crossings should not be used.
- *Moderate potential* - Relatively intact or undisturbed habitats, but not considered critical wildlife habitat, such as: (a) habitats that lack special conservation value or designation but are suitable for moving wildlife, and (b) habitats that may not be suitable at present but future restoration is planned.
 - **Associated wildlife crossing types:** In these areas mixed-use wildlife crossings become an option, but landscape bridges and viaducts or flyovers should not be built.
- *Low potential* - Habitats with human disturbance or regular human activity.
 - **Associated wildlife crossing types:** These areas are low potential for wildlife habitat connectivity; overpass structures designed specifically for wildlife are not recommended. However, underpasses adapted for wildlife use (wildlife underpasses with waterflow, modified culverts) and mixed-use and specialized smaller crossing types (small- to medium-sized mammal underpass; amphibian and reptile tunnels) are suggested options.

Topography

Topography strongly influences what type of wildlife crossing can be built at each location. The proximity to water (lakes, ponds, rivers, streams) is another factor, as is the water table at the location, but these factors will not be discussed here. Four general topographies have been identified where wildlife crossings may be constructed on roadways as sketched in Figure 24.

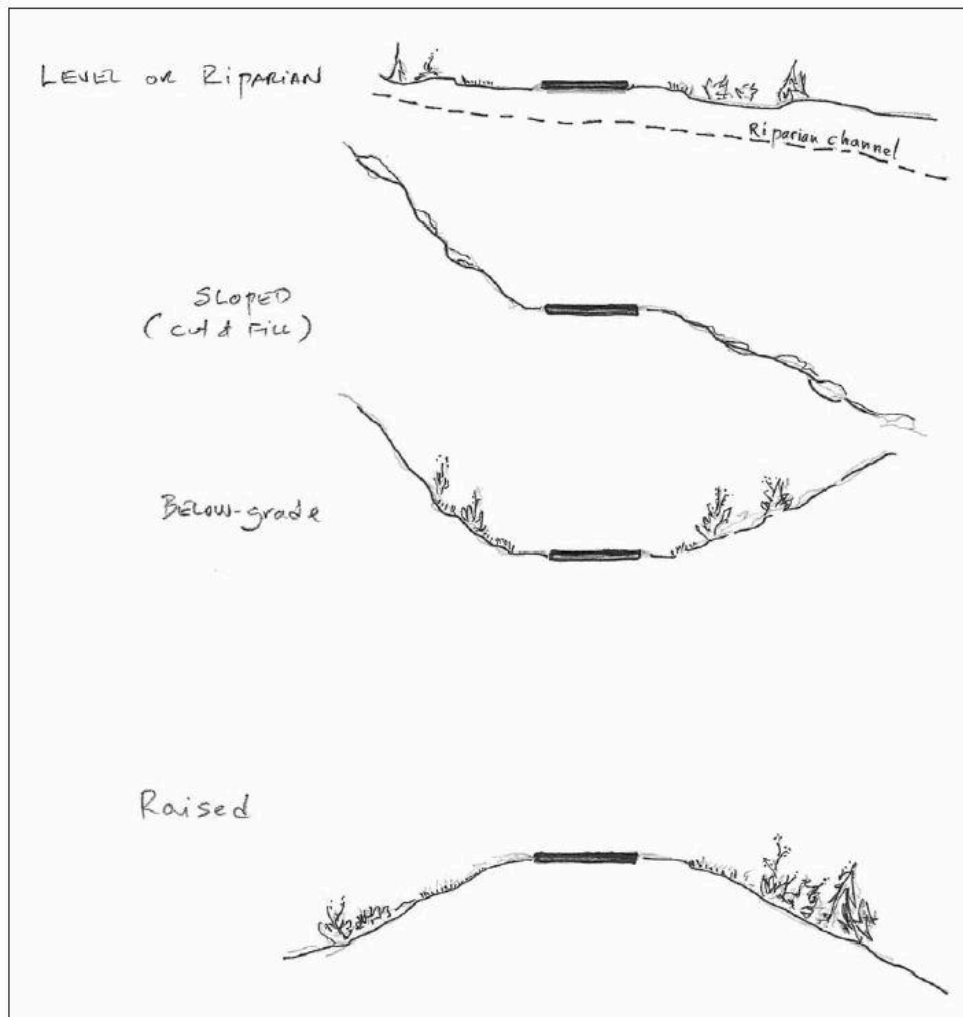


Figure 24. Schematic. Four general types of topography where wildlife crossings maybe constructed on roadways (Credit: Tony Clevenger).

- *Level or riparian* - Sections of road and rights-of-way that traverse level terrain or cross over riparian habitats and drainages.
 - **Associated wildlife crossing types:** Most wildlife crossing types can be constructed in these areas. Some may require raising the road grade to obtain elevation necessary at the crossing site for underpass or lower the road below grade and excavate to allow the overpass design to fit into the local terrain.
- *Sloped* - Road sections on cut-and-fill slopes.
 - **Associated wildlife crossing types:** Road sections on sloped terrain (cut-and-fill) make it difficult to construct overpass designs and canals - adapted design.
- *Below-grade* - Roads that are in cut sections and well below grade level.
 - **Associated wildlife crossing types:** These areas are best suited for overpass structures (landscape connectors, overpasses, canopy crossings) given the ease of construction having embankments and natural support on one or both sides of the highway.
- *Raised* - Road sections built on fill and are elevated compared to adjacent terrain including rights-of-way.
 - **Associated wildlife crossing types:** Raised sections of road are ideal for all underpass structures. Today, small tunnel-boring machines can perforate roadbeds of two-lane roads making underpasses for small- and medium-sized mammals and amphibian and reptile tunnels an option.

WILDLIFE SPECIES GROUPS AND CROSSING STRUCTURE CLASSIFICATION

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Planning and designing wildlife crossings will often be focused on a certain species of conservation interest (e.g., threatened or endangered species), a specific species group (e.g., amphibians) or abundant species that pose a threat to motorist safety (e.g., Deer, Elk).

In this handbook we refer to North American wildlife and species groups when discussing the appropriate wildlife crossing designs. The eight groups mentioned below are general in composition. However, recommendations will be provided, if it is available, for species-specific design requirements (Appendix C, Hot Sheets 1-11). Their ecological requirements and how roads affect them are described along with some sample wildlife species for each group.

1. **Large mammals** (*ungulates* [Deer, Elk, Moose, Pronghorn], *carnivores* [Bears, Wolves]) - Species with large area requirements and potential migratory behavior; large enough to be a motorist safety concern; traffic-related mortality may cause substantial impacts to local populations; susceptible to habitat fragmentation by roads.
2. **High mobility medium-sized mammals** (*Bobcat, Fisher, Coyote, Fox*) - Species that range widely; fragmentation effects of roads may impact local populations.
3. **Low mobility medium-sized mammals** (*Raccoon, Skunk, Hare, Groundhog*) - Species with smaller area requirements; common road-related mortality; relatively abundant populations.
4. **Semi-arboreal mammals** (*Marten, Red Squirrel, Flying Squirrel*) - Species that are dependent on forested habitats for movement and meeting life requisites; common road-related mortality.
5. **Semi-aquatic mammals** (*River Otter, Mink, Muskrat*) - Species that are associated with riparian habitats for movement and life requisites; common road-related mortality.
6. **Small mammals** (*Ground Squirrels, Voles, Mice*) - Species that are common road-related mortality; relatively abundant populations.
7. **Amphibians** (*Frogs, Toads, Salamanders, Turtles*) - Species with special habitat requirement; relatively abundant populations at the local scale; populations are highly susceptible to road mortality.
8. **Reptiles** (*Snakes, Lizards*) - Species with special habitat requirement; road environment tends to attract individuals; relatively abundant populations.

DESIGN AND DIMENSIONS

General Design Specifications For Wildlife Species

- As a rule, wildlife crossings should be designed so they allow for movement of the greatest diversity of wildlife species or taxa possible. The diversity of taxa will strongly depend on location and adjacent land use and conservation status. Wildlife species groups and taxa can be associated with different structure types based on general design and dimensions as shown in Tables 3 and 4. Length, width and height of crossings are shown in Figures 25 and 26.

Table 3. General guidelines for minimum and recommended dimensions of wildlife overpass designs.

Type	Usage	Species & Groups	Dimensions Minimum	Dimensions Recommended
Landscape bridge	Wildlife only	All wildlife species Amphibians (if adapted)	W: 230 ft (70 m)	W: >330 ft (>100 m)
Wildlife overpass	Wildlife only	Large mammals High-mobility medium-sized mammals Low mobility medium-sized mammals Small mammals Reptiles Amphibians (if adapted)	W: 130 - 165 ft (40 - 50 m)	W: 165 - 230 ft (50 - 70 m)
Multi-use overpass	Mixed use: Wildlife & Human activities	Large mammals High-mobility medium-sized mammals Low mobility medium-sized mammals Small mammals Amphibians (if adapted) Reptiles	W: 32 ft (10 m)	W: 50 - 130 ft (15 - 40 m)
Canopy crossing	Wildlife only	Semi-arboreal mammals	-	-

Table 4. General guidelines for minimum and recommended dimensions of wildlife underpass designs.

Type	Usage	Species groups	Dimensions: Minimum	Dimensions: Recommended
Viaduct or flyover	Multi-purpose	All wildlife species	<i>There are no minimum dimensions. Structures are generally larger than the largest wildlife underpass structures</i>	<i>There are no recommended dimensions. Structures are generally larger than the largest wildlife underpass structures</i>
Large mammal underpass	Wildlife only	Large mammals High-mobility medium-	W: 23 ft (7 m)	W: >32 ft (>10 m)

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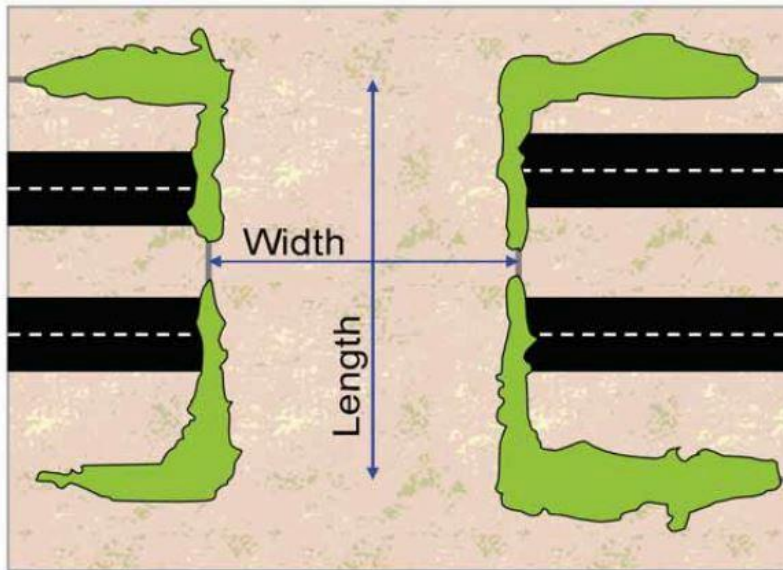


Figure 25. Schematic. Length and width measurements of wildlife overpass (Credit: Tony Clevenger).

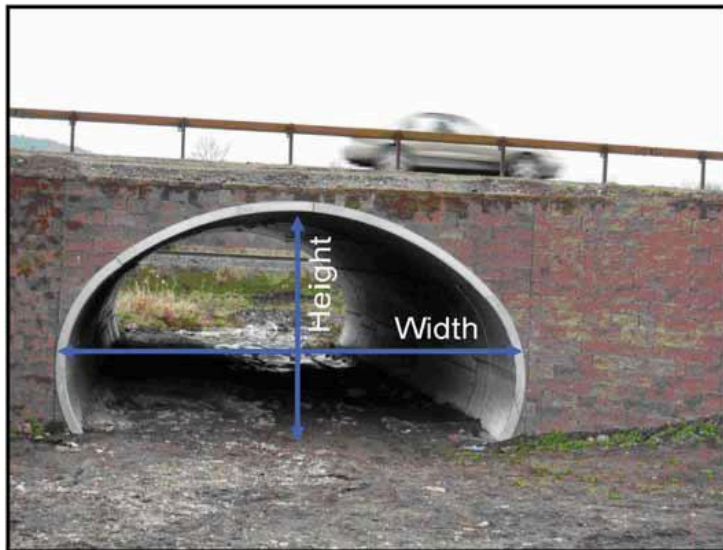


Figure 26. Photo. Width and height measurements of wildlife underpass structure (Credit: Marcel Huijser/WTI).

- Divided vs. undivided highways: Divided highways contain a central median and consist of two separate physical structures; one for each direction of traffic. Undivided highways have traffic lanes bundled and consist of one physical crossing structure. Although crossing structures on undivided highways have less daytime light than those with a central median, the open median generally has higher traffic noise levels. Crossing structures on undivided highways are shorter in length compared to structures on divided highways and have lower noise levels. We recommend that a shorter structure, with less daytime light and lower noise levels will be more effective than crossing structures designed on divided highways. This recommendation is based primarily on structure length and traffic noise levels. The amount of light an underpass receives is not an important factor on which to base crossing structure design when a large part of wildlife movement typically occurs during nighttime hours.
- Normally, wildlife crossings are not be greater than 230 - 260 ft (70 - 80 m) in length except in special situations such as spanning >6-lane highways or spanning highways in addition to other types of infrastructure, for example, frontage roads

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and railway line as Figure 27 shows.



Figure 27. Photo. Most wildlife overpasses or landscape bridges are less than 70-80 m long; however, the one shown above near Hilversum, The Netherlands, is 800 m long and spans two roads and a railroad. (Credit: Goois Natuurreservaat, The Netherlands/Photo: W. Metz).

- The recommended and minimum dimensions for each of the 11 wildlife crossing types are provided below. The measurements are for crossing structures designed for 4-lane highways. The guidelines should be followed if the crossings are at minimum to allow for the simplest and most basic connectivity requirement of crossings structures, i.e., the exchange of individuals within populations. Crossings designed for exchange of individuals may not allow for normal demographic processes, thus allowing passage use by few individuals and biased towards male movement. Both genders need to mix freely across the highway for wildlife crossings to perform effectively, and monitoring should be able to document that.
- Follow-up monitoring is discussed in the following chapter, but should determine whether the basic functions of wildlife crossings are being met and provide demographic information on the number of individuals using the crossing structure and their gender. Whether the crossings are functional for local populations affected by a highway will depend largely on how well the structure is planned and designed to integrate species' biological needs with the larger landscape and ecological context in which it is placed.

Specific Design of Wildlife Crossings and Adjacent Habitat

The dimensions shown earlier in Tables 3 and 4 are meant to serve as a general guideline when planning and designing for species groups or taxa. However, oftentimes project objectives are species-specific and design must be customized to their needs.

Our monitoring and research of crossing structures in North American during the last 10 years has yielded valuable information on design needs of a variety of wildlife species. Research results were published in scientific journals and internal agency reports. In Table 5 we synthesized the research results to determine the suitability of the 11 crossing structure types for the most common wildlife species or taxonomic groups in North America. We list 26 wildlife species or taxa and we categorize the suitability of each of the 11 crossing design types for each species as follows:

- Recommended/Optimum solution
- Possible - if adapted to local conditions
- Not recommended
- Unknown - more data are required
- Not applicable

Table 5. Suitability of wildlife crossing design types from Appendix C, Hot Sheets 1-11 for distinct wildlife species and taxa.

	Landscape bridge (Sheet 1)	Wildlife overpass (Sheet 2)	Multi- use overpass (Sheet 3)	Canopy crossing (Sheet 4)	Viaduct or flyover (Sheet 5)	Large mammal underpass (Sheet 6)	Multi-use underpass (Sheet 7)	Underpass with waterflow (Sheet 8)	Small- to medium- sized mammal underpass (Sheet 9)	Modified culvert design (Sheet 10)	Amphibian and reptile tunnel (Sheet 11)
Ungulates											
Moose	•	•	⊗	-	•	⊙	⊗	⊙	⊗	⊗	-
Elk	•	•	•	-	•	•	•	•	⊗	⊗	-
Deer sp.	•	•	•	-	•	•	•	•	⊗	⊗	-
Pronghorn	•	•	⊗	-	•	?	⊗	⊙	⊗	⊗	-
Bighorn sheep	•	•	⊗	-	•	⊙	⊗	⊙	⊗	⊗	-
Mountain goat	•	•	⊗	-	•	⊙	⊗	⊙	⊗	⊗	-
Carnivores											
Black bear	•	•	⊗	-	•	•	⊗	•	⊗	⊗	-
Grizzly bear	•	•	⊗	-	•	⊙	⊗	⊙	⊗	⊗	-
Wolf	•	•	⊗	-	•	⊙	⊗	⊙	⊗	⊗	-
Coyote	•	•	•	-	•	•	•	•	•	⊙	-
Fox1 (<i>V vulpes</i> , <i>Urocyon</i>)	•	•	•	-	•	•	•	•	•	⊙	-
Fox2 (<i>V macrotis</i> , <i>V velox</i>)	•	•	•	-	•	⊙	⊙	⊙	⊙	⊙	-
Cougar	•	•	⊗	-	•	•	⊗	•	⊗	⊗	-
Bobcat	•	•	•	-	•	•	•	•	⊗	⊙	-
Lynx	•	•	⊗	-	•	?	⊗	?	⊗	⊗	-
Wolverine	•	•	⊗	-	•	?	⊗	?	⊗	⊗	-
Fisher		• • • • •	⊙ • • • •	⊙ • • • •	-						-
Marten		• • • • •	⊙ • • • •	⊙ • • • •	-						-
Weasel		• • • • •	- • • • •	⊙ • • • •	-						-
Badger		• • • • •	- • • • •	⊙ • • • •	⊗	-					-
Low mobility medium		• • • • •	- • • • •	• • • • •	⊙						
Semi-arboreal mammals		⊙ • • • •	⊙ • • • •	⊙ • • • •	⊗ • • • •						
Semi-aquatic mammals		⊙ • • • •	- • • • •	⊙ • • • •	• • • • •						
Small mammals		• • • • •	⊙ • • • •	• • • • •	• • • • •	⊙					
Amphibians		⊙ • • • •	- • • • •	⊙ • • • •	• • • • •						
Reptiles		• • • • •	- • • • •	⊙ • • • •	• • • • •						

- Recommended/Optimum solution; ⊙ Possible if adapted to local conditions; ⊗ Not recommended; ? Unknown, more data are required; - Not applicable

OPENNESS?

$$\frac{\text{Height} \times \text{Width}}{\text{Length}}$$

The measure of *openness* was used early on to describe and measure the stimulus of a given underpass to approaching Deer, by calculating the above formula. The thought was that, in theory, an underpass could be so long and confining that it could preclude Deer use1 and that Deer prefer underpasses with a clear view of the horizon. Since then, openness has been used on many

occasions in planning the design of wildlife underpasses and researching their effectiveness. Openness has gained popularity, likely due to its ease and assumed validity based on a simple metric or "magic number." Engineers, planners and biologists alike tend to aim for the magical openness measure and expect performance without much critical thought of other factors (structural and environmental) that might influence performance. However the relationship between openness and underpass performance may be species-specific and time dependent.

An *openness index* combines underpass width, height, and length. Problems have been identified with its use such as inconsistent use of metric vs. Imperial units, as well as a changing understanding of how openness is measured - as an index, a ratio, or simply a state or concept. Further, underpasses are not always rectilinear, but can be arched, circular or elliptical. There is no guidance regarding how different shaped underpass designs may affect the openness index. As mentioned, the index may be metric or in Imperial measure and can be confused. Some suggested "minimum" openness indices have ranged from 0.6 (metric) for Mule Deer and 0.75 (metric) for Roe Deer and 1.5 (metric) for Red Deer (Elk). Like other roadway geometric design components, designing for the "minimum" is not recommended or appropriate in most cases. However, despite the appeal and popularity of openness indices, there has never been a critical evaluation of the measure for designing wildlife underpasses. There is no recognized guidance on use other than the absolute values that have been bounced around in the grey and published literature.

The validity of using openness as a proven and reliable measure in planning and designing wildlife underpasses is questionable. Openness has been found to be highly correlated to underpass length. Similarly the three main underpass structural measures (length, width, height) exhibit multicollinearity - i.e., they tend to be redundant and highly correlated with one another. We **DO NOT** recommend the use of the openness index in planning and designing wildlife crossings due to the reasons stated above. We **DO** recommend the use of underpass measures (length, width, height) in conjunction with other structural (divided vs. undivided highway configurations) and environmental (habitat quality, target species, etc.) factors when designing wildlife crossing structures.

¹ Reed, D. F., A. L. Ward. 1985. Efficacy of methods advocated to reduce deer - vehicle accidents: research and rationale in the USA. Pages 285 - 293 in *Routes et faune sauvage*. Service d'Etudes Techniques de Routes et Autoroutes, Bagneaux, France.

Detailed design information for the 26 species and 11 crossing structure types are found in Appendix C, Hot Sheets 1-11.

Hot Sheets 1-11 - Wildlife Crossing Prescriptions (Appendix C)

The Hot Sheets are a guide for the general design, basic building prescriptions, landscaping, possible design variations, and maintenance of each of the 11 crossing structure types. Being a logical endpoint for this chapter, by starting broadly and progressively narrowing the taxonomic focus, the Hot Sheets provide the most detailed design guidelines for the 26 wildlife species and taxa in North America.

Hot Sheets 12-14 - Fencing and Gate Guidelines (Appendix C)

Fencing is a key part of a mitigation plan involving wildlife crossings. Hot Sheets 12-14 provide details on fence configurations, construction specifics, design alternatives and maintenance.

Fences and wildlife crossings have been around many years, however, relatively little is known about effective fence designs and other innovative solutions to keep wildlife away from roads and traffic.

Small- and medium-sized mammals can pass through most fence types for large mammals. Different fencing types and designs are needed to keep these smaller animals from reaching roads (Hot Sheet 13).

When wildlife become trapped inside fenced areas measures need to be in place to allow them to safely exit the right-of-way. Steel swing gates, hinged metal doors or earthen ramps or jump-outs are some commonly used methods (Hot Sheet 14).

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A^{.7} NRMCA LCA Benchmark Report V3.2



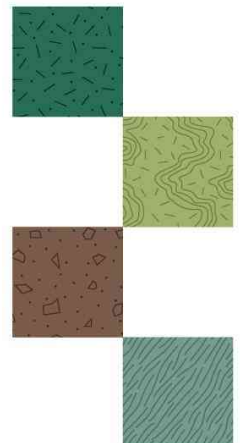
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December 2021

Appendix C: NRMCA Member National and Regional LCA Benchmark (Industry Average) Report – V 3.2

Summary: Appendix C is intended for use by NRMCA members, who participated in the IW-EPD, that have developed product specific third-party verified LCAs and/or EPDs to compare the environmental impacts of their products with industry average impacts.



The users of this benchmark report can use this appendix, along with their own product-specific EPDs to demonstrate compliance with the following:

LEED v4 and 4.1(beta) MR Credit Building Product Disclosure and Optimization

A company with product-specific EPDs can demonstrate impact reductions below industry average in LEED v4. The following is an excerpt from LEEDv4 MR Credit Building Product Disclosure and Optimization – Environmental Product Declarations – Option 2 Multi-Attribute Optimization (1 point).

“Third party certified products that demonstrate impact reduction below industry average in at least three of the following categories are valued at 100% of their cost for credit achievement calculations.

- *global warming potential (greenhouse gases), in CO₂e;*
- *depletion of the stratospheric ozone layer, in kg CFC-11;*
- *acidification of land and water sources, in kg SO₂;*
- *eutrophication, in kg nitrogen or kg phosphate;*
- *formation of tropospheric ozone, in kg O₃; and*
- *depletion of nonrenewable energy resources, in MJ. “*

Architecture 2030 Challenge for Products

A company with product-specific EPDs can use the document to demonstrate progress toward meeting the Architecture 2030 Challenge for Products which asks architects to specify products with carbon footprint 35% below industry average in 2015 and increasing to 50% below industry average by 2030.

International Green Construction Code (IgCC)

A company with product-specific EPDs can meet the new Material Selection and Properties section of the 2015 International Green Construction Code. As one option under 505.3 Multi-attribute material declaration and certification, not less than 55 percent of the total building materials used in the project, based on mass, volume or cost, shall have an EPD comply with the provisions of ISO 14025 and ISO 21930 and be externally verified.

Green Globes For New Construction

Companies use the Industry-Wide EPD or product-specific EPDs to meet the EPD requirement in Green Globes. The following is an excerpt from Section 3.5 Materials and Resources, 3.5.1.2 Path B: Prescriptive Path for Building Core and Shell (up to 20 points).

Based upon the appropriate application and specification of comparable materials and products, what percentage of the products selected for the building core and shell (based upon cost) have:

Environmental Product Declarations (EPDs) that utilize recognized Product Category Rules, conform to ISO standards, and minimally includes cradle-to-gate scope:

- *Industry Wide (Generic) EPD: Products specified for the building core and shell shall include Type III Environmental Product Declaration (EPD)? and/or*

- *Product Specific EPD: Products specified for the building core and shell shall include Type III Environmental Product Declaration (EPD) , where the EPDs are specific to particular products from identified manufacturers*

Designing Low Impact Concrete Mixtures

Finally, a company can use the document to help it design products that have lower environmental impacts than industry and regional average by comparing the environmental impacts of its mix designs with those of the industry average.

Companies claiming compliance with LEED v4 and Architecture 2030 Challenge for Products and other standards should reference this document.

How this benchmark document is structured

This document presents the key life cycle impact assessment indicators for both the U.S. national and eight NRMCA regions for 9 benchmark ready mixed concrete products, which vary by compressive strength and cementitious material content. The benchmark concrete products also include 3 lightweight mix designs in each region. Each NRMCA region is represented in a separate section and the results are presented so companies with third-party verified LCAs and/or EPDs can benchmark their products against the regional benchmarks. For each region (see Figure 1 for a definition of each NRMCA region) a production summary is provided indicating the number and type of plants the

benchmark is based on and the average, minimum and maximum production per plant (Table A).

The regional report then presents the 6 normal weight benchmark ready mixed concrete products by compressive strength (2,500 psi, 3,000 psi, 4,000 psi, 5,000 psi, 6,000 psi, and 8,000 psi) as well as 3 lightweight compressive strengths (3,000 psi lightweight, 4,000 psi lightweight, and 5,000 psi lightweight). The mixture proportions of each concrete product is also shown for reference purposes and these vary by region (Table B). For more on how these benchmark mix designs were determined, see the mix design methodology section below.

The report then shows the weighted average transportation mode and distance for high mass materials (Table C). While truck transportation is the dominant mode a number of raw materials and intermediate product inputs arrive via more than one mode.

Next, the report lists the weighted average plant (gate-to-gate) energy and water use as well as solid wastes produced per cubic yard and cubic meter of ready mixed concrete for each region (Table D). These values reflect the weighted average product by region – i.e., the batch water and hence total water consumption will vary by mix design, but the results displayed here only reflect the weighted average mix design. These plant/facility level data are a good reference point for NRMCA members wishing to compare their individual products manufactured at their facilities with the regional benchmarks.

Next, the LCA results for the 9 benchmark concrete products are presented on a cubic yard basis (Table E).

Benchmark mix design methodology

The ACI 211 compressive strength to water to cementitious materials ratio (w/cm) relationship is assumed to apply across all regions. To calculate the cementitious materials (CM) content for each region, an average strength is calculated for a region based on the regional w/cm and average material quantities reported in the respective regional plant surveys. To estimate mixture proportions above and below the regional average strength level the change in strength is assumed to follow the typical strength to w/cm ratio relationship defined in ACI 211. The following are some broad assumptions:

- The regional Supplementary Cementitious Materials (SCM) to total CM ratio is maintained across all compressive strengths.
- The ratio of fine to coarse aggregate is maintained across all compressive strengths for normal weight concrete. The ratio of fine to coarse aggregate for lightweight concrete is adjusted to maintain a target unit weight for concrete.
- Water demand for higher strength concretes (above 5000 psi) will increase because of increased paste content and the use of smaller coarse aggregate size.
- Water reducing admixtures (and high range water reducing admixtures) are assumed to be used as the strength level is increased to impact a change in the mixing water content and is reflected in an assumed change in water content across different compressive strengths.
- It is assumed that the volume of concrete remains constant regardless of material quantities so

the specific gravities of coarse and fine aggregate are adjusted for each region to maintain this volume.

- As the paste content changes, some change in the total aggregate content is assumed – decreased as paste volume is increased for higher strength. The percent change in aggregate content is adjusted up or down to maintain volume.

Calculation steps

1. Identify the average material quantities used for each region from the plant survey.
2. Determine the average total batching water for the region by taking the average batch water reported and adding moisture content of 1% for coarse aggregate and 5% for fine aggregate.
3. Determine the total aggregate content for a region by totalling the average coarse aggregate, fine aggregate and other aggregate for the region.
4. Calculate the Saturated Surface Dry (SSD) coarse aggregate content by taking the average coarse aggregate content and dividing by 101%.
5. Calculate the SSD fine aggregate content by taking the average fine aggregate content and dividing by 105%.
6. Calculate the average w/cm for the region by taking the average total batching water and dividing by the total CM (cement + fly ash + slag).
7. Calculate the average compressive strength for each region based on average material quantities and average w/cm using ACI 211 w/cm curves.
8. Adjust the specific gravity of coarse and fine aggregate to maintain volume for the average mix.

9. For each specified compressive strength class (2500, 3000, 4000, 5000, 6000 and 8000 psi) identify the w/cm from ACI 211. Use air entrainment for mixes 5000 psi and less, use no air entrainment for mixes above 5000 psi.
10. Adjust mixing water up by the same percentage as was used in the Industry-Wide EPD based on strength level. Calculate the CM content by dividing the water content by the w/cm.
11. Calculate the average fly ash percentage by taking the average fly ash use and dividing by the total CM use.
12. Calculate the average slag percentage by taking the average slag use and dividing by the total CM use.
13. Adjust aggregate content up or down by a certain percentage to adjust volume up or down to maintain volume.
14. Calculate the adjusted coarse and fine aggregate based on the ratio of average coarse and fine aggregate average from the region.
15. Adjust the fine to coarse aggregate ratio to maintain a target unit weight of 118 lb/ft³ (1890 kg/m³) for lightweight concrete mixes.
16. Assume the same admixture content as was used in the original mix designs for the Industry-Wide EPD.

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The following section presents the U.S. national and regional LCA benchmarks results. NRMCA regions are defined in Figure F1.



Figure D1-NRMCA Regions

The regional results are presented in ascending order as follows:

1. National NRMCA average
2. Eastern Region
3. Great Lakes Midwest Region
4. North Central Region
5. Pacific Northwest Region
6. Pacific Southwest Region
7. Rocky Mountains Region
8. South Central Region
9. South Eastern Region

D-1 : NRMCA U.S. National

Table A1-NRMCA National Production Data Summary		
Number of Plants	489	
% Transit Mix Plants	81%	
% Central Mix Plants	19%	
% Batch Waste	0.20%	
	yd3	m3
Average Production	62,207	47,561
Total Production	30,419,087	23,257,054
Minimum Production	263	201
Maximum Production	412,066	315,047

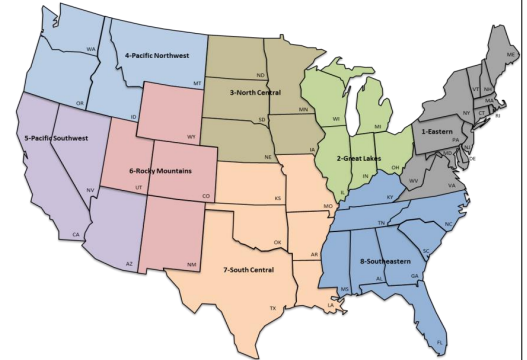


Table B1-NRMCA U.S. National Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	354	394	475	576	610	719	394	475	556
Fly Ash	lbs	62	69	83	101	107	126	69	83	97
Slag Cement	lbs	17	19	23	28	30	35	19	23	27
Mixing Water	lbs	305	305	305	315	341	341	308	308	308
Crushed Coarse Aggregate	lbs	1,126	1,115	1,083	1,029	1,061	1,018	0	0	0
Natural Coarse Aggregate	lbs	553	547	531	505	521	499	0	0	0
Crushed Fine Aggregate	lbs	169	167	162	154	159	152	161	149	136
Natural Fine Aggregate	lbs	1,282	1,270	1,233	1,171	1,208	1,159	1,225	1,130	1,035
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	980	990	1,000
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,867	3,886	3,895	3,878	4,037	4,049	2,178	2,168	2,159

Table C1-NRMCA U.S. National Transportation Modes and Distances - High Mass Materials

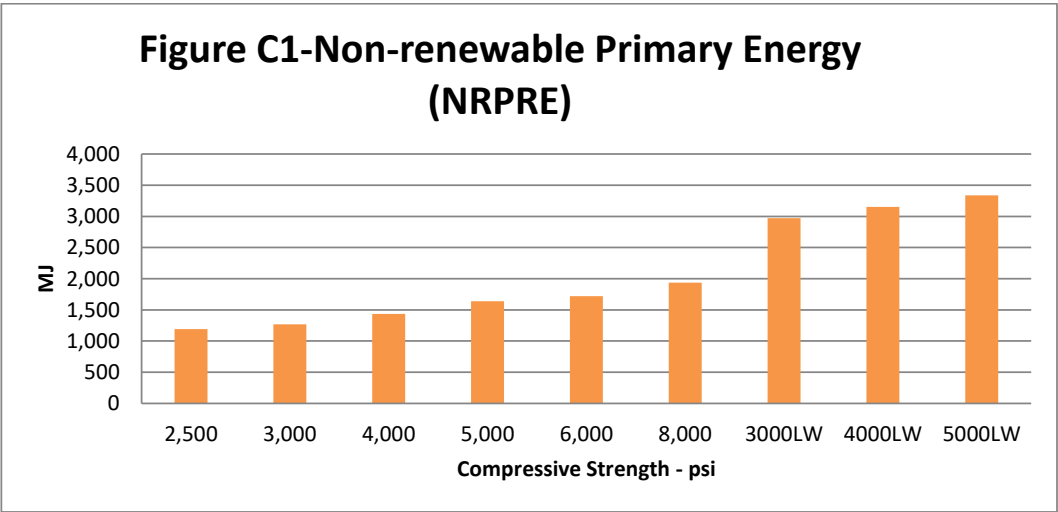
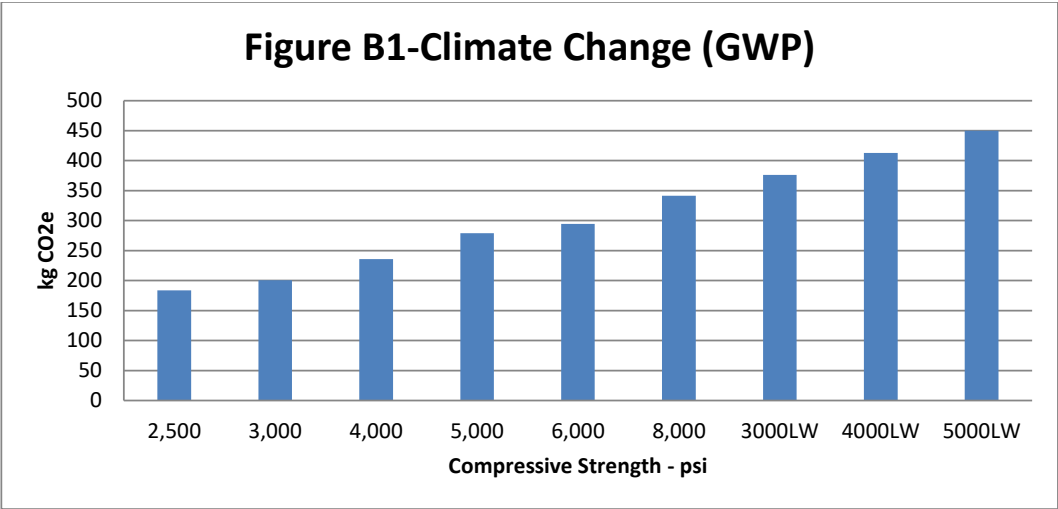
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	75.1	61.7	33.8	24.5	21.7	6.7	40.0
Rail	mi	45.1	30.5	6.5	30.5	6.0	15.0	2.1
Ocean	mi	249.5	29.5	390.5	6.6	8.5	0.0	29.6
Barge	mi	41.9	0.0	25.9	6.1	0.4	2.7	2.7

Table D1-NRMCA National Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	3.22	4.21
Natural Gas	cuft	11.98	15.66
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.01	0.01
Diesel	gal	0.32	0.42
Gasoline	gal	0.00	0.00
LPG (Liquified Propane Gas)	gal	0.01	0.01
Other	gal	0.00	0.00
Process water consumption	gal	49.23	64.39
Hazardous Solid Waste	lbs	0.02	0.03
Non-Hazardous Solid Waste	lbs	6.95	9.09

Table E1- NRMCA U.S. National LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	183.49	200.57	235.61	278.99	294.57	341.31	376.42	412.94	449.77
ODP	kg CFC11e	5.12E-06	5.51E-06	6.30E-06	7.26E-06	7.64E-06	8.68E-06	1.39E-05	1.48E-05	1.57E-05
AP	kg SO2e	0.66	0.70	0.78	0.87	0.92	1.02	1.90	1.99	2.08
EP	kg Ne	0.24	0.26	0.29	0.34	0.36	0.41	0.67	0.71	0.75
SFP	kg O3e	14.48	15.30	16.94	18.92	19.81	22.00	25.29	26.99	28.70
ADP _f	MJ, NCV	390.76	402.66	426.27	457.52	476.88	509.83	1,990.52	2,030.14	2,074.36
ADP _e	kg Sbe	1.17E-04	1.20E-04	1.25E-04	1.30E-04	1.36E-04	1.43E-04	1.67E-04	1.74E-04	1.81E-04
RPRE	MJ, NCV	13.75	13.69	13.53	13.46	13.77	13.61	223.58	225.72	228.10
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,190.42	1,270.56	1,433.92	1,637.30	1,718.92	1,938.09	2,970.35	3,150.47	3,335.61
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	84.13	93.54	112.92	136.89	145.03	170.84	93.71	112.90	132.10
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FW	m3	0.61	0.63	0.67	0.72	0.75	0.80	0.84	0.88	0.92
CCE	kg CO2e	77.21	85.85	103.64	125.64	133.11	156.80	86.01	103.62	121.23
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	1.97E-08	1.98E-08	1.99E-08	1.98E-08	2.04E-08	2.05E-08	5.31E-08	5.37E-08	5.43E-08
LLRW	m3	3.01E-07	3.05E-07	3.13E-07	3.20E-07	3.31E-07	3.41E-07	1.76E-06	1.78E-06	1.81E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F1- NRMCA U.S. National LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	239.99	262.34	308.17	364.91	385.29	446.41	492.34	540.11	588.28
ODP	kg CFC11e	5.12E-06	7.21E-06	8.24E-06	9.49E-06	9.99E-06	1.14E-05	1.82E-05	1.93E-05	2.05E-05
AP	kg SO2e	0.66	0.91	1.01	1.14	1.20	1.34	2.48	2.60	2.72
EP	kg Ne	0.24	0.34	0.38	0.45	0.47	0.54	0.87	0.93	0.98
SFP	kg O3e	14.48	20.01	22.16	24.74	25.91	28.77	33.07	35.30	37.54
ADP _f	MJ, NCV	390.76	526.66	557.54	598.41	623.74	666.83	2,603.50	2,655.32	2,713.16
ADP _e	kg Sbe	1.17E-04	1.57E-04	1.63E-04	1.70E-04	1.78E-04	1.86E-04	2.19E-04	2.28E-04	2.37E-04
RPRE	MJ, NCV	17.98	17.91	17.70	17.61	18.01	17.81	292.43	295.23	298.34
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,557.01	1,661.83	1,875.50	2,141.50	2,248.26	2,534.92	3,885.07	4,120.66	4,362.81
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	110.03	122.35	147.70	179.05	189.69	223.46	122.57	147.67	172.77
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FW	m3	0.80	0.82	0.87	0.94	0.98	1.05	1.10	1.15	1.21
CCE	kg CO2e	100.99	112.29	135.56	164.33	174.10	205.08	112.49	135.53	158.57
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	2.58E-08	2.59E-08	2.60E-08	2.59E-08	2.67E-08	2.68E-08	6.95E-08	7.02E-08	7.10E-08
LLRW	m3	3.93E-07	3.99E-07	4.09E-07	4.18E-07	4.33E-07	4.46E-07	2.30E-06	2.33E-06	2.36E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-3: Great Lakes Midwest Region

Table A3-Great Lakes Midwest Production Data Summary		
Number of Plants	69	
% Transit Mix Plants	66%	
% Central Mix Plants	34%	
% Batch Waste	0.08%	
	yd3	m3
Average Production	73,876	56,482
Total Production	5,097,459	3,897,286
Minimum Production	1,263	966
Maximum Production	412,066	315,047



Table B3-Great Lakes Midwest Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	341	382	468	576	611	733	383	468	556
Fly Ash	lbs	39	44	54	67	71	85	44	54	64
Slag Cement	lbs	24	27	33	41	44	52	27	33	40
Mixing Water	lbs	267	267	267	276	300	300	271	271	271
Crushed Coarse Aggregate	lbs	1,517	1,489	1,445	1,387	1,431	1,373	0	0	0
Natural Coarse Aggregate	lbs	245	240	233	224	231	221	0	0	0
Crushed Fine Aggregate	lbs	14	14	14	13	14	13	14	12	11
Natural Fine Aggregate	lbs	1,460	1,432	1,390	1,335	1,376	1,321	1,371	1,248	1,138
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	1,050	1,070	1,080
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,908	3,895	3,905	3,919	4,076	4,098	2,110	2,087	2,080

Table C3-Great Lakes Midwest Transportation Modes and Distances - High Mass Materials

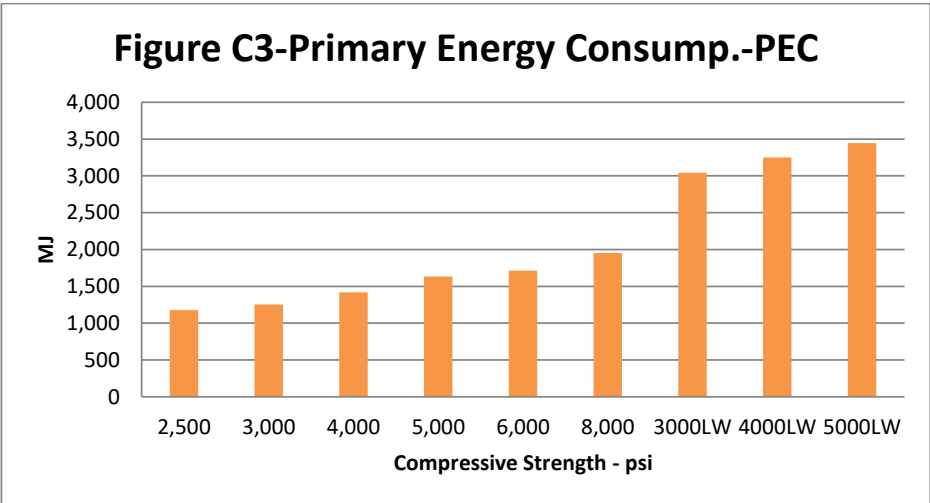
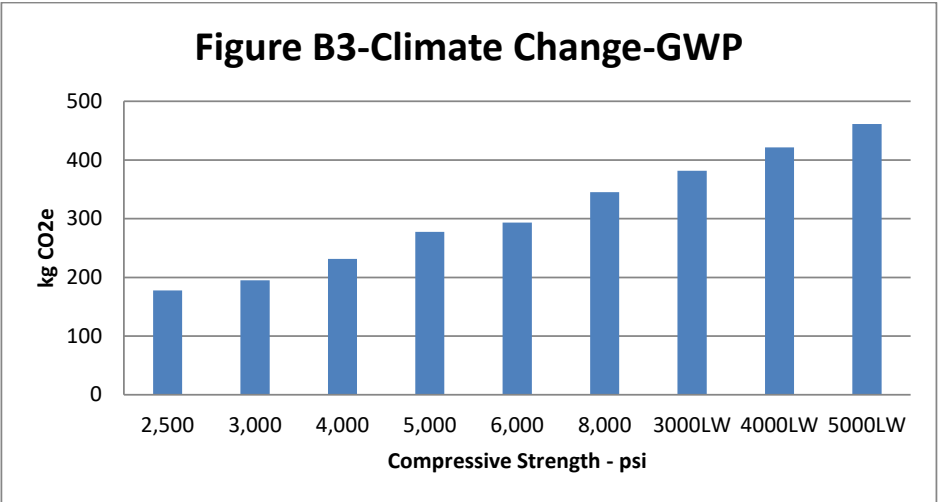
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	42.9	66.3	44.2	25.1	18.5	1.3	29.6
Rail	mi	27.5	0.0	24.3	5.2	0.0	0.7	0.0
Ocean	mi	23.7	0.0	54.5	0.0	0.0	0.0	0.0
Barge	mi	167.4	0.0	116.6	22.6	0.4	0.0	8.5

Table D3-Great Lakes Midwest Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	3.12	4.08
Natural Gas	cuft	38.76	50.70
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.01
Diesel	gal	0.26	0.33
Gasoline	gal	0.00	0.01
LPG (Liquified Propane Gas)	gal	0.01	0.01
Other	gal	0.00	0.00
Process water consumption	gal	37.02	48.42
Hazardous Solid Waste	lbs	0.00	0.00
Non-Hazardous Solid Waste	lbs	0.84	1.10

Table E3-Great Lakes Midwest LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	177.60	194.79	231.38	277.61	293.12	345.26	381.58	421.63	461.28
ODP	kg CFC11e	5.17E-06	5.56E-06	6.41E-06	7.48E-06	7.87E-06	9.08E-06	1.45E-05	1.55E-05	1.65E-05
AP	kg SO2e	0.61	0.65	0.73	0.83	0.87	0.98	1.92	2.03	2.12
EP	kg Ne	0.25	0.27	0.30	0.35	0.37	0.43	0.69	0.74	0.79
SFP	kg O3e	12.63	13.36	14.96	16.96	17.77	20.04	23.89	25.67	27.41
ADP _f	MJ, NCV	349.77	355.49	373.03	399.84	415.99	445.27	2,046.70	2,099.27	2,140.78
ADP _e	kg Sbe	1.24E-04	1.26E-04	1.32E-04	1.38E-04	1.44E-04	1.52E-04	1.68E-04	1.77E-04	1.85E-04
Use of Primary Resources										
RPRE	MJ, NCV	7.97	7.87	7.83	8.03	8.24	8.33	235.33	239.84	242.39
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,178.10	1,253.59	1,419.45	1,632.67	1,712.58	1,952.78	3,044.58	3,248.32	3,444.50
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	80.94	90.66	111.13	136.83	145.01	174.04	90.91	111.17	132.04
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.53	0.55	0.59	0.65	0.68	0.73	0.78	0.82	0.86
CCE	kg CO2e	74.28	83.21	101.99	125.58	133.09	159.73	83.44	102.03	121.18
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	2.78E-08	2.78E-08	2.79E-08	2.80E-08	2.88E-08	2.91E-08	5.86E-08	5.98E-08	6.06E-08
LLRW	m3	4.09E-07	4.14E-07	4.27E-07	4.43E-07	4.59E-07	4.78E-07	1.92E-06	1.96E-06	2.00E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F3-Great Lakes Midwest LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	232.29	254.78	302.63	363.10	383.38	451.58	499.09	551.47	603.33
ODP	kg CFC11e	5.17E-06	7.27E-06	8.39E-06	9.78E-06	1.03E-05	1.19E-05	1.89E-05	2.03E-05	2.15E-05
AP	kg SO2e	0.61	0.85	0.95	1.08	1.14	1.29	2.52	2.65	2.78
EP	kg Ne	0.25	0.35	0.40	0.46	0.49	0.56	0.90	0.97	1.03
SFP	kg O3e	12.63	17.48	19.56	22.18	23.24	26.22	31.25	33.58	35.85
ADPf	MJ, NCV	349.77	464.97	487.91	522.98	544.10	582.39	2,676.98	2,745.74	2,800.04
ADPe	kg Sbe	1.24E-04	1.65E-04	1.72E-04	1.81E-04	1.88E-04	1.99E-04	2.20E-04	2.31E-04	2.42E-04
Use of Primary Resources										
RPRE	MJ, NCV	10.42	10.29	10.24	10.51	10.77	10.90	307.80	313.70	317.04
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,540.90	1,639.63	1,856.57	2,135.46	2,239.97	2,554.14	3,982.16	4,248.64	4,505.24
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	105.87	118.58	145.35	178.96	189.67	227.64	118.91	145.40	172.70
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.70	0.72	0.77	0.84	0.88	0.96	1.01	1.07	1.13
CCE	kg CO2e	97.16	108.83	133.40	164.25	174.07	208.92	109.13	133.45	158.50
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	3.63E-08	3.63E-08	3.65E-08	3.67E-08	3.77E-08	3.81E-08	7.67E-08	7.82E-08	7.93E-08
LLRW	m3	5.35E-07	5.42E-07	5.59E-07	5.79E-07	6.00E-07	6.25E-07	2.51E-06	2.57E-06	2.61E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-4: North Central Region**Table A4-North Central Production Data Summary**

Number of Plants	28	
% Transit Mix Plants	61%	
% Central Mix Plants	39%	
% Batch Waste	0.07%	
	yd3	m3
Average Production	46,057	35,213
Total Production	1,289,592	985,964
Minimum Production	2,834	2,167
Maximum Production	172,000	131,503

**Table B4-North Central Benchmark Mix Designs (per cubic yard)**

		2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	352	392	476	579	615	728	393	476	559
Fly Ash	lbs	65	73	88	107	114	135	73	88	103
Slag Cement	lbs	4	4	5	7	7	8	4	5	6
Mixing Water	lbs	291	291	291	301	327	327	294	294	294
Crushed Coarse Aggregate	lbs	784	769	747	709	739	709	0	0	0
Natural Coarse Aggregate	lbs	932	914	888	843	879	843	0	0	0
Crushed Fine Aggregate	lbs	222	218	212	201	210	201	219	203	183
Natural Fine Aggregate	lbs	1,211	1,188	1,154	1,096	1,142	1,096	1,195	1,105	1,000
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	980	990	1,010
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,862	3,850	3,860	3,843	4,032	4,047	2,179	2,172	2,147

Table C4-North Central Transportation Modes and Distances - High Mass Materials

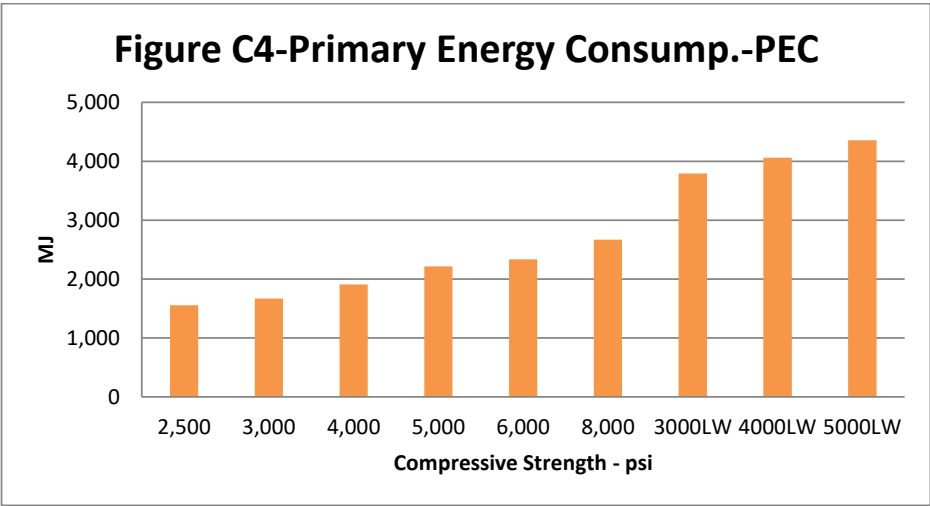
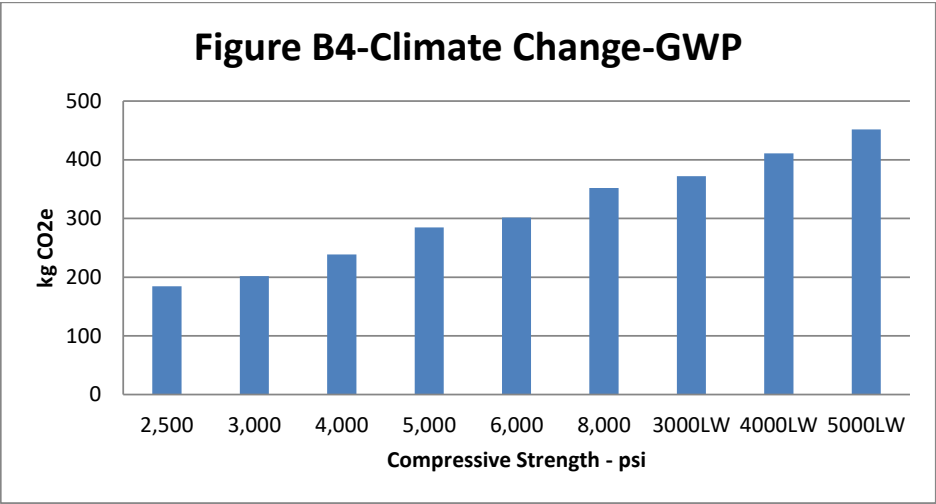
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	204.8	132.3	118.3	44.6	17.2	2.7	16.2
Rail	mi	82.0	186.3	0.0	0.0	2.1	0.0	2.1
Ocean	mi	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Barge	mi	188.9	0.0	0.0	0.0	0.0	0.0	0.0

Table D4-North Central Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	2.69	3.52
Natural Gas	cuft	17.47	22.85
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.00
Diesel	gal	0.12	0.15
Gasoline	gal	0.00	0.00
LPG (Liquified Propane Gas)	gal	0.00	0.00
Other	gal	0.00	0.00
Process water consumption	gal	43.48	56.87
Hazardous Solid Waste	lbs	0.00	0.00
Non-Hazardous Solid Waste	lbs	2.42	3.17

Table E4-North Central LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	184.24	201.89	238.79	284.71	301.52	351.81	372.11	410.72	451.74
ODP	kg CFC11e	4.49E-06	4.86E-06	5.64E-06	6.59E-06	6.97E-06	8.03E-06	1.35E-05	1.44E-05	1.53E-05
AP	kg SO2e	0.63	0.67	0.77	0.89	0.94	1.07	1.84	1.95	2.07
EP	kg Ne	0.28	0.30	0.34	0.38	0.41	0.46	0.69	0.73	0.78
SFP	kg O3e	13.30	14.27	16.33	18.84	19.90	22.69	23.60	25.77	28.06
ADPf	MJ, NCV	418.31	437.07	480.77	538.30	566.39	629.62	1,953.19	2,016.71	2,101.36
ADPe	kg Sbe	1.07E-04	1.09E-04	1.14E-04	1.20E-04	1.26E-04	1.33E-04	1.68E-04	1.75E-04	1.83E-04
Use of Primary Resources										
RPRE	MJ, NCV	16.58	16.30	15.94	15.63	16.08	15.74	224.93	226.90	231.26
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,190.05	1,276.16	1,460.59	1,692.08	1,785.33	2,039.87	2,897.99	3,102.95	3,331.91
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	83.62	93.16	112.93	137.48	145.95	172.79	93.38	112.97	132.72
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.57	0.59	0.63	0.68	0.71	0.76	0.80	0.84	0.89
CCE	kg CO2e	76.74	85.50	103.65	126.18	133.95	158.58	85.70	103.68	121.81
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	1.18E-08	1.17E-08	1.16E-08	1.13E-08	1.17E-08	1.15E-08	4.86E-08	4.89E-08	4.96E-08
LLRW	m3	2.10E-07	2.08E-07	2.07E-07	2.03E-07	2.10E-07	2.08E-07	1.69E-06	1.70E-06	1.73E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F4-North Central LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	240.98	264.06	312.33	372.39	394.37	460.14	486.70	537.20	590.85
ODP	kg CFC11e	4.49E-06	6.35E-06	7.37E-06	8.62E-06	9.12E-06	1.05E-05	1.77E-05	1.88E-05	2.00E-05
AP	kg SO2e	0.63	0.88	1.00	1.16	1.22	1.39	2.40	2.54	2.71
EP	kg Ne	0.28	0.39	0.44	0.50	0.53	0.60	0.90	0.95	1.02
SFP	kg O3e	13.30	18.67	21.36	24.65	26.02	29.68	30.86	33.70	36.71
ADPf	MJ, NCV	418.31	571.66	628.82	704.07	740.81	823.51	2,554.68	2,637.75	2,748.48
ADPe	kg Sbe	1.07E-04	1.42E-04	1.49E-04	1.57E-04	1.65E-04	1.75E-04	2.20E-04	2.29E-04	2.39E-04
Use of Primary Resources										
RPRE	MJ, NCV	21.68	21.31	20.85	20.44	21.03	20.59	294.19	296.78	302.48
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,556.53	1,669.15	1,910.37	2,213.16	2,335.12	2,668.06	3,790.43	4,058.50	4,357.98
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	109.36	121.85	147.71	179.82	190.90	226.00	122.14	147.75	173.59
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.75	0.77	0.82	0.89	0.93	1.00	1.05	1.10	1.16
CCE	kg CO2e	100.37	111.83	135.57	165.03	175.20	207.42	112.10	135.61	159.32
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	1.54E-08	1.53E-08	1.51E-08	1.48E-08	1.53E-08	1.50E-08	6.36E-08	6.40E-08	6.49E-08
LLRW	m3	2.74E-07	2.72E-07	2.70E-07	2.65E-07	2.75E-07	2.72E-07	2.21E-06	2.23E-06	2.27E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-5: Pacific Northwest Region

Table A5-Pacific Northwest Production Data Summary		
Number of Plants	32	
% Transit Mix Plants	60%	
% Central Mix Plants	40%	
% Batch Waste	0.78%	
	yd3	m3
Average Production	61,404	46,947
Total Production	1,964,932	1,502,298
Minimum Production	1,652	1,263
Maximum Production	136,600	104,438

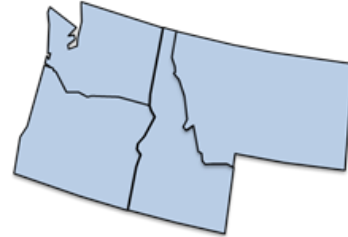


Table B5-Pacific Northwest Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	362	406	500	619	655	791	407	500	597
Fly Ash	lbs	93	105	129	159	169	204	105	129	154
Slag Cement	lbs	11	13	16	19	21	25	13	16	19
Mixing Water	lbs	302	302	302	313	339	339	306	306	306
Crushed Coarse Aggregate	lbs	135	133	129	121	125	117	0	0	0
Natural Coarse Aggregate	lbs	1,695	1,663	1,614	1,518	1,566	1,469	0	0	0
Crushed Fine Aggregate	lbs	79	78	75	71	73	69	71	63	56
Natural Fine Aggregate	lbs	1,340	1,315	1,277	1,200	1,238	1,162	1,200	1,072	956
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	1,060	1,070	1,070
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	4,018	4,014	4,042	4,019	4,186	4,176	2,101	2,085	2,088

Table C5-Pacific Northwest Transportation Modes and Distances - High Mass Materials

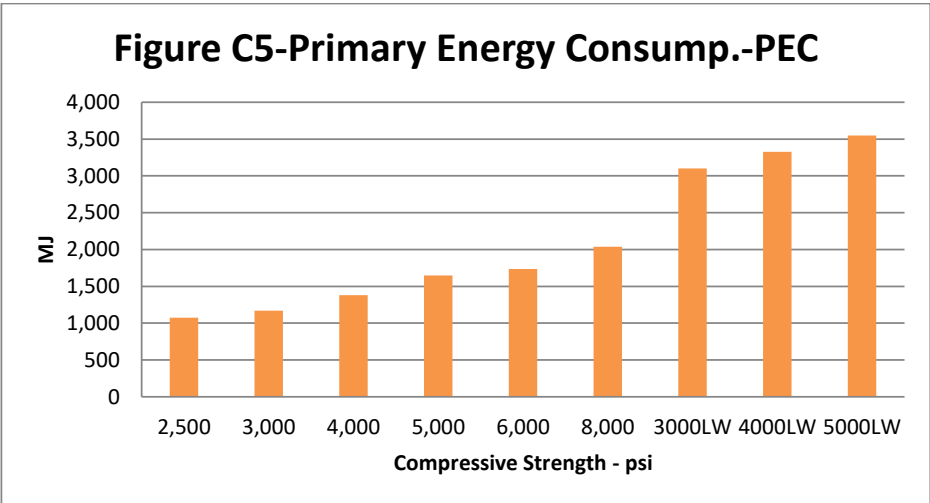
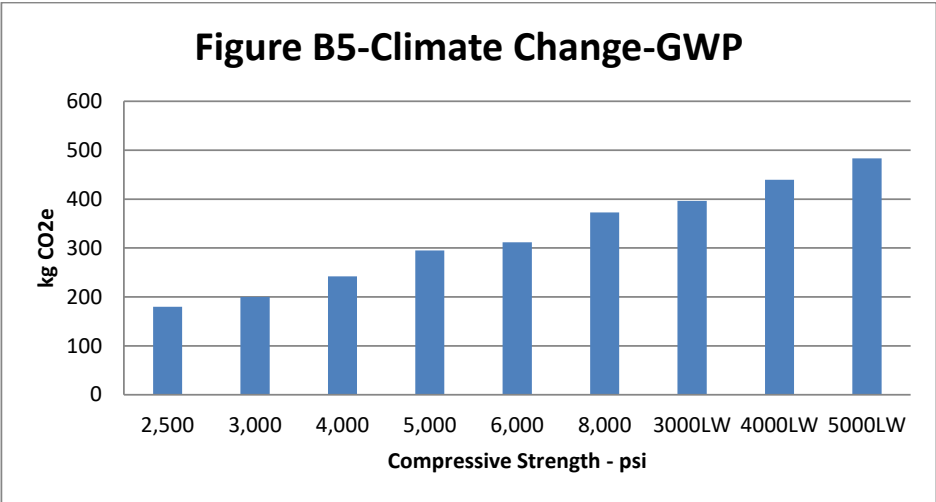
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	37.8	75.4	11.5	9.0	10.4	1.9	10.5
Rail	mi	123.6	46.1	0.0	1.3	3.5	13.7	3.5
Ocean	mi	1,308.4	0.0	1,680.4	0.0	2.1	0.1	2.1
Barge	mi	11.6	0.0	0.0	0.0	0.0	11.1	0.4

Table D5-Pacific Northwest Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	3.61	4.72
Natural Gas	cuft	10.87	14.22
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.00
Diesel	gal	0.27	0.35
Gasoline	gal	0.00	0.00
LPG (Liquified Propane Gas)	gal	0.04	0.05
Other	gal	0.00	0.00
Process water consumption	gal	48.41	63.32
Hazardous Solid Waste	lbs	0.36	0.47
Non-Hazardous Solid Waste	lbs	29.73	38.89

Table E5-Pacific Northwest LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	180.02	199.84	241.95	295.20	311.94	372.65	396.24	439.72	483.36
ODP	kg CFC11e	4.78E-06	5.20E-06	6.11E-06	7.24E-06	7.63E-06	8.94E-06	1.47E-05	1.57E-05	1.66E-05
AP	kg SO2e	0.63	0.69	0.81	0.96	1.01	1.19	2.03	2.16	2.29
EP	kg Ne	0.22	0.24	0.29	0.35	0.37	0.43	0.71	0.76	0.81
SFP	kg O3e	14.49	15.78	18.54	21.99	23.14	27.10	27.28	30.10	32.94
ADP _f	MJ, NCV	320.52	342.00	388.81	450.38	472.31	538.27	2,111.78	2,174.00	2,226.10
ADP _e	kg Sbe	8.43E-05	8.74E-05	9.46E-05	1.03E-04	1.08E-04	1.17E-04	1.75E-04	1.82E-04	1.90E-04
Use of Primary Resources										
RPRE	MJ, NCV	19.02	18.88	18.71	18.50	18.84	18.42	248.06	249.97	249.95
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,072.32	1,170.65	1,380.77	1,648.05	1,734.93	2,036.34	3,102.07	3,327.28	3,547.82
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	86.50	97.10	119.57	147.93	156.66	189.14	97.30	119.55	142.72
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.61	0.63	0.67	0.73	0.77	0.83	0.87	0.92	0.96
CCE	kg CO2e	79.39	89.12	109.74	135.76	143.78	173.59	89.30	109.72	130.98
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	7.54E-09	7.62E-09	7.84E-09	8.05E-09	8.29E-09	8.55E-09	5.13E-08	5.19E-08	5.21E-08
LLRW	m3	1.97E-07	1.99E-07	2.06E-07	2.11E-07	2.19E-07	2.26E-07	1.84E-06	1.87E-06	1.87E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F5-Pacific Northwest LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	235.46	261.38	316.46	386.11	408.01	487.41	518.26	575.13	632.21
ODP	kg CFC11e	4.78E-06	6.80E-06	7.99E-06	9.47E-06	9.98E-06	1.17E-05	1.92E-05	2.05E-05	2.17E-05
AP	kg SO2e	0.63	0.90	1.06	1.26	1.33	1.56	2.66	2.83	3.00
EP	kg Ne	0.22	0.32	0.38	0.46	0.48	0.57	0.93	0.99	1.05
SFP	kg O3e	14.49	20.64	24.25	28.76	30.27	35.45	35.68	39.37	43.08
ADPf	MJ, NCV	320.52	447.33	508.54	589.08	617.76	704.03	2,762.10	2,843.49	2,911.63
ADPe	kg Sbe	8.43E-05	1.14E-04	1.24E-04	1.35E-04	1.41E-04	1.53E-04	2.28E-04	2.38E-04	2.48E-04
Use of Primary Resources										
RPRE	MJ, NCV	24.88	24.69	24.47	24.20	24.64	24.09	324.45	326.95	326.93
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,402.55	1,531.15	1,805.97	2,155.57	2,269.21	2,663.43	4,057.36	4,351.92	4,640.38
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	113.14	127.00	156.39	193.48	204.91	247.38	127.27	156.37	186.67
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.79	0.82	0.88	0.96	1.00	1.08	1.14	1.20	1.26
CCE	kg CO2e	103.83	116.56	143.53	177.57	188.06	227.04	116.80	143.51	171.32
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	9.86E-09	9.97E-09	1.03E-08	1.05E-08	1.08E-08	1.12E-08	6.71E-08	6.79E-08	6.82E-08
LLRW	m3	2.58E-07	2.61E-07	2.69E-07	2.76E-07	2.86E-07	2.96E-07	2.41E-06	2.44E-06	2.45E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-6: Pacific Southwest Region

Table A6-Pacific Southwest Production Data Summary		
Number of Plants	51	
% Transit Mix Plants	66%	
% Central Mix Plants	34%	
% Batch Waste	1.03%	
	yd3	m3
Average Production	97,308	74,397
Total Production	4,962,694	3,794,251
Minimum Production	7,561	5,781
Maximum Production	403,143	308,225



Table B1-NRMCA U.S. National Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	379	419	497	594	632	731	419	498	573
Fly Ash	lbs	55	61	73	87	92	107	61	73	84
Slag Cement	lbs	0	0	0	0	0	0	0	0	0
Mixing Water	lbs	328	328	328	340	369	369	332	332	332
Crushed Coarse Aggregate	lbs	780	772	750	719	742	712	0	0	0
Natural Coarse Aggregate	lbs	742	735	713	684	706	677	0	0	0
Crushed Fine Aggregate	lbs	186	184	178	171	177	169	179	167	153
Natural Fine Aggregate	lbs	1,318	1,305	1,267	1,216	1,254	1,203	1,269	1,183	1,084
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	900	910	930
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,789	3,804	3,807	3,811	3,972	3,968	2,260	2,252	2,227

Table C6-Pacific Southwest Transportation Modes and Distances - High Mass Materials

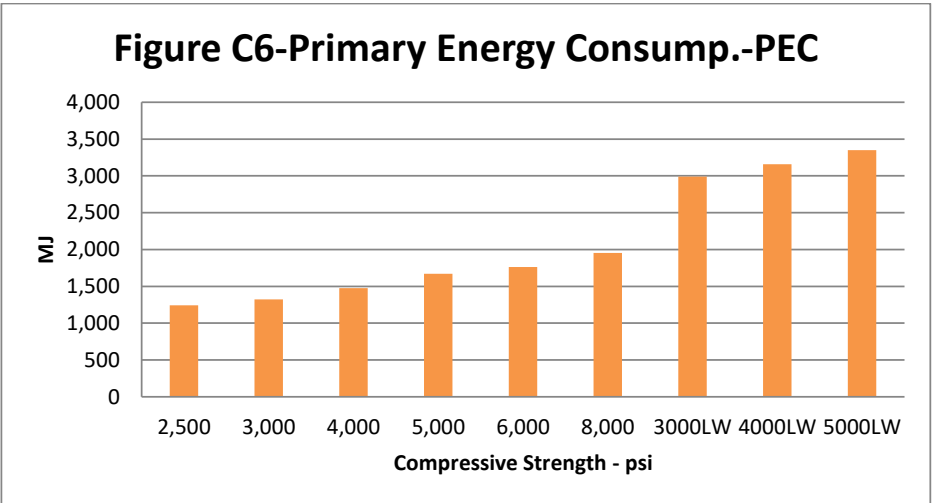
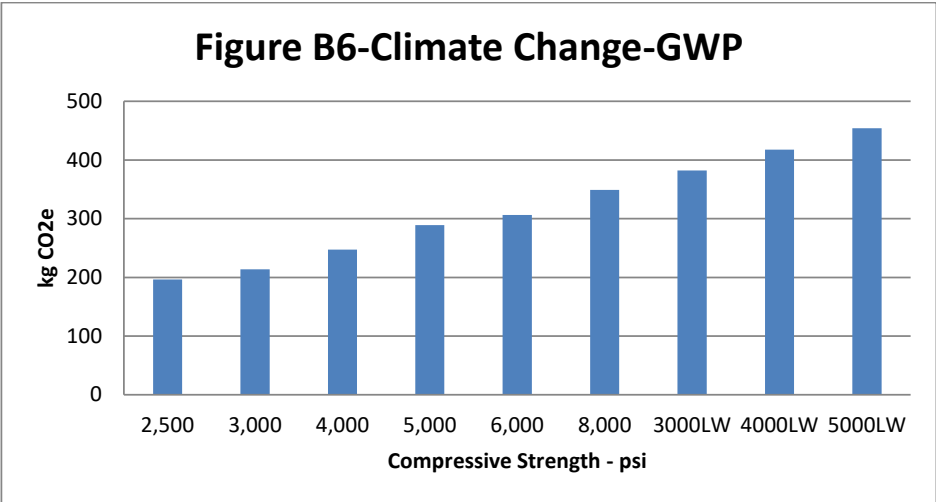
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	81.4	38.8	12.9	13.4	40.6	8.2	48.2
Rail	mi	36.0	105.3	0.0	77.3	0.6	73.4	0.6
Ocean	mi	317.4	181.1	402.6	0.2	51.1	0.1	180.4
Barge	mi	0.0	0.0	0.0	0.0	1.6	0.0	1.6

Table D6-Pacific Southwest Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	2.79	3.65
Natural Gas	cuft	0.06	0.08
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.00
Diesel	gal	0.32	0.42
Gasoline	gal	0.00	0.00
LPG (Liquified Propane Gas)	gal	0.01	0.01
Other	gal	0.00	0.00
Process water consumption	gal	50.45	65.99
Hazardous Solid Waste	lbs	0.00	0.00
Non-Hazardous Solid Waste	lbs	37.23	48.70

Table E6-Pacific Southwest LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	196.51	213.46	247.32	288.90	306.44	348.96	382.19	417.50	453.93
ODP	kg CFC11e	4.91E-06	5.28E-06	6.01E-06	6.90E-06	7.30E-06	8.22E-06	1.32E-05	1.40E-05	1.49E-05
AP	kg SO2e	0.74	0.78	0.85	0.94	0.99	1.08	1.95	2.03	2.13
EP	kg Ne	0.24	0.26	0.29	0.34	0.36	0.41	0.65	0.69	0.73
SFP	kg O3e	17.35	18.12	19.59	21.37	22.41	24.24	28.83	30.35	31.92
ADPf	MJ, NCV	458.40	470.65	492.46	522.89	545.74	572.52	2,010.53	2,047.49	2,104.97
ADPe	kg Sbe	1.08E-04	1.11E-04	1.16E-04	1.22E-04	1.28E-04	1.34E-04	1.63E-04	1.70E-04	1.77E-04
Use of Primary Resources										
RPRE	MJ, NCV	20.79	20.67	20.30	20.04	20.46	19.96	211.98	213.91	218.25
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,242.13	1,321.09	1,476.48	1,670.18	1,760.81	1,955.40	2,988.29	3,159.34	3,348.77
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	90.92	100.32	119.22	142.30	151.51	175.27	100.53	119.24	137.40
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.64	0.66	0.70	0.75	0.78	0.83	0.86	0.90	0.94
CCE	kg CO2e	83.44	92.07	109.42	130.60	139.05	160.86	92.26	109.44	126.10
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	6.93E-09	6.88E-09	6.75E-09	6.57E-09	6.72E-09	6.54E-09	4.28E-08	4.32E-08	4.39E-08
LLRW	m3	1.72E-07	1.71E-07	1.67E-07	1.62E-07	1.66E-07	1.61E-07	1.55E-06	1.57E-06	1.60E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F6-Pacific Southwest LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	257.02	279.20	323.49	377.87	400.81	456.43	499.88	546.07	593.72
ODP	kg CFC11e	4.91E-06	6.90E-06	7.86E-06	9.02E-06	9.55E-06	1.07E-05	1.73E-05	1.84E-05	1.95E-05
AP	kg SO2e	0.74	1.02	1.12	1.23	1.29	1.41	2.55	2.66	2.78
EP	kg Ne	0.24	0.34	0.38	0.44	0.47	0.53	0.85	0.90	0.96
SFP	kg O3e	17.35	23.70	25.62	27.95	29.31	31.71	37.71	39.69	41.75
ADPf	MJ, NCV	458.40	615.58	644.11	683.91	713.80	748.82	2,629.67	2,678.02	2,753.19
ADPe	kg Sbe	1.08E-04	1.45E-04	1.52E-04	1.60E-04	1.67E-04	1.75E-04	2.14E-04	2.22E-04	2.32E-04
Use of Primary Resources										
RPRE	MJ, NCV	27.19	27.04	26.55	26.21	26.77	26.11	277.27	279.79	285.46
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,624.64	1,727.93	1,931.16	2,184.51	2,303.05	2,557.56	3,908.54	4,132.26	4,380.03
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	118.92	131.21	155.93	186.12	198.17	229.25	131.49	155.97	179.71
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.84	0.87	0.91	0.98	1.03	1.09	1.13	1.18	1.23
CCE	kg CO2e	109.14	120.42	143.11	170.81	181.87	210.40	120.68	143.14	164.93
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	9.06E-09	9.01E-09	8.82E-09	8.59E-09	8.79E-09	8.55E-09	5.60E-08	5.64E-08	5.74E-08
LLRW	m3	2.25E-07	2.24E-07	2.18E-07	2.12E-07	2.17E-07	2.10E-07	2.03E-06	2.05E-06	2.09E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-7: Rocky Mountains Region

Table A7-Rocky Mountains Production Data Summary		
Number of Plants	22	
% Transit Mix Plants	55%	
% Central Mix Plants	45%	
% Batch Waste	0.01%	
	yd3	m3
Average Production	105,461	80,631
Total Production	2,320,132	1,773,868
Minimum Production	6,778	5,182
Maximum Production	325,595	248,935

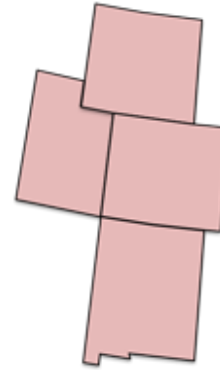


Table B7-Rocky Mountains Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	362	402	486	588	625	736	403	486	568
Fly Ash	lbs	69	77	93	112	119	141	77	93	109
Slag Cement	lbs	0	0	0	0	0	0	0	0	0
Mixing Water	lbs	303	303	303	314	341	341	307	307	307
Crushed Coarse Aggregate	lbs	929	920	893	849	875	840	0	0	0
Natural Coarse Aggregate	lbs	826	818	794	754	778	747	0	0	0
Crushed Fine Aggregate	lbs	19	19	19	18	18	17	19	18	16
Natural Fine Aggregate	lbs	1,369	1,356	1,316	1,250	1,290	1,237	1,360	1,254	1,147
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	990	1,000	1,010
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,877	3,895	3,904	3,886	4,047	4,058	2,167	2,157	2,147

Table C7-Rocky Mountains Transportation Modes and Distances - High Mass Materials

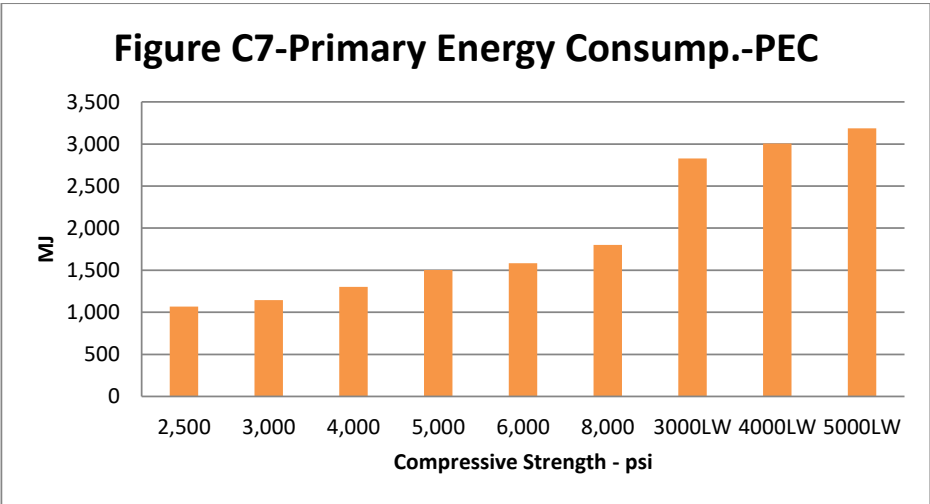
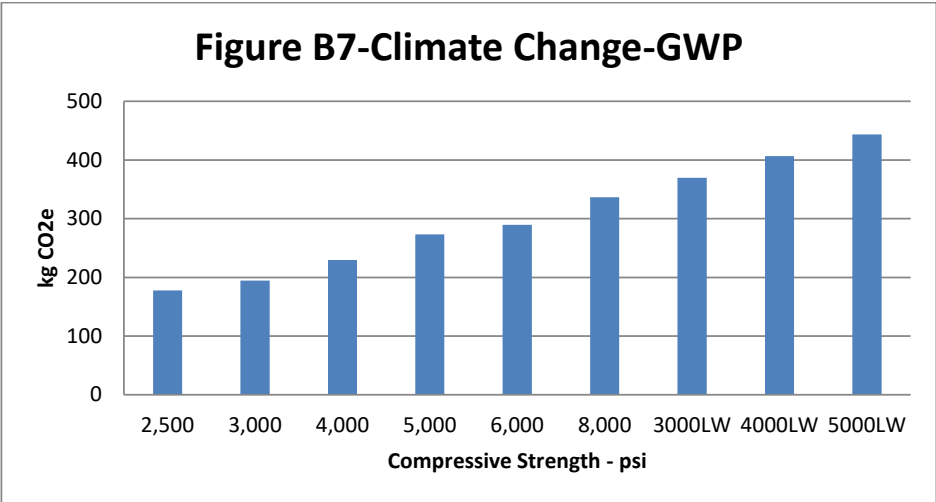
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	61.1	159.5	0.0	20.4	16.7	0.0	28.9
Rail	mi	24.2	18.5	0.0	0.0	0.0	0.0	0.0
Ocean	mi	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Barge	mi	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table D7-Rocky Mountains Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	3.04	3.97
Natural Gas	cuft	19.84	25.95
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.00
Diesel	gal	0.23	0.30
Gasoline	gal	0.00	0.00
LPG (Liquified Propane Gas)	gal	0.01	0.01
Other	gal	0.00	0.00
Process water consumption	gal	50.58	66.16
Hazardous Solid Waste	lbs	0.00	0.00
Non-Hazardous Solid Waste	lbs	0.10	0.13

Table E7-Rocky Mountains LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO ₂ e	177.48	194.58	229.76	273.39	289.58	336.69	369.75	406.48	443.51
ODP	kg CFC11e	4.63E-06	5.01E-06	5.77E-06	6.71E-06	7.09E-06	8.11E-06	1.37E-05	1.45E-05	1.54E-05
AP	kg SO ₂ e	0.54	0.57	0.65	0.73	0.77	0.87	1.75	1.84	1.92
EP	kg Ne	0.22	0.24	0.28	0.32	0.34	0.39	0.66	0.70	0.74
SFP	kg O ₃ e	11.27	11.98	13.42	15.15	15.92	17.84	21.16	22.66	24.15
ADPf	MJ, NCV	325.77	334.63	354.15	381.36	397.92	427.58	1,887.67	1,924.58	1,966.03
ADPe	kg Sbe	1.06E-04	1.09E-04	1.15E-04	1.21E-04	1.26E-04	1.33E-04	1.64E-04	1.71E-04	1.78E-04
Use of Primary Resources										
RPRE	MJ, NCV	22.02	21.80	21.33	20.82	21.25	20.74	229.04	230.98	233.16
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,067.76	1,144.52	1,303.44	1,502.74	1,583.05	1,798.90	2,827.64	3,004.70	3,186.66
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	85.85	95.45	115.19	139.60	148.30	174.64	95.64	115.19	134.75
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m ³	0.62	0.63	0.67	0.72	0.76	0.81	0.85	0.89	0.93
CCE	kg CO ₂ e	78.79	87.60	105.72	128.12	136.11	160.28	87.77	105.72	123.67
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m ³	7.17E-09	7.12E-09	6.98E-09	6.74E-09	6.89E-09	6.70E-09	4.60E-08	4.63E-08	4.67E-08
LLRW	m ³	1.58E-07	1.57E-07	1.53E-07	1.46E-07	1.50E-07	1.45E-07	1.66E-06	1.68E-06	1.69E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F7-Rocky Mountains LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	232.13	254.50	300.51	357.59	378.76	440.37	483.61	531.66	580.08
ODP	kg CFC11e	4.63E-06	6.55E-06	7.55E-06	8.78E-06	9.27E-06	1.06E-05	1.79E-05	1.90E-05	2.01E-05
AP	kg SO2e	0.54	0.75	0.84	0.96	1.01	1.14	2.29	2.40	2.51
EP	kg Ne	0.22	0.31	0.36	0.42	0.45	0.51	0.86	0.91	0.97
SFP	kg O3e	11.27	15.67	17.55	19.82	20.83	23.33	27.68	29.63	31.59
ADPf	MJ, NCV	325.77	437.68	463.21	498.80	520.45	559.25	2,468.98	2,517.25	2,571.48
ADPe	kg Sbe	1.06E-04	1.43E-04	1.50E-04	1.58E-04	1.65E-04	1.74E-04	2.14E-04	2.23E-04	2.33E-04
Use of Primary Resources										
RPRE	MJ, NCV	28.80	28.52	27.90	27.23	27.79	27.13	299.58	302.12	304.96
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,396.58	1,496.98	1,704.84	1,965.51	2,070.55	2,352.88	3,698.41	3,930.00	4,168.00
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	112.29	124.84	150.67	182.59	193.98	228.43	125.09	150.67	176.25
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.81	0.83	0.88	0.95	0.99	1.06	1.11	1.16	1.22
CCE	kg CO2e	103.06	114.58	138.28	167.58	178.03	209.64	114.80	138.28	161.76
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	9.38E-09	9.31E-09	9.13E-09	8.82E-09	9.02E-09	8.77E-09	6.02E-08	6.06E-08	6.10E-08
LLRW	m3	2.07E-07	2.05E-07	2.00E-07	1.92E-07	1.97E-07	1.90E-07	2.18E-06	2.19E-06	2.21E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



D-8: South Central Region

Table A8-South Central Production Data Summary		
Number of Plants	91	
% Transit Mix Plants	80%	
% Central Mix Plants	20%	
	yd3	m3
Average Production	49,568	37,897
Total Production	4,510,685	3,448,665
Minumum Production	263	201
Maximum Production	232,476	177,741



Table B8-South Central Benchmark Mix Designs (per cubic yard)										
Compressive Strength	psi	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW
Portland Cement	lbs	328	364	438	528	561	658	365	437	510
Fly Ash	lbs	61	68	82	99	105	123	68	82	95
Slag Cement	lbs	1	1	1	1	1	2	1	1	1
Mixing Water	lbs	279	279	279	289	314	314	283	283	283
Crushed Coarse Aggregate	lbs	1,276	1,264	1,227	1,190	1,227	1,177	0	0	0
Natural Coarse Aggregate	lbs	428	424	412	399	412	395	0	0	0
Crushed Fine Aggregate	lbs	21	21	20	20	20	19	21	20	18
Natural Fine Aggregate	lbs	1,423	1,409	1,367	1,326	1,367	1,312	1,441	1,348	1,239
Man.Lightweight Aggregate	lbs	0	0	0	0	0	0	980	990	1,010
Air %	%	6%	6%	6%	6%	6%	0	6%	6%	2%
Air Entraining Admixture	oz	1	1	1	1	1	1	1	1	0
Plasticizer & Superplasticizer	oz	3	3	3	7	3	3	3	7	7
Set Accelerator	oz	25	20	15	10	25	20	15	10	10
Total Weight	lbs	3,818	3,830	3,826	3,852	4,008	4,001	2,179	2,171	2,147

Table C8-South Central Transportation Modes and Distances - High Mass Materials

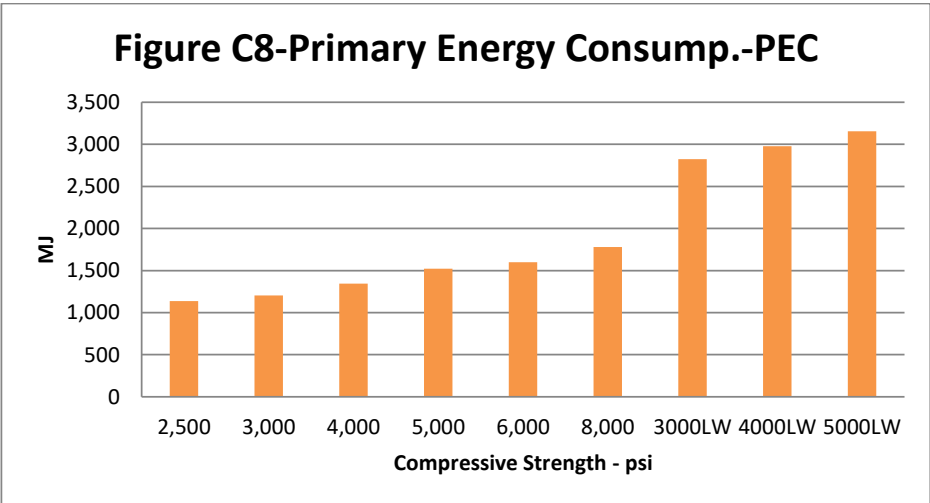
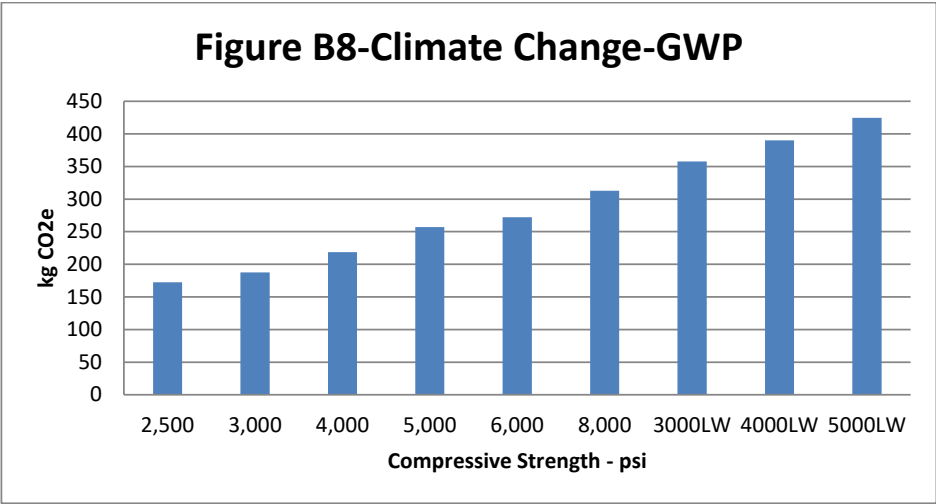
Transportation Mode	Units	Portland Cement	Fly Ash	Slag Cement	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	58.8	55.1	1.3	33.0	15.2	3.5	42.2
Rail	mi	47.6	0.5	6.4	48.3	6.0	0.0	2.1
Ocean	mi	169.6	0.0	0.0	0.0	0.0	0.0	0.0
Barge	mi	8.2	0.0	0.0	1.5	0.0	0.0	0.0

Table D8-South Central Gate to Gate Manufacturing Energy Use

		per yd3	per m3
Purchased Electricity	kWh	3.33	4.35
Natural Gas	cuft	5.98	7.83
Secondary Fuels - Liquid (waste solvents, etc.)	lb	0.00	0.00
Secondary Fuels - Solid (tires, etc.)	tn.sh	0.00	0.00
Fuel Oil (other than diesel)	gal	0.00	0.00
Diesel	gal	0.37	0.49
Gasoline	gal	0.00	0.01
LPG (Liquified Propane Gas)	gal	0.00	0.00
Other	gal	0.00	0.00
Process water consumption	gal	44.39	58.06
Hazardous Solid Waste	lbs	0.00	0.00
Non-Hazardous Solid Waste	lbs	1.53	2.00

Table E8-South Central LCA Results (per cubic yard)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	172.43	187.67	218.61	257.19	272.16	312.79	357.72	390.21	424.47
ODP	kg CFC11e	4.84E-06	5.17E-06	5.84E-06	6.66E-06	7.02E-06	7.89E-06	1.35E-05	1.42E-05	1.51E-05
AP	kg SO2e	0.62	0.65	0.71	0.79	0.83	0.91	1.79	1.86	1.95
EP	kg Ne	0.23	0.25	0.28	0.32	0.34	0.38	0.65	0.68	0.73
SFP	kg O3e	13.65	14.29	15.56	17.15	17.95	19.61	22.78	24.14	25.57
ADP _f	MJ, NCV	379.92	389.08	405.44	431.90	449.64	470.98	1,909.34	1,941.60	1,993.63
ADP _e	kg Sbe	1.14E-04	1.16E-04	1.21E-04	1.27E-04	1.32E-04	1.37E-04	1.60E-04	1.66E-04	1.74E-04
Use of Primary Resources										
RPRE	MJ, NCV	12.26	12.20	12.00	12.04	12.29	12.02	222.01	224.12	228.65
RPRM	MJ, NCV	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
NRPRE	MJ, NCV	1,136.36	1,205.63	1,344.05	1,521.93	1,599.00	1,780.65	2,822.96	2,978.63	3,154.77
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	77.85	86.38	103.84	125.35	133.25	156.18	86.55	103.82	120.93
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.55	0.57	0.60	0.65	0.68	0.73	0.79	0.82	0.86
CCE	kg CO2e	71.45	79.28	95.31	115.05	122.29	143.34	79.44	95.28	110.99
Indicators Describing Waste										
HWD	kg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NHWD	kg	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
HLRW	m3	1.29E-08	1.28E-08	1.26E-08	1.23E-08	1.26E-08	1.23E-08	4.82E-08	4.85E-08	4.92E-08
LLRW	m3	2.15E-07	2.14E-07	2.09E-07	2.05E-07	2.10E-07	2.04E-07	1.68E-06	1.69E-06	1.72E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F8-South Central LCA Results (per cubic meter)										
Strength	psi @28 days	2,500	3,000	4,000	5,000	6,000	8,000	3000LW	4000LW	5000LW
Core Mandatory Impact Indicator										
GWP	kg CO2e	225.54	245.46	285.93	336.39	355.97	409.11	467.89	510.37	555.19
ODP	kg CFC11e	4.84E-06	6.76E-06	7.63E-06	8.72E-06	9.18E-06	1.03E-05	1.76E-05	1.86E-05	1.97E-05
AP	kg SO2e	0.62	0.85	0.93	1.04	1.09	1.20	2.34	2.44	2.55
EP	kg Ne	0.23	0.32	0.37	0.42	0.44	0.50	0.85	0.90	0.95
SFP	kg O3e	13.65	18.69	20.35	22.43	23.47	25.64	29.80	31.57	33.44
ADP _f	MJ, NCV	379.92	508.89	530.29	564.90	588.11	616.02	2,497.32	2,539.51	2,607.58
ADP _e	kg Sbe	1.14E-04	1.52E-04	1.58E-04	1.66E-04	1.73E-04	1.80E-04	2.09E-04	2.17E-04	2.27E-04
Use of Primary Resources										
RPRE	MJ, NCV	16.03	15.95	15.69	15.75	16.08	15.72	290.38	293.14	299.06
RPRM	MJ, NCV	0.00	1.31	2.62	3.92	5.23	6.54	7.85	9.16	10.46
NRPRE	MJ, NCV	1,486.30	1,576.90	1,757.95	1,990.61	2,091.41	2,329.00	3,692.29	3,895.90	4,126.28
NRPRM	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Material, Secondary Fuel and Recovered Energy										
SM	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSF	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NRSF	MJ, NCV	101.82	112.99	135.82	163.96	174.28	204.28	113.21	135.79	158.17
RE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mandatory Inventory Parameters										
FW	m3	0.73	0.75	0.79	0.85	0.89	0.95	1.03	1.07	1.13
CCE	kg CO2e	93.45	103.70	124.65	150.48	159.95	187.48	103.90	124.62	145.17
Indicators Describing Waste										
HWD	kg	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
NHWD	kg	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64	9.64
HLRW	m3	1.69E-08	1.68E-08	1.65E-08	1.61E-08	1.65E-08	1.61E-08	6.30E-08	6.34E-08	6.44E-08
LLRW	m3	2.81E-07	2.79E-07	2.73E-07	2.68E-07	2.75E-07	2.67E-07	2.19E-06	2.21E-06	2.25E-06
CRU	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MR	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MER	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	MJ, NCV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



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A^{.8} Cosmic Explorer Promotional Video

As part of the Feasibility Study, a promotional video highlighting the key features and functions of the Cosmic Explorer (CE) facility has been developed. The video is publicly available on the CE website: <https://cosmicexplorer.org/>.

