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Gen 3 Particle Pilot Plant (G3P3) Life Cycle Management Plan

Jeremy N. Sment
Clifford K. Ho

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

The National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories New Mexico (SNL/NM) developed this Life Cycle Management Plan (LCMP) to document its process for executing, monitoring, controlling and closing-out Phase 3 of the Gen 3 Particle Pilot Plant (G3P3). This plan serves as a resource for stakeholders who wish to be knowledgeable of project objectives and how they will be accomplished.

The scope of the LCMP covers:

- Cost, schedule, and scope
- Project reporting
- Staffing plan
- Quality assurance plan
- Environment, safety, security, and health
- Close-out

This document is a tailored approach for the Infrastructure Operations Division (IO) to meet the project management principles of DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, and DOE G 413.3-15, *DOE Guide for Project Execution Plans.*

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ACRONYMS AND DEFINITIONS

Table 1. Table of Acronyms and Definitions

Abbreviation	Definition
AMSL	Above Mean Seal Level
AGL	Above Ground Level
CSP	Concentrating Solar Power
DOE	Department of Energy
ES&H	Environmental Safety and Health
FAA	Federal Aviation Administration
FHA	Fire Hazard Analysis
FMEA	Failure Modes and Effects Analysis
IO	Infrastructure Operations Division
FOA	Funding Opportunity Announcement
G3P3	Generation 3 Particle Pilot Plant
GC	General Contractor
IBC	International Building Code
ML	Manufacturing Liaison
KPP	Key Performance Parameter
MMRP	Military Munitions Response Program
NEPA	National Environmental Policy Act
NSTTF	National Solar Thermal Test Facility
COTS	Commercial Off-the-Shelf
PEP	Project Execution Plan
PI	Principal Investigator
PPE	Personal Protective Equipment
PM	Project Manager
RDTM	Required Documents Traceability Matrix
R&D	Research and Development
RDTX	Required Document Traceability Matrix
RPI	Risk Priority Index
sCO_2	Supercritical Carbon Dioxide
SETO	Office of Solar Energy Technologies
SNL	Sandia National Laboratories
TAC	Technical Advisory Council

Abbreviation	Definition
TBD	To Be Determined
UXO	Unexploded Ordinance
WBS	Work Breakdown Structure

1. INTRODUCTION

1.1. Background

Particle receivers are being pursued to enable higher temperatures (>700 °C) with direct storage for next-generation dispatchable concentrating solar power (CSP) plants, process heating, thermochemistry, and solar fuels production. Unlike conventional CSP receivers that use fluids flowing through tubes, the proposed particle-receiver system uses solid particles (ceramic or sand) that are heated directly as they fall through a beam of concentrated sunlight. Because the solar energy is directly absorbed by the particles, the flux limitations associated with tubular receivers are mitigated, enabling higher concentration ratios. Once heated, the particles are stored in an insulated bin before passing through a particle-to-working-fluid heat exchanger to power a high-efficiency Brayton cycle (sCO2). The cooled particles are collected and then lifted back to the top of the receiver. Aside from the particle lift, the entire process is based on gravity-driven flow of the particles through each component, which can reduce parasitic power consumption.

Sandia National Laboratories has successfully developed and demonstrated a 250 kWt high-temperature falling particle receiver system that has achieved particle temperatures over 700 °C. Key findings from these studies indicated that direct irradiance of falling particles enabled very high heating rates (up to several hundred °C over ~ 1 – 2 m of drop height with ~1 – 7 kg/s and up to 1000 kW/m^2), but additional methods to reduce heat (convective and (convective and radiative) and particle losses are needed to increase receiver thermal efficiencies, reduce costs, and mitigate potential health risks from inhalation of particle fines. In addition, a 100 kWt particle-to-sCO2 heat exchanger and sCO2 flow loop are currently under construction and will be integrated with Sandia's Particle Test Loop (SPTL) by the summer of 2018 to study high-temperature particle flow and heat transfer in a shell-and-plate heat exchanger.

Other particle receiver designs besides direct irradiance free-falling receivers have also been considered by researchers, including obstructed flow [1, 3], centrifugal [4, 5], flow in tubes with or without fluidization [6-8], and multi-pass recirculation [9, 10]. In Phases 1 and 2, we will team with international researchers leading these studies to assess and address remaining risks for down selection in the integrated Phase 3 design. We will focus our efforts on technologies that have been demonstrated on-sun, which include the falling particle receiver at Sandia, the centrifugal receiver at DLR, and the fluidized receiver at CNRS-PROMES. Each technology has advantages and challenges that need to be assessed for scalability and long-term operation with consideration of cost, performance, complexity, reliability, and manufacturability.

Until now, DOE SunShot funding has focused primarily on component-level research that developed new particle-receiver designs, process and performance models, and small-scale proof-of-concept demonstrations. However, integration with other required subsystems such as storage, heat exchangers, and particle lift systems remains to be demonstrated at larger scales and for significant durations. The next step is to move towards demonstration of larger-scale integrated systems utilizing designs and components that show promise based on previous research studies.

1.2. Gen 3 Particle Pilot Plant (G3P3)

Following a de-risking and down selection process of three technologies (gas, liquid, and solid pathways) to achieve higher temperature in Phases 1 and 2, DOE awarded Sandia with $25M to construct a Gen 3 Particle Pilot Plant (G3P3) in Phase 3 from 2021 to 2024.

Successful demonstration of G3P3 in Phase 3 will pave the way for commercial adoption and deployment of particle-based CSP plants that meet the SunShot goal of $0.06/kWh by enabling higher temperature, higher efficiency power cycles. Our team members consist of leading researchers and key members of the CSP community that have significant interest in advancing this technology, supporting the success of G3P3, and ultimately commercializing particle-based CSP systems.

The G3P3 system will consist of a ≥1 MWt particle receiver situated on top of a tower to heat the particles to nearly 800 °C in a single pass. The particles will be collected in an insulated high-temperature particle storage tank capable of holding nearly 200 metric tons of particles for 10 hours before being discharged for 6 hours through a 1 MWt particle-to-working-fluid heat exchanger. The heat exchanger will be connected to a flow system capable of providing pressurized working fluid (e.g., sCO2) that will be heated from ~580 °C to ≥775 °C. The particles are then collected in a "low-temperature" insulated storage bin, and a high-efficiency insulated particle lift system will carry the particles (~570 °C) back to the top of the receiver. A control system will maintain a constant working-fluid outlet temperature, even with varying inlet conditions (e.g., particle and working-fluid inlet temperatures, mass flow rates).

Based on lessons learned from prior design and on-testing of Sandia's high-temperature particle test loop, a larger-scale integrated G3P3 system has been designed. The G3P3-USA system will be situated next to the existing tower at the NSTTF and will utilize the existing 5 – 6 MWt heliostat field (Figure 1). The G3P3-USA system consists of a vertically integrated high-temperature multistage particle receiver, high- and low-temperature storage bins, particle-to-sCO2 heat exchanger, and particle lift, and in-line weigh hoppers to accurately measure particle mass flow at various locations. Figure 3 shows the G3P3 tower and labeled components.

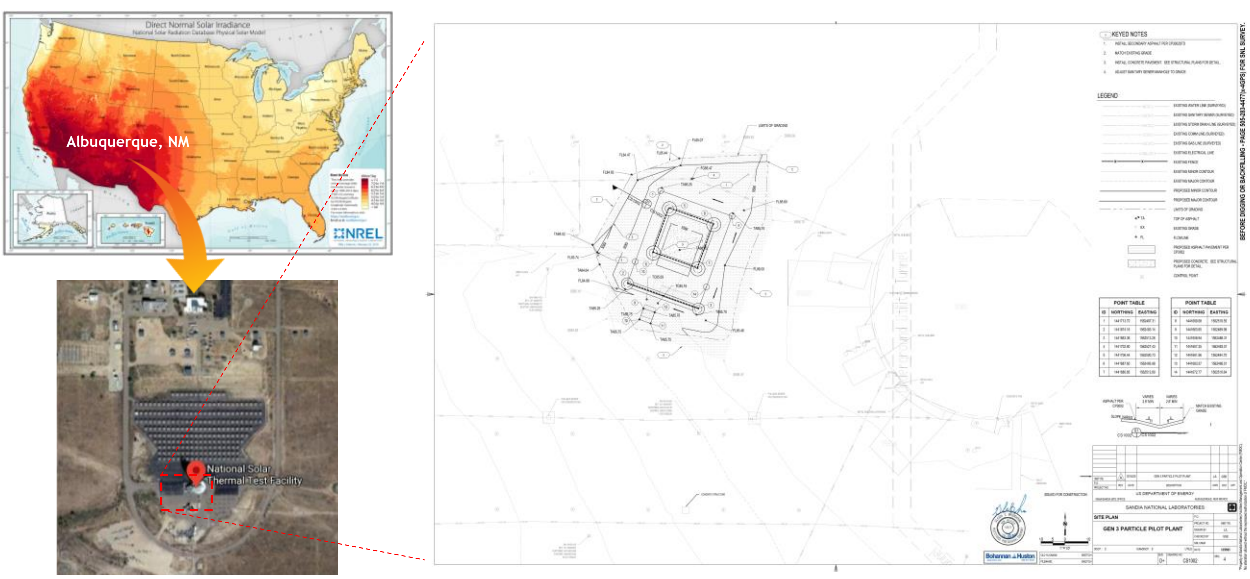

Figure 1. Proposed G3P3 tower immediately west of existing tower.

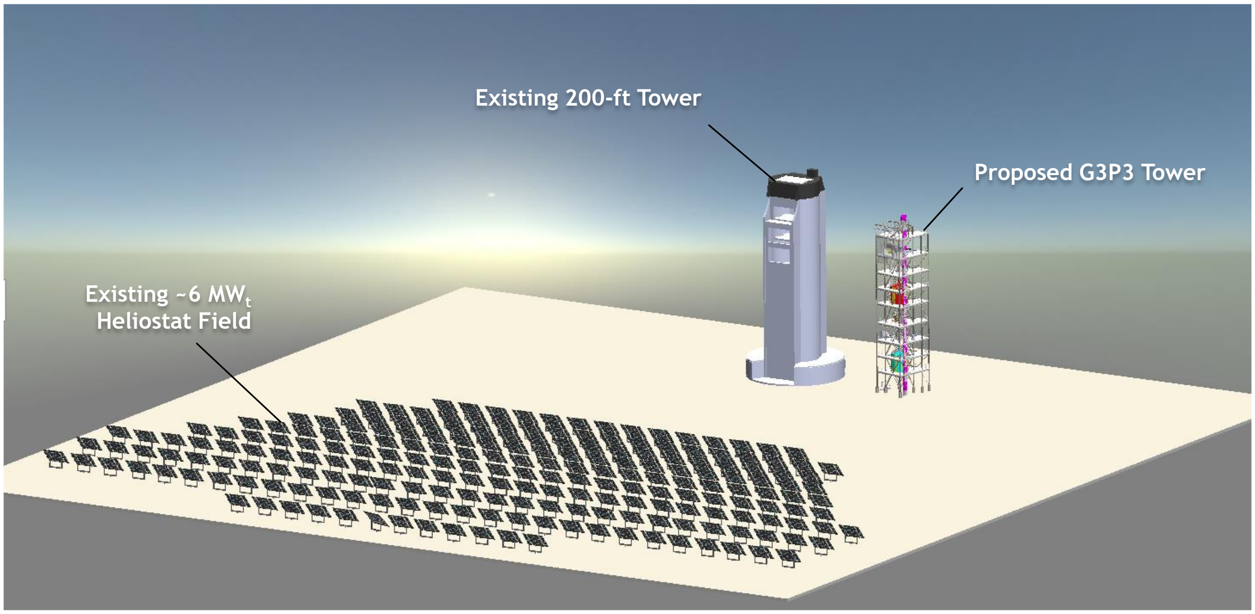

Figure 2. Rendering of proposed G3P3 tower.

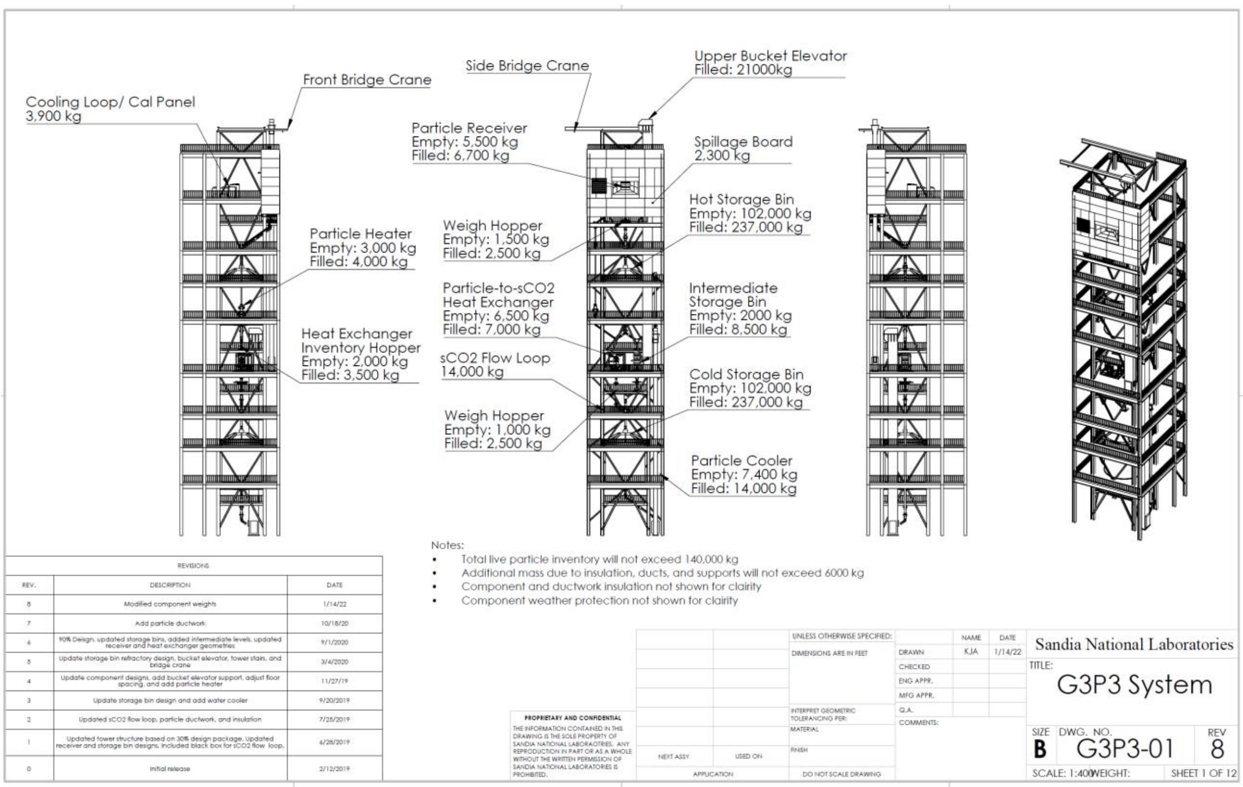

Figure 3. G3P3 system model with and without tower. Measurements are in units of meters.

The official documentation of the G3P3 tower location and design is provided in the NSTTF Gen 3 Particle Pilot Plant Design Analysis and supporting materials provided by Bridgers & Paxton [1]. The official definition of the G3P3 solar system design is provided in the Piping and

Instrumentation diagram and the engineering drawing package and is described in the G3P3 design basis report [2].

1.3. Key Performance Parameters

Key performance parameters (KPPs) are key indicators for quantifying G3P3 performance. A metric may be called out as a KPP when it generally has one or more of the following characteristics.

- Parameter is important because it directly informs target metrics for SETO SunShot 2030 goals
- Data shows low margin or high variability relative to the requirement and must be closely monitored.
- System or component performance is highly sensitive to small changes in the parameter value

Table 2 defines the KPPs for G3P3 as described in DE-FOA-0001697 [3].

Table 2. Summary of KPPs and target performance metrics for each component and overall G3P3 system. Cost targets are for commercial scale (~100 MW_e).

Component	Target Metrics	Basis
Particles	Cost ≤ \$1/kg Attrition ≤ 0.01% of flow	• Cost target based on price competitiveness with molten salts • Attrition target related to cost metrics for storage and LCOE
Receiver	Thermal duty: 1 – 2 MW_t Cost ≤ \$150/kW_t Thermal eff. ≥ ~80 - 85% (pilot), 85-90% (commercial) T_{out} ≥ 750 °C $\dot{m}$ ≥ 5 kg/s	• Thermal duty meets FOA goals and matches capability at NSTTF • Cost and outlet temperature meet SunShot goals • Recent System Advisor Model simulations show that a commercial receiver efficiency of 85-90% can still yield \$0.06/kWh_e; pilot-scale efficiency scales down with receiver size **[4]** • Mass flow based on required thermal duty
Thermal Storage	Cost ≤ \$15/kWh_t Heat loss ≤ 1%/10hrs Capacity ≥ 6 MWh_t	• Preliminary cost and heat loss performance studied previously by our partner, KSU **[5]** • Capacity and duration meet 6 hours of storage (deferred 10 hours) for 1 MW_t heat exchanger per FOA
Heat Exchanger	Particle mass flow ≥ 5 kg/s U ≥ 100 W/m^2-K T_{out} ≥ 700 °C	• Mass flow rate enables ≥ 1 MW_t as required by FOA • Overall heat transfer coefficient (U) and temperature targets designed to meet cost and performance requirements **[6]**
Particle Lift	Mass flow rate ≥ 5 kg/s Lift efficiency ≥ 50% (commercial) T_{max} ~600 °C	• Mass flow rate enables ≥ 1 MW_t • Lift efficiency required to reduce particle attrition and parasitics; can be achieved with preliminary design of hoist system **[7]**

Component	Target Metrics	Basis
		• Temperature of "cold" particles being lifted will be up to 600 °C
System (~100 MW_e)	LCOE ≤ $0.06/kWh	• Estimated from preliminary technoeconomic analysis **[8]**, which will be updated based on new designs and results in Phases 1 and 2.

2. MANAGEMENT STRUCTURE AND INTEGRATED TEAM

The project will involve integration of several organizations with general lines of communication and project authority flow-down as shown in Figure 4. Central to the project is the core research and development team and electromechanical technicians employed on-site at the NSTTF under the direct supervision of the principal investigator. The construction of the tower including civil, structural, electrical and data acquisition ports will be managed by Facilities management who are tasked as experts in contracting and construction. Facilities managers will interface with the core R&D team to understand the requirements of the system. The general contractor will work with the facilities managers to erect the tower. Facilities (Org. 4722) will hire and manage sub-contractors as needed to execute the following list of subcontracts.

List of subcontracts:

1. Welding and assembly storage bin structure (2 x)
2. Lift and set the CSP components into tower
3. Installation of bucket lift
4. Installation of ductwork
5. Insulation of ductwork and components.

The PI will be solely responsible for coordinating direct communication to the project managers at the SETO office. The NSTTF Site Manager will have a role in assuring all aspects of the project integrate with all other facility activities, staffing, ES&H enforcement, and site support. The Center Director and level 2 managers must oversee the implementation of the project. The Project Management Professional (PMP) will communicate with the Facilities Manager and Construction Manager to track and monitor the project execution of the tower and sub-contracts and will advise the PI on any variation in schedule, scope, or budget.

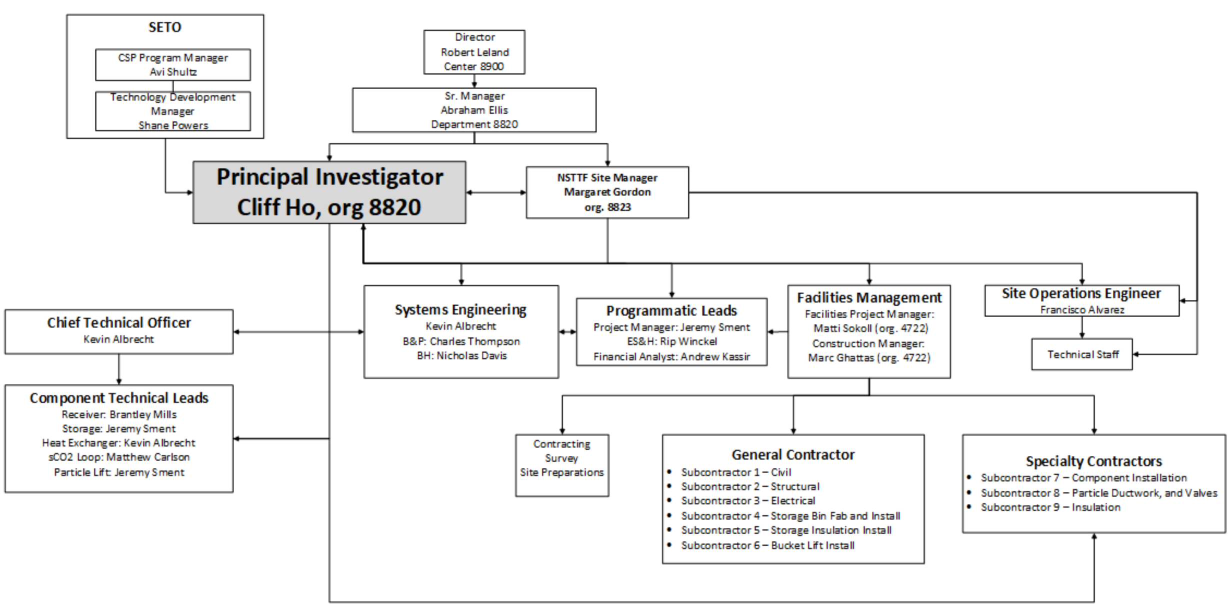

Figure 4: G3P3 Organization Chart

Roles and responsibilities are presented in Figure 5. The roles are defined as follows:

- Principal Investigator (PI) – Ultimate authority on project scope and spending. All changes to baseline plan must be approved by PI. All communications with customer are routed through PI.
- NSTTF Site Manager – Responsible for staffing and scheduling needs at NSTTF. Site Manager is responsible for the safety and security of the site and must approve activity level tasks.
- Chief Technical Officer – System designer and technical lead on system integration of components and tower structure.
- Component Technical Lead – Technical lead on designated components listed in Figure 5.
- Project Management Professional – Advisor and assistant to the PI on project planning and execution. PMP acts as agent of the PI and will interface with multiple agencies as needed to execute the project.
- Construction Manager – Responsible for oversight of the tower construction including verification of compliance with all applicable permitting and regulations and code inspections.
- General Contractor – Erection of tower including civil, structural, electrical, and data ports. Responsible for all permitting, staffing, training, procurement of materials and equipment, planning, staging and executing construction. General contractor may choose to bid on sub-contractor scope.
- Sub-Contractor – Planning, permitting, staffing, and procurement of materials and equipment necessary to execute of tasks identified in list of subcontracts in section 2.
- Site Operations Engineer – Coordinates with NSTTF technicians to prioritize activities with work for others.
- Technology Development Manager – Main point of contact from Department of Energy (customer). Approves all changes to baseline requested by PI. Coordinates progress updates.
- CSP Program Manager – Manages execution of SETO directives. Informed of project progress. Approves project charter.
- Senior Manager – Manager of Renewable Energy Technologies group at SNL.
- Director – Director of Climate Change Security at SNL. Project approval required.

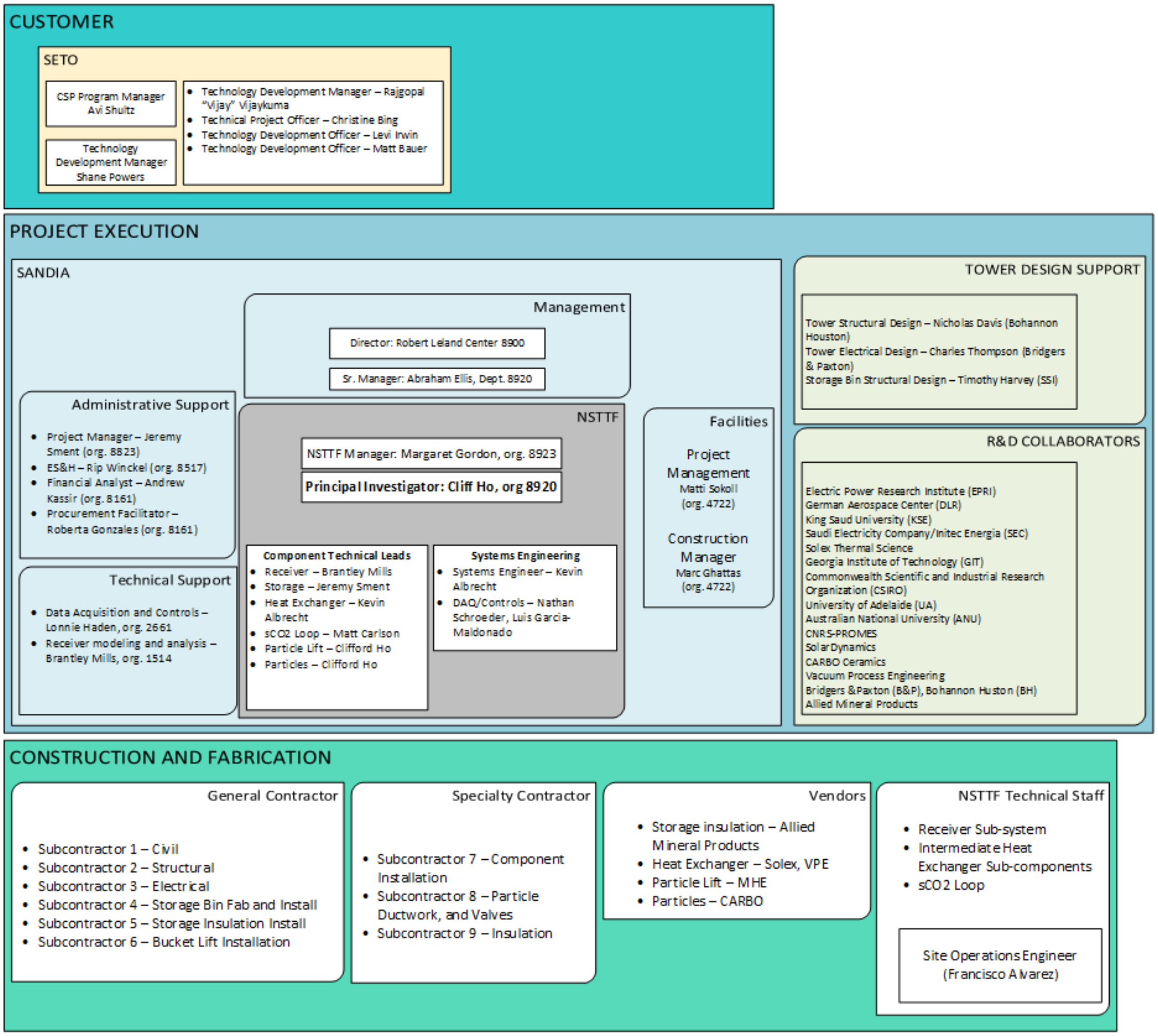

Figure 5. Roles and Responsibilities

The G3P3 project incorporates multiple organizations with individual management protocols. In order to provide a productive work environment this project plan provides for tailored management strategies that allow each individual organization to perform within their respective processes.

The NSTTF technical staff will be focused on the design, research, and development of the G3P3 tower. The NSTTF electromechanical technicians will primarily comply within their skill set in developing components and subcomponents for the G3P3 system under the ES&H guidelines and operating procedures of the NSTTF.

The IOIO specializes in managing construction projects at SNL and interfacing with contractors and Kirtland AFB. The IO will be responsible for managing the construction of the G3P3 system to the scope specified in this plan, but will define project execution plans for all general construction and sub-contractor scope independently of this PMP. The IO scope will include but is not limited to: all required planning, permitting, worker safety plans, site preparations, inspections, approvals. IO representatives for this project may be called upon to make updates and communications to the G3P3 stakeholders that comply with this plan.

The awarded contractor will execute the construction of the G3P3 system to the scope specified in this PMP but will have an independent set of protocols and management procedures that are tailored to the awardee's company policies and in compliance with the IO. Any communications between the contractor and G3P3 researchers will be coordinated outside the scope of this document on an as-needed basis.

3. INTEGRATED BASELINE

The G3P3 performance baseline includes a complete description of scope, estimated schedule, and total budget breakdown, how each is to be monitored and reported, and how each will be managed or corrected if significant variations occur that would impact the baseline.

3.1. Scope

Upon funds posting, the engineer-stamped drawings will be released for bid. While the contracting process is underway, component leads will begin to procure components and materials and the NSTTF technical staff will begin to fabricate the receiver, hoppers, and sCO_2 loop. Fabrication and procurement are expected to continue after tower construction begins. The general contractor will completely manage the construction sequence with oversight from IO.

By the time the tower has been constructed, all procurements will have been completed and delivered and the NSTTF staff will have fabricated steel framing and insulation for each component and the calibration panel so it is ready for lifting and setting.

A sub-contractor hired by IO will be hired to weld the steel shells for the storage bins and prepare them to be inserted into the tower.

A sub-contractor will be hired by IO to lift components and set them into position inside the tower.

A sub-contractor will be hired by IO to install the bucket lift.

A sub-contractor will be hired to install the ductwork and connect it to each component.

Optionally the NSTTF technicians may install the ductwork

A sub-contractor will be hired by IO to insulate the ductwork and components.

Optionally the NSTTF may contract insulation sub-contractor

A sub-contractor will be hired by IO to install the refractory insulation inside the storage bins and install storage bin roof.

Optionally the NSTTF may contract the refractory sub-contractor

IO will manage all final inspections and certify that the tower is ready for occupancy.

NSTTF staff will install sensors and data acquisition equipment.

NSTTF staff will commission the system beginning with gradual fill of the storage bins with particles. Next, NSTTF staff will bring the particles, receiver, heat exchanger, and storage bins to 600° C. Next, NSTTF staff will commission receiver by gradually proving it can sustain max flux at minimum particle curtain. Once hot particles have been routed through all pathways and the control and data acquisition system has been demonstrated, component and systems leads will certify that the system is ready for testing.

Data will be logged continuously for G3P3 allowing all system and component test objectives to be tested simultaneously. System operations include start-up/shutdown, continuous operations, load follow, storage, off-design and emergency shutdown. Component leads will be responsible for accessing, analyzing, and reporting the data concurrently with testing.

Major milestones for each of the three years are as follows:

1. **Phase 3 (Year 3)**
    a. Initiate contracts with Sandia Facilities and EPC (integrator)
    b. Initiate procurement of G3P3 system components
    c. Complete NSTTF facilities preparation (NEPA, permitting, utilities, ES&H)
    d. Begin construction of G3P3 tower
    e. Fabrication of components
    f. Initiate commissioning and off-sun testing of available components
    g. Work with R&D teams to refine and improve component technologies
    h. Procurements Received
    - **Expected outcome**: Completion of G3P3 facilities preparation and procurement contracts; tower construction begins; publication and dissemination of R&D
    - **Go/No-No Go**: Successful completion of facilities preparation and procurements
2. **Phase 3 (Year 4)**
    a. Final delivery of G3P3 system components
    b. Construction and assembly of structural support/framing
    c. Installation of CSP components into tower
    d. Commissioning of G3P3 components and system
    e. Work with R&D teams to refine and improve component technologies
    - **Expected outcome**: Successful construction and assembly of G3P3 system; commissioning has begun
    - **Go/No-No Go**: Completion of construction and installation
3. **Phase 3 (Year 5)**
    a. On-sun testing begins
    b. Parametric performance evaluation (efficiency vs. irradiance, mass flow rate, and particle temperature)
    c. Long-term on-sun operational testing and demonstration with start-up/shut-down procedures (includes 6-hour storage demonstration)
    d. Development of scale-up and commercial deployment plan
    e. Work with R&D teams to refine and improve component technologies
    - **Expected outcome**: > 2000 hours of testing between the G3P3-USA and G3P3-Saudi systems that validate the performance of subsystem components under steady and transient conditions, including start-up, shut-down, and deferred storage

3.1.1. Work Breakdown Structure

The complete Work Breakdown Structure (WBS) is managed in the current MS Project file for G3P3 Phase 3. Information in the MS Project file supersedes information in the figures below. The Phase 3 WBS is divided into 6 categories:

1. Programmatic
2. Procurements and Fabrication
3. Construction and Assembly
4. Commissioning of G3P3 System
5. Component Testing
6. System Testing
7. Work from External Partners

Figure 6 shows the major categories of the programmatic implementation:

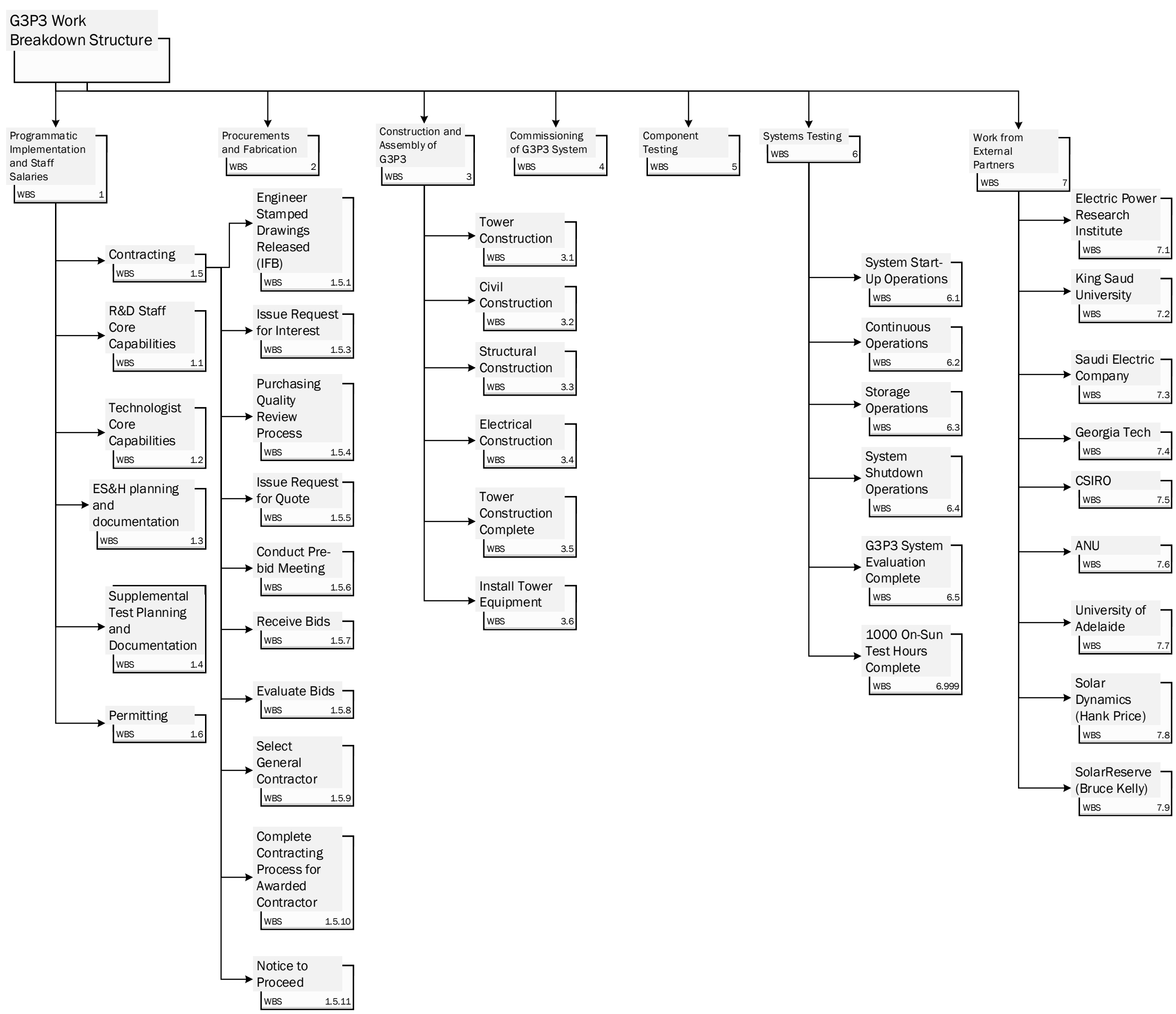

Figure 6. Work Breakdown Structure (selected layers)

3.1.2. Project Reporting Against SOPO

The scope of phase 3 includes all tasks required to build G3P3, conduct >1000 hours of on-sun system testing (G3P3-USA), evaluate the system and subsystem performance in representative environmental conditions and publish analysis and results. The specific deliverables are identified in the work breakdown structure which describes all the work to be performed and the responsible party performing the work. Once the baseline scope is approved any changes to scope including adding or subtracting tasks will require approval by the PI and SETO. Milestones will be added as a means of tracking progress toward project completion. Milestones themselves are not tasks. Milestones should follow "SMART" guidelines being specific, measurable, achievable, realistic and timely. Changes to milestones will be approved by the PI and SETO will be notified.

3.2. Schedule Baseline

G3P3 is a five year project in three phases. Phase 1 is 18 months. Phase 2 is 6 months. Phase 3 lasts three years including construction, procurement, commissioning, and testing. Phase 2 will conclude at the end of FY20 with the Issue for Bid which is the complete set of engineer stamped drawings needed to construct the tower and install the CSP components. Phase 3 will begin when the award announcement is made by SETO and funds are received.

Figure 7 shows the major phases of the project including tower construction, component installation, commissioning and testing.

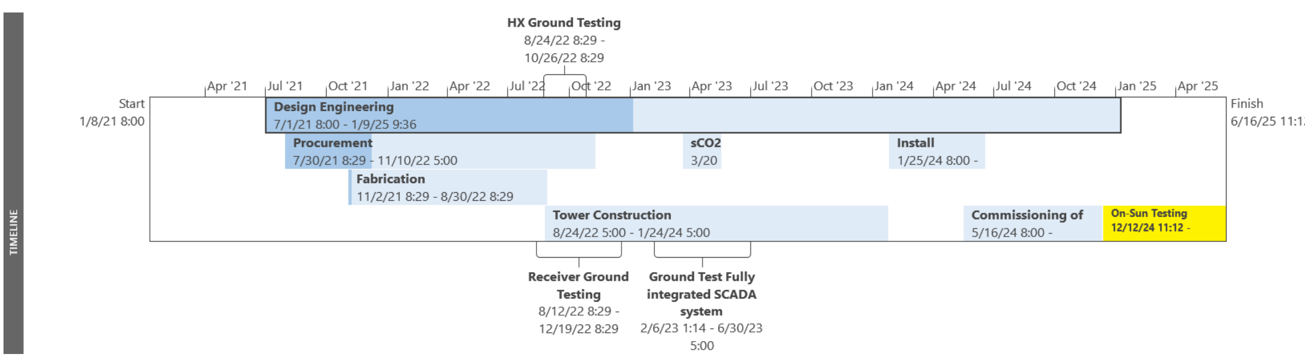

Figure 7. Timeline for G3P3 Phase 3

3.2.1. Schedule Management Plan

Key milestones will be carefully managed to ensure the maximum amount of available on-sun test time. Tower construction is the largest task and hiring of the contractor as quickly as possible is the most important step. Contractors with the shortest quoted durations may be given preference. Efforts must be made to get the final inspections and approvals as soon as the tower is complete. Efforts must be made to sequence the lifting, setting, installation, and insulation of the CSP equipment with minimal lag.

This PEP does not govern the sequence or details of the tower construction. An 18 month path toward tower completion has been professionally estimated and ±20% durations are used in the best/worst case scenarios above.

Critical Path

The schedule will be planned by estimating all task durations in the Work Breakdown Structure and assigning dependencies and resources to identify the critical path. Tower construction is assumed to be 18 months followed by 6 months of CSP component installation and commissioning of the system, leaving 6 months of system and component test time. It is assumed that G3P3 will have priority consideration when it comes to use of the NSTTF facility. It is assumed that 66% of work days will exhibit weather conditions adequate for at least 6 hours of on-sun testing. This amounts to ~1000 hours available for on-sun testing. In addition, several project objectives can be met from deferred thermal storage, auxiliary heating, and off-sun.

Schedule Monitoring and Reporting

The schedule will be monitored continuously through routine meetings and communications at the individual and sub-team level. Progress toward a task will be asserted by each task owner at regular intervals to be assigned based on project priorities along with detailed presentations of progress quarterly to all stakeholders. Gantt chart and schedule management software tools including *MS Project* and *Visio* will be used to illustrate progress and communicate schedule requirements to staff and stakeholders. A copy of the full project schedule will be located and maintained in a Sandia collaborative folder accessible to SNL personnel.

Preventing Schedule Deviation

To prevent schedule deviations severe enough to impact budget or scope, the following procedures will be followed. In the event of unplanned events or schedule variance that is substantial enough to begin to impact the critical path, the project manager, PI, and owner of the affected task will meet to evaluate the impact to project and release an update to all stakeholders of the impact along with a short list of options and solutions to catch up. In the event that the schedule slip is due to overloaded resources, leadership may look carefully at the deliverable to make sure it does not exceed required scope for the project. Resource leveling will be considered along with additional hiring depending on the circumstance.

Preliminary activities to procure a general contractor that must be performed prior to the funds post date in order to minimize lag time are as follows.

- All permits completed and approved in Phase 2
- Engineer-Stamped Drawings issued in Phase 2
- Request for Interest issued and discussions with potential contractors commence

During the tower construction the following activities must be performed concurrently in order to ensure minimal time lag:

- Components are procured, received, and assembled into steel frames ready to lift
- Component sensors, or sensor ports are installed prior to lift unless there is a risk of damage
- Component and system data acquisition system is connected to component cRIOs to verify functionality and nominal readings

- System controls are simulated
- Storage bin is welded at grade (storage refractory installation is not a critical path item).

3.3. Cost Baseline

G3P3 will be funded from the Phase 3 award of $25M. Figure 38 shows the planned cash flow diagram with an expected cumulative total spending of $23.0 million and a pessimistic estimate designed to accumulate $25 million in costs. The bars represent the amount of spending per quarter beginning in January 2021. Figure 38 assumes an announcement date in April 2021 followed by spending on procurements and in-house fabrication of some components. Spending increases during tower construction and purchasing and is assumed to be pro-rated over an 18 month build.

Labor rates are estimated based on actual charges made during Phases 1 and 2 of G3P3 and the building, commissioning, and testing of the SuNLaMP and FPR module. During the tower construction period, R&D and Technologist labor is expected to decrease to about 50% of the phase 1-2 levels. Once the tower is constructed component installation and commissioning will cause an increase in in-house labor charges to 100% of Phase 1 and 2 and are expected to level off in April of 2023 once routine system testing is underway.

Cost information was determined for tower construction by a professional estimator based on the 90% complete tower design. Costs include materials, labor, and work conditions specific to the NSTTF. All contractor costs that involve on-site construction include 15% corporate tax plus a 2% bond fee, a 2.76% escalation rate to Q4 in FY21, and a IO management fee that pays for the interactions and project management services of the Facilities and Operations Management of SNL. The estimate uses a 3-part PERT method to calculate the expected costs where uncertainty is captured as “expected,” “optimistic,” and “pessimistic.” Optimistic costs are -5% and pessimistic are +15% for the 90% complete design. The same approach was applied to the component set and lift procedures and the storage bin refractory installation and assembly with -15% and +30% adjustments for the optimistic and pessimistic costs respectively. Additional uncertainties were captured as follows: Budgetary estimates obtained from contractors or sales consultants ± 15%, items built in-house -5% +20%, commercially available items found by online search ±5%, parametric estimates (ducts, valves) ±20%, quotes from vendors -0% +5%, labor ±5% FTE.

The parametric approach was used to estimate the duct lines and valves. A representative section was professionally estimated and the cost was multiplied by the number and length of the remaining duct lines. Similarly, quotes from machinists to fabricate and assemble the valves were obtained for a representative valve and the cost was assumed for all other valves of similar size and complexity.

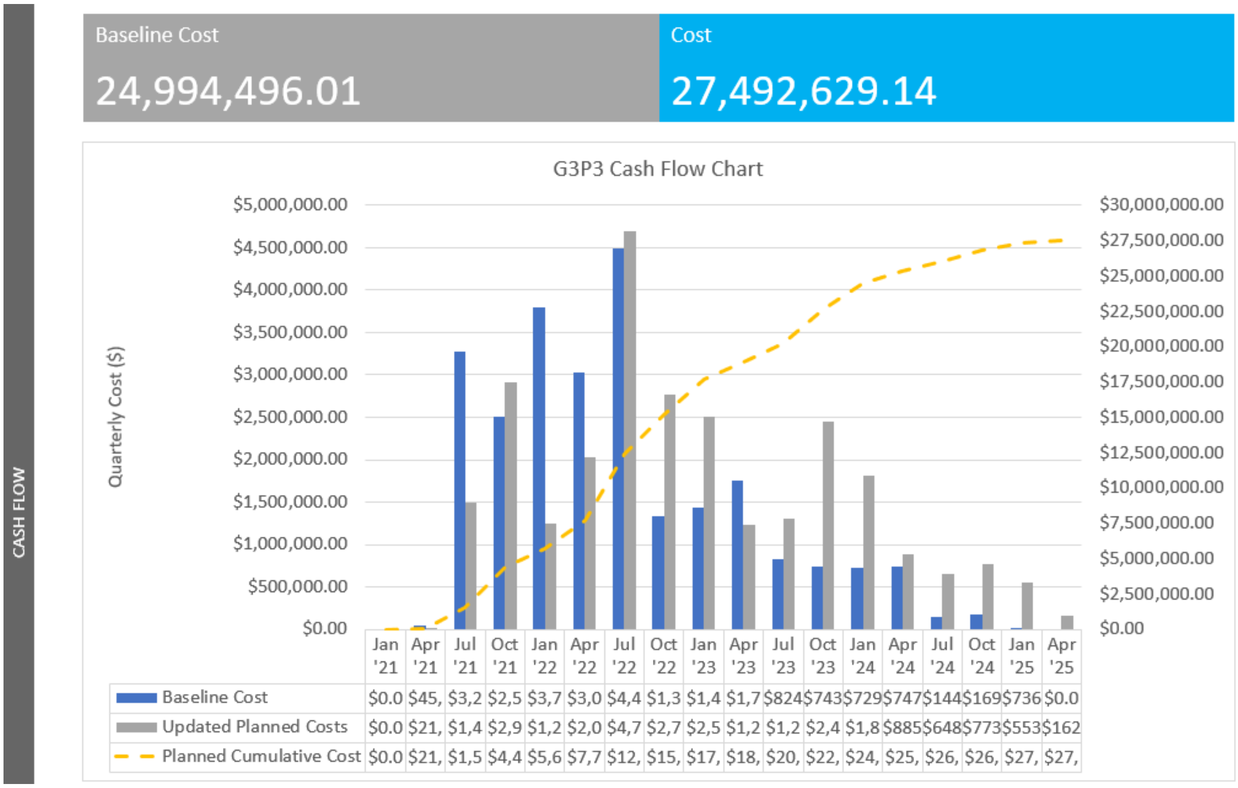

Figure 8. Planned Spending Over 3 Year Project

4. PROCUREMENT MANAGEMENT PLAN

Component and systems leads shall identify each part and material needed for fabrication. The following categories of procurements will be managed as follows:

- **Prototype equipment** developed by partners during phase 1 and 2 may receive sole source justification as the technologies are under patent and do not exist anywhere else. Such items will be designed and costed during phases 1 and 2 and will be procured as soon as funds post in the event that G3P3 is awarded the phase 3 contract. These items include the following:
  - Heat Exchanger (Solex, VPE)
  - Bucket Lift (MHE)
  - Pre-cast molded refractory parts (Allied Mineral Products)
  - Data Acquisition Hardware (National Instruments)
  - Particles (CARBO)

  These items will have a quality level of 3 and will require documented inspection upon receipt.

- **Custom hardware** will be defined as items that must be custom made but do not necessarily constitute a patented prototype technology. These items do not qualify for a sole-source justification and will be open to multiple vendors through a bidding processes facilitated by the Manufacturing Liaison (ML) at SNL. Component designers will produce detailed drawings of all parts requiring custom fabrication and submit them to the ML who will request quotes from available reputable vendors. The design team will have the opportunity to review the quotes and accept or reject the offers on the criteria of cost and schedule. The design team may redesign parts when necessary to reduce costs or lead time. Items in this category include:
  - Valves
  - Slide gates
  - Filters
  - Storage Bin Structural Components

  These items will have a quality level of 3 and will require documented inspection upon receipt.

- **Commercial Off-the-shelf (COTS)** procurements will be defined as component and system parts that were designed for an existing part. All such items will be bundled into procurement packages for each required vendor. For items costing more than $20,000 SNL's Purchasing Department will be tasked with developing a purchase order and determining whether the cost is justified and whether multiple offers need to be solicited. Items less than $20,000 do not need sole-source justification and may be coordinated by an SPA.
  - Chillers
  - Blowers

  - sCO_2 Loop Components
  - Calibration Equipment
  - Sensors and instrumentation

  These items will have a quality level of 3 and will require documented inspection upon receipt.

- **Raw Material** procurements will be defined as material procurements intended to be fabricated on site. Component and systems design leads will perform an analysis of the quantity of raw material required for each item to be built in-house. These quantities will be organized and bundled into procurements packages per each required vendor. Upon receiving the raw materials, the quantities and definitions will be verified. Raw materials will then be sorted and divided as necessary into the work zone location for unambiguous use in the fabrication of multiple parts. Each material will be marked or tagged with the identity of the intended component in which it is to be applied. Examples of raw materials include:
  - Steel
    - Sheet
    - Bar
    - Channel
    - Plate
  - RSLE board
  - Fixtures
  - Tubing
  - Pipe
  - Unistrut
- **Tooling** procurements will be led by the electromechanical technicians responsible for building the components. Each workstation shall be stocked with a complete set of common hand and electric tools with replacement parts for limited life components such as bits, abrasion devices, and safety PPE. The complete design package in phase 1 and 2 will identify specialty tooling required and such tooling will be bundled into procurement packages divided by vendor. Tooling items include:
  - 5 Independent Work Stations provided by site funds
    - 5 independent tool sets with the basic items like wrenches, drivers, pliers, etc.
  - Specialty tools provided by site funds
    - Lathes, Mills, Drill presses, Saws, etc.
  - Heavy equipment provided by site funds
    - Fork Lift, Boom Lift, etc.
  - Personal Protective Equipment (PPE) provided by site funds
    - Eye protection, Helmets, Gloves, Suits, Shoes, Harnesses, etc

5. QUALITY MANAGEMENT PLAN

Quality will be managed per building code with required inspection points such as break tests for cast concrete and weld tests. All inspection and certifications will be under the purview of the construction manager. The tower drawings will be certified by a professional engineer.

CSP components will be designed by the project staff and with project partners. Part and system models will be delivered to specialists for conversion to manufacturing and assembly drawings to be disseminated to potential vendors through the SNL manufacturing liaison office who will ensure suppliers conform to the quality standards of SNL and that outgoing drawings from the project team meet criteria. Vendors who are part of the design process may render drawings in house.

All items will be inspected per corporate practice ISCM001.2 upon receipt to ensure orders are complete and have not been damaged in shipping. Quality level designations are used to specify the rigor of the inspection process.

Component design leads will designate critical inspection criteria for any features that are necessary to guarantee the form, fit, or function of the component or system on the detailed design drawings. These critical inspection criteria must be inspected upon receipt and/or following installation as appropriate.

5.1. Data Management Plan

Data quality will be the shared responsibility of the entire R&D team who will review data after each major test and periodically. Data will be inspected for drift (values changing unexpectedly), sensor failures, or data that does not match expectations. Prior to testing, all channels will be reviewed to ensure quality readings are obtained and recorded for each channel. Technicians will be at the tower and will communicate on a pre-test inspection protocol similar to the current procedure at the NSTTF solar tower.

The elements for a data management plan (DMP) are informed by the Department of Energy Office of Science. The data management plan shall be included in the G3P3 Test Plan document.

5.2. Design Philosophy

G3P3 is a unique prototype system that includes elements which rely on industry codes and standards such as the truss tower, in addition to several particle-based CSP components with design features that have never been attempted before within the current field of knowledge. In the case that an unforeseen event causes a change to the project plan, the resolution will be prioritized as follows:

1. Safety
2. Cost
3. Schedule
4. Performance

For tower elements of the design which have precedence, the design is to comply with industry best practices, computational modeling, civil codes, and standards, and must acquire all necessary permits, and pass all applicable inspections and evaluations.

For elements of the G3P3 system that are novel, all design analysis will be conducted to the highest rigor possible to ensure the highest likelihood of successful performance, structural integrity, and safety. Design for novel components will include high factors of safety, where applicable, to hedge against modeling uncertainty. Efforts will be made to improve manufacturability, ease of assembly, and lower costs. However, optimizing these attributes may not be necessary as only a single prototype will be produced and the savings at scale may not materialize in this context. Design decisions must consider failure analysis. Any feature that could fail catastrophically causing grave impacts to the project plan or safety hazards should be accompanied by an engineered control to mitigate the extent of the impact. The failure modes and effects analysis (FMEA) will inform the need and priority for such design features.

6. ENVIRONMENTAL SAFETY AND HEALTH PLAN

The environmental safety and health (ES&H) plan complies with MN471022, ES&H Manual for work planning and control criteria for safe design an operations. This plan is organized around the philosophy of *Safe by Design Intent*. There are five focus categories:

- Define Scope
- Analyze Hazards
- Control Hazards
- Prepare to Perform Work
- Feedback and Improve

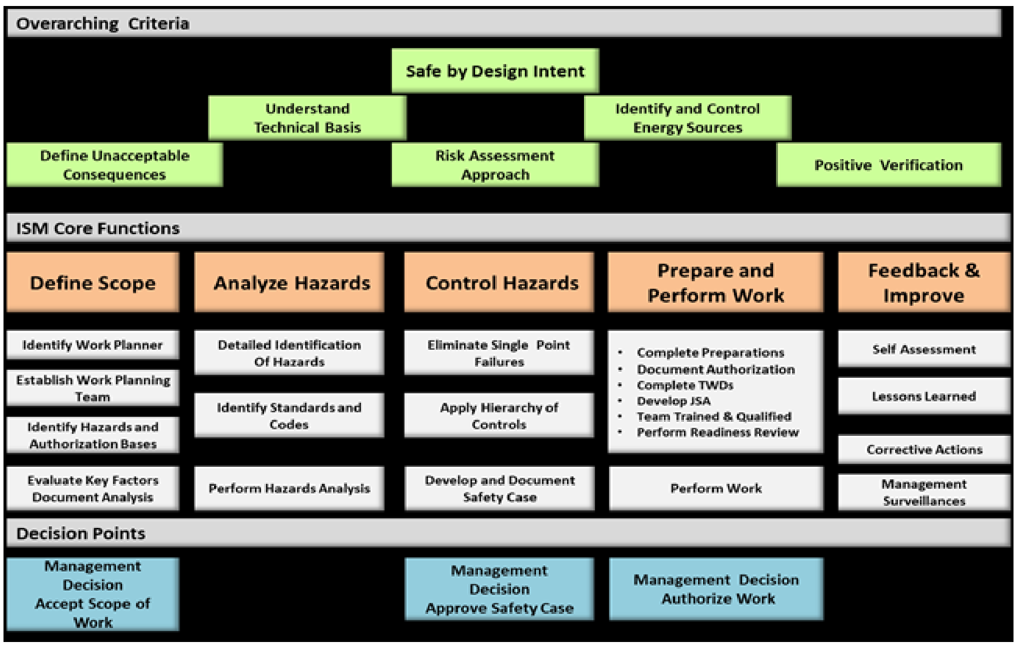

Figure 9: Integrated Safety Management Core Functions

6.1. Permit, Codes, and Standards Compliance Matrix

G3P3 NEPA and AF813 (DOD NEPA) have been approved. The approval provided by the completed NEPA checklists to perform the proposed activities requires meeting all stated permits and other requirements of the NEPA checklist, all applicable ES&H requirements, including, but not limited to those in the SNL ES&H Manual, MN471022, and all applicable requirements within the Sandia National Laboratory Policy System. Relevant building codes for the construction of the tower are provided in the 90% Design Review documentation submitted by Bridgers and Paxton.

6.1.1. Sandia National Labs (SNL) Requirement(s)

- Air Requirements: A Fugitive Dust Control Permit is required prior to commencement of active operations. Air Quality Control personnel would contact the project manager to begin the application process.
- Stormwater Requirements: National Pollution Elimination Discharge System (NPDES) Construction General Permit (CGP) coverage would be required for this project.
- Wastewater Requirements: An internal discharge approval would be required for discharges to the sanitary sewer of closed loop process water.
- Biological Requirements: Implementation of standby aiming strategies that reduce avian hazardous exposure times. Bio Survey required three weeks in advance of start date of outdoor activities during the breeding season (March 1- September 15). Open trench/excavation mitigation. Notification of any bird mortalities to the Ecology Program.

6.1.2. DOE/DOD Requirement(s)

- Geotechnical Analysis: Ensure this tower can take a shaking from the nearby explosive ranges and conduct a geotechnical analysis. This factor is incorporated into the design and recommendations associated with the project Geotechnical Report (9980 G3P3 2072724) which was conducted by Wood Environmental & Infrastructure Services on October 18th, 2019. Results of this analysis indicate a Seismic Site Class C building recommendation in accordance with IBC2015.
- Proposed tower structure construction area overlaps MMRP site AL120e. AL120e is a former Proximity Fuse Range. Contractor needs to understand that encountering subsurface munitions could be expected and this work requires UXO clearance prior to any soil disturbance.
- Digging Holes/Trenching: Potential exists for reptiles/amphibians/small mammals dropping into holes/trenching projects and becoming trapped. Holes require covers and trenches require ramps at no more than 45 degrees so that trapped animals may exit the hole/trench. Dig Permit required prior to excavation.
- Construction Crane will need to be vetted with FAA - use FAA Form 7460.
- DD332 (Base Civil Engineering Work Request): This form primarily exists as a means of coordinating SNL Facilities Engineering Project support with that of Kirtland Air Force Base (KAFB). The form is essentially a tag up with KAFB to make sure all appropriate construction permits, and requirements are fulfilled for both SNL & DOD purposes.

6.1.3. Federal Aviation Administration (FAA)

- The Federal Aviation Administration has conducted an aeronautical study (2019-ASW-16603-OE) under the provisions of 49 U.S.C., Section 44718 and if applicable Title 14 of the Code of Federal Regulations, part 77, concerning:
  - Structure: Solar Tower G3P3 Tower
  - Location: Albuquerque, NM

    - Latitude: 34-57-44.30N NAD 83
    - Longitude: 106-30-36.30W
    - Heights: 5593 feet site elevation (SE)
    - 172 feet above ground level (AGL)
    - 5765 feet above mean sea level (AMSL)
- This aeronautical study revealed that the structure does not exceed obstruction standards and would not be a hazard to air navigation. Based on this evaluation, marking and lighting are not necessary for aviation safety. However, marking/lighting will be accomplished on a voluntary basis and installed in accordance with FAA Advisory circular 70/7460-1 L Change 2.

6.1.4. SNL Health & Safety (Primary Hazard Screening)

Summary of the analysis conducted by SNL/DOE regarding the question of a second means of egress on the proposed G3P3 Tower and applicability of a formal FHA / Life Safety Code Analysis.

- 2016 International Building Code: There is no classification within the IBC for a tower to the design specs for G3P3. In Chapter 31 Special Construction, where structures like telecommunication and broadcast towers are addressed, there are no egress provisions for these structures. Nor does this structure meet the building definition requirements of DOE-STD-1066-2016 Fire Protection Standards.
- 2018 NFPA 101 Life Safety Code: Section 11.3 specifically addresses life safety code requirements for towers. The means of egress section for towers only requires a single exit and allows for only a fire escape ladder provided that the tower is designed for an occupancy of not more than 3 persons. Subsequently, the code waives several requirements for towers where the escape ladders are permitted. The code does require the tower to be noncombustible. Construction materials, and specific heat shielding panels, have been / or will be specified to address the noncombustible design requirements and unique conditions around the Tower receiver during on sun testing.
- Transformer Fire Barrier Wall: Per Sandia's Standard for Transformer Fire Barrier Walls (WP3003STD.DGN) A 6' high wall is specified for 18.7' distance from a building (although the Tower does not meet the building definition, this will be adopted to address issues with egress in the event of a transformer fire near the stairway entrance/exit). B&P to specify the 6' wall to face away from the tower and path of egress.
- Special Hazards: Per SNL's Work Planning & Controls (WPC) requirements, an FMEA (Failure Modes Effects Analysis) will be conducted (in progress) and internal test related procedures will be established to address hazards associated with this Tower structure for both off and on sun testing. FMEA on component level systems within the G3P3 Tower and initial construction considerations have been completed. Reconciliation with other aspects of the G3P3 Tower is ongoing and will continue to be reviewed until the design package is 100% complete.

Based on the internal review of the above referenced requirements; a second means of egress on the proposed G3P3 Tower is not required, nor would a formal contracted FHA / Life Safety Code review be required, or value added.

6.1.5. G3P3 Phase 3 FMEA

A detailed Failure Modes and Effects Analysis (FMEA) was performed for the G3P3 Phase 3 activities. The work elements were separated into four categories: (1) Test Component/Work Package, (2) Construction/Facilities/O&M, (3) Environmental & Natural Hazards, and (4) Personnel. The Test Component/Work Package category considers failures in the major components of the G3P3 system (receiver, storage bins, heat exchanger, particle lift, ducting/piping, electrical systems, and heliostats (sCO2 loop has its own separate FMEA managed in a separate work package by M. Carlson). The Construction/Facilities/O&M category includes failures in the tower structure, foundation, electrical systems, welding and construction, and heavy machinery. Environmental & Natural Hazards include failures and hazards due to wind, earthquakes, lightning, and wildlife. Finally, the Personnel category considers fatigue, stress, and other human errors.

For each category, meetings were held with a variety of staff, subject matter experts, technologists, and manager. For each possible failure or hazard, a risk priority rating was determined, along with engineered and administrative controls. Personal protective equipment (PPE) was also identified. Prior to work commencing, the FMEA and all recommended controls will be reviewed and implemented, as appropriate. Details of the FMEA can be found in Appendix E of Ho et al (2021) [9].

7. PROJECT COMPLETION PLAN

Technical documentation will be released throughout all phases of the G3P3 project that addresses the milestones and technical de-risking activities via conference proceedings, journal articles, and internal reports to the SETO. Upon project completion, a closeout report will be released to the SETO office and an end of project review will be held to present the major findings. Lessons learned will be documented as part of the closeout report and per Sandia policy CA001 will be entered into the Sandia corporate Lessons Learned archive. Closeout activities are assigned tasks in the WBS to ensure sufficient budget and resources are available.

A closeout team comprised of NSTTF staff will be established to develop closeout requirements in the final quarter of the Phase 3 project. The scope of the closeout considerations should include but is not limited to the following:

- Defining the Scope, Schedule, and Budget for closeout activities
- Safety assessment of structure and components
- Permanent data archive and accessibility procedures
- Documentation archive and accessibility procedures
- Criteria for evaluating the feasibility and requirements for continuing operations beyond the G3P3 Phase 3 scope
- Subsequent project proposals
- Presentation and information materials (posters etc.) for tours and visitors

The G3P3 project is strictly a technology demonstration investment. Actual production or operation is not the motivation for the project. Per DOE FMH Chapter 10 Attachment 10-1, the useful life for towers is 25 years; however, G3P3's current useful life is expected to be less than seven years. Since the current expectation is significantly less than the timeframe listed in the DOE FMH Chapter 10, Sandia has determined that this would qualify as a limited useful life.

To further confirm this, Sandia verified scope and intent with the program. After consulting with DOE Solar Energy Technologies Office, they confirmed there is an existing scope of work with Sandia to fund the operations and maintenance of the National Solar Thermal Test Facility, where the G3P3 tower will reside, including construction and decommissioning of programmatic equipment. The life cycle and decommissioning of the G3P3 tower, when it becomes necessary, will fall under this existing scope of work.

If a decision is made to continue or extend/alter the use of the tower, the characterization should and will be revisited.

8. REFERENCES

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