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TFR-2575 MARVEL Power Generation System (PGS)

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Changing the World's Energy Future

Brandon L Moon

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Technical and Functional Requirements

MARVEL Power Generation System (PGS)

Idaho National Laboratory

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CONTENTS

1. INTRODUCTION

1.1 System Identification

This document contains the Level 3 requirements associated with the two subsystems of the Power Generation System (PGS) in the Microreactor Applications Research Validation and Evaluation (MARVEL) project:

- Electrical Production Subsystem (EPS)
- Engine Cooling Subsystem (ECS)

These subsystems interface directly with subsystems in the MARVEL Reactor Structure (MRS) to receive thermal energy and convert it to electrical power. Communication with subsystems in the Instrumentation and Control System (ICS) ensures that the reactor and power generation equipment perform cohesively.

1.2 Limitations of the T&FR

Safety classifications are pending the issuance of the MARVEL Preliminary Documented Safety Analysis (PDSA)

1.3 Ownership of the T&FR

The TREAT Engineering Manager is the owner of this T&FR. The current Cognizant System Engineer for the MARVEL Power Generation System is responsible for the overall development and maintenance of the T&FR.

1.4 Definitions/Glossary

High-Grade Heat	Process heat typically > 400°C
Low-Grade Heat	Process heat typically <100°C
Net Electrical Power	Electrical power that has been conditioned from its gross output form to meet the necessary parameters of downstream users.

1.5 Acronyms

ALARA	As Low As Reasonably Achievable
CAN	Controller Area Network
COR	Code of Record
ECAR	Engineering, Calculation, and Analysis Report
ECS	Engine Cooling Subsystem
EPS	Electrical Production Subsystem
FCS	Fuel and Core System
HFP	Hot Full Power
HRU	Heat Rejection Unit
ICS	Instrumentation and Control System
I&C	Instrumentation and Control
MARVEL	Microreactor Applications Research Validation and Evaluation
MRS	MARVEL Reactor Structure
NSR	Non-Safety Related
NSR-AR	Non-Safety Related with Augmented Requirements
PDSA	Preliminary Documented Safety Analysis
PGS	Power Generation System
SCS	Secondary Coolant Subsystem
SDD	System Design Description
SOS	Secondary Output Structure
SR	Safety Related
SSCs	Structures, Systems, and Components
TREAT	Transient Reactor Test Facility
T-REXC	TREAT Facility Micro-Reactor Experiment Cell
UPS	Uninterruptible Power Supply

2. GENERAL OVERVIEW

2.1 System Functions

2.1.1 EPS Functions

The subsystem performs the following functions. Each function is traceable to the functional requirements in Section 3.

EPS.1: Absorb High-Grade Heat from Secondary Coolant

EPS.2: Convert Low-Grade Heat into Gross AC Power

EPS.3: Transfer Gross AC Power for Conditioning

EPS.4: Condition Power as Needed

EPS.5: Deliver Net Electrical Power to User Load

EPS.6: Convert Excess Gross Electricity to Thermal Energy

EPS.7: Start Engine

EPS.8: Control Engine Output

EPS.9: Stop Engine

The following diagram clarifies the functions performed by the subsystem in sequential fashion. Functions highlighted in red are those that are Safety-Related (SR) per the MARVEL safety basis. Functions highlighted in orange are those that are Non-Safety-Related with Augmented Requirements (NSR-AR). Other Non-Safety Related (NSR) functions are not colored. The classification of these functions is derived from ECAR-6440.

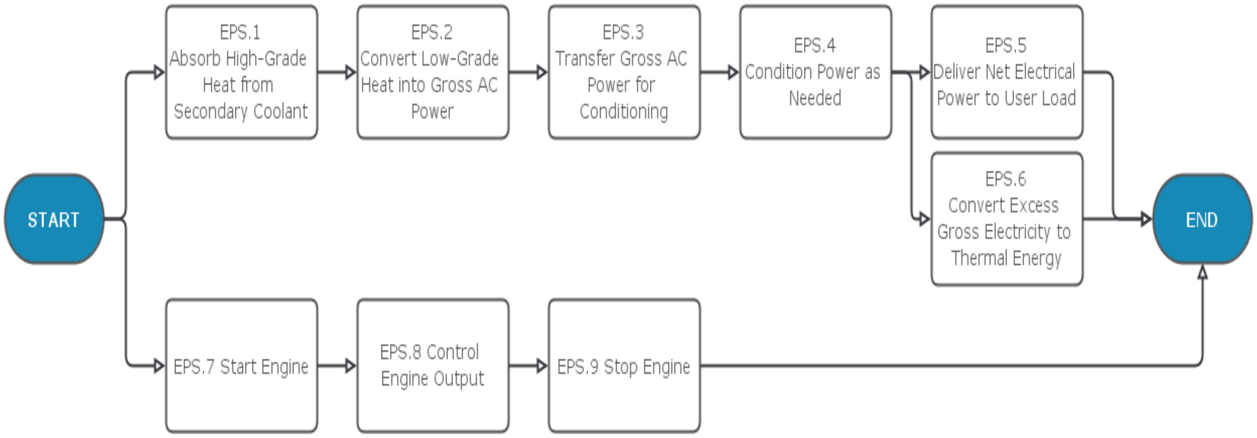

Figure 1. Electrical Production Subsystem Functional Diagram.

2.1.2 ECS Functions

The subsystem performs the following functions. Each function is traceable to the functional requirements in Section 3.

ECS.1: Extract Low-Grade Heat from Engine

ECS.2: Extract Excess Heat from Engine Controller

ECS.3: Reject Heat to Ambient Environment

ECS.4: Measure Engine Cooling Loop Temperature

ECS.5: Measure Engine Cooling Loop Flow

ECS.6: Measure Engine Cooling Loop Coolant Level

ECS.7: Transmit Engine Cooling Parameters to Control System

The following diagram clarifies the functions performed by the subsystem in sequential fashion. Functions highlighted in red are those that are Safety-Related (SR) per the MARVEL safety basis. Functions highlighted in orange are those that are Non-Safety-Related with Augmented Requirements (NSR-AR). Other Non-Safety Related (NSR) functions are not colored. The classification of these functions is derived from ECAR-6440.

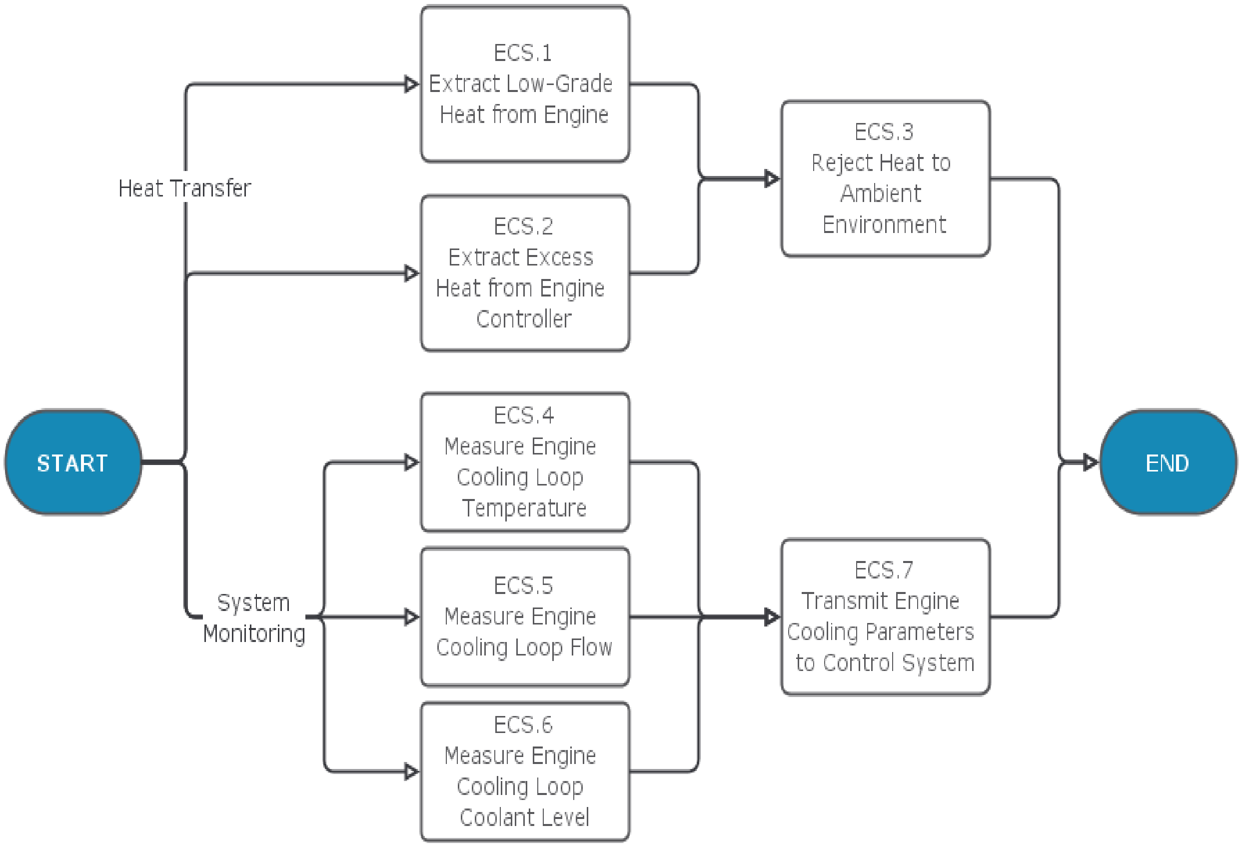

Figure 2. Engine Cooling Subsystem Functional Diagram.

2.2 System Classification

The table below provides the classifications for the subsystems of the PGS based on the highest ranking (most important) requirements identified for the subsystems. Note that this classification is pending issuance of the project Preliminary Documented Safety Analysis (PDSA).

Table 1. PGS Subsystem Classifications.

Acronym	Subsystem	Classification
EPS	Electrical Production Subsystem	Non-Safety Related (NSR)
ECS	Engine Cooling Subsystem	NSR

2.3 Basic Operational Overview

The following diagram shows the overall system architecture of the PGS and how each of the subsystems (in blue) interface. Grey boxes surrounding the system boundary represent interfacing subsystems not within the scope of the PGS. Red lines represent thermal interfaces, orange lines represent electrical interfaces, teal lines represent instrumentation and control (I&C) interfaces, and black lines represent important mechanical or structural interfaces. The PGS subsystems are described in more detail in the following subsections.

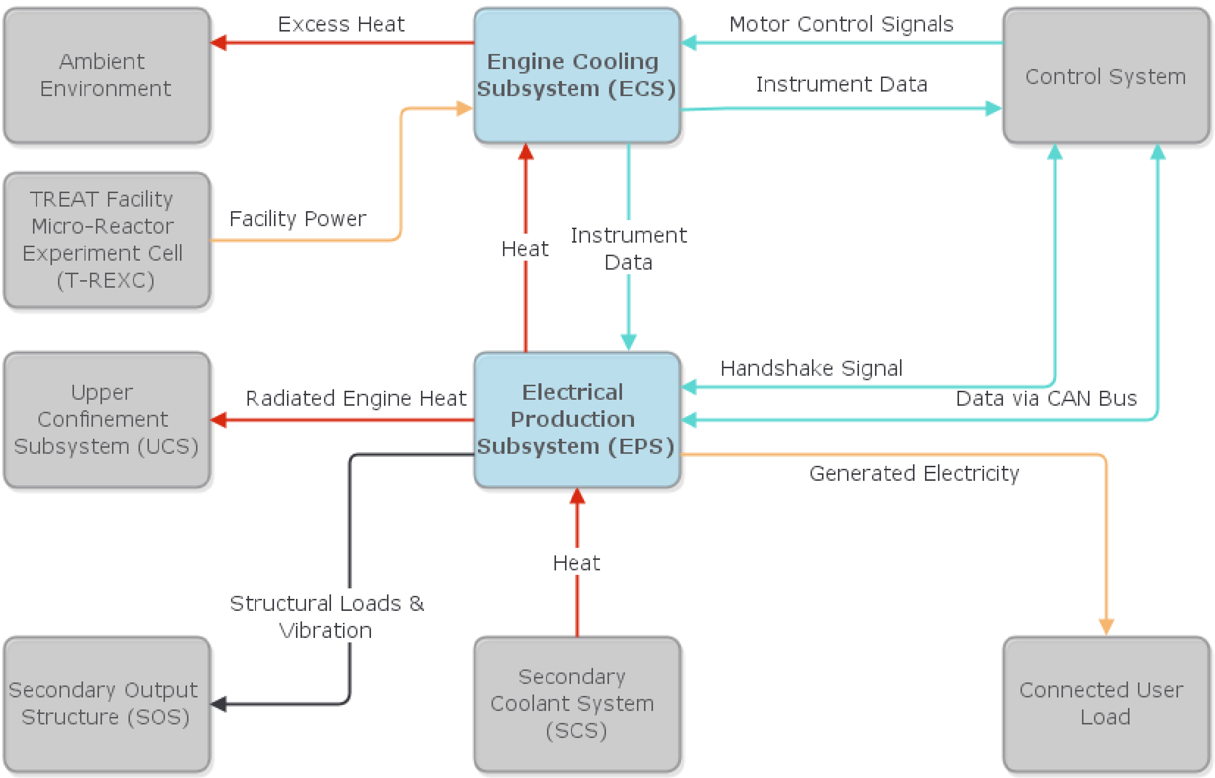

Figure 3. Power Generation System Architecture and Interfaces.

2.3.1 EPS Basic Operational Overview

The EPS consists of the Stirling engines and their associated engine controllers. The engines absorb high-grade heat from the Secondary Coolant Subsystem (SCS) media through passive conduction when not actively operational due to the natural circulation of the primary and secondary coolants. Once activated via a DC impulse, the engines extract additional heat that is absorbed into the closed power cycle of the engines. This heat is converted first into pressure variation within the working media, then into sympathetic, concurrent motion of the resonant internal components, and finally into either of low-grade heat from the power cycle or gross electric AC power delivered to the engine controllers. Low-grade heat is removed by actively circulating engine cooling loops. The engines are mounted to the Secondary Output

Structure (SOS) which is designed to dampen the vibration caused by the inertial force of the engines.

Gross electrical power produced in the engine is then conditioned by the engine controller according to the unique user loads present. The engine controller is also capable of modulating the engine in order to dynamically follow end user loads. Any excess gross electricity is converted back into thermal energy and removed by the ECS. The engine controller also serves as the primary communication mechanism between the engine and the control system using controller area network (CAN) bus protocols and an e-stop "handshake" signal. The CAN bus interface is used to command the power generation equipment from the control system and to report back engine and conditioned electrical output parameters. The bi-directional e-stop is used to sync operational readiness between the PGS and the control system. The signal from the engine controller to the control system confirms that the engine has passed all pre-operational health checks and that the engine is operating as expected. The signal from the control system to the engine controller confirms that the reactor subsystems are ready for active heat extraction from the secondary coolant.

2.3.2 ECS Basic Operational Overview

Independent engine cooling loops circulate a coolant through each set of engine and engine controller to remove excess heat from the power generation process. These inner coolant loops, fully located within the TREAT Facility, then transfer heat to outer loops that reject heat to the ambient environment outside the TREAT Facility building envelope. Control of the engine coolant loops is performed by the control system, which provides the ability to modulate the pump and heat rejection unit (HRU) motor speeds. Select data from the inner cooling loops is provided to the engine controller to support the health checks prior to engine start up. All instrument data is provided to the control system.

3. REQUIREMENTS AND BASES

3.1 Requirements

This section provides the requirements that must be met in the system design and will require design verification. The MARVEL project requirements are stored in the IBM DOORS Next software tool. This software was used to generate this document. Therefore, each requirement has a unique number in brackets [ ] to the left of the requirement used to identify the requirement in the database and to provide a hyperlink back to the software. Each requirement also includes a bolded title summarizing the concept and a rationale statement in italics explaining where the requirement comes from or why it provides value. Finally, the links within the requirements database showing how requirements relate to one another are displayed beneath the rationale. The Level 3 requirements in this document are derived from the Level 2 requirements contained in FOR-868, "Microreactor Applications Research Validation and Evaluation (MARVEL) Project," and FOR-684, "Transient Reactor Test (TREAT) Facility Micro-Reactor Experiment Cell (T-REXC)" The calculational and design documents that verify that these requirements have been met by the design are listed in VM-118 "MARVEL Design Verification Matrix."

3.2 Bases

Each requirement in this document is followed by a "rationale" statement which explains why the requirement exists, why it is specified in a particular manner, and why it has particular value.

3.3 References

See Appendix A for a complete list of references and source documents.

3.4 General Requirements

3.4.1 System Functional Requirements

3.4.1.1 EPS Functional Requirements

[109176] Active Heat Extraction from Secondary Coolant: Each engine shall be capable of extracting at least 20.45 kWth of heat from the secondary coolant when the reactor is operating at hot full power (HFP).

Rationale: The nominal thermal output of the Fuel and Core System (FCS) is expected to be around 85kWth during HFP conditions. However, approximately 3.2 kWth of heat loss is anticipated through other pathways in the MRS per ECAR-6332.

Derived By: [105349] Heat Extraction from Reactor

Linked From: SCS.2, EPS.1

[109177] Gross Electrical Production Efficiency: Each engine shall be capable of producing at least 1 kWe of gross electrical power at HFP conditions.

Rationale: A certain efficiency standard is required of the engines to ensure generated heat is not wasted and the MARVEL mission is viable.

Derived By: [105350] Electricity Generation

Linked From: EPS.2

[109178] Gross Electrical Power Transfer: The engines shall transfer all gross electrical power to the engine controllers.

Rationale: The engine controllers are responsible for conditioning the gross power to meet the unique user load requirements.

Derived By: [105350] Electricity Generation

Linked From: EPS.3

[109179] User Load Matching: The engine controllers shall be capable of matching net electrical power output to the demand of the connected user load.

Rationale: The engine controllers should be able to dynamically follow the connected user load to prevent constant operator adjustment.

Derived By: [105351] Electrical Supply

Linked From: EPS.4

[109180] Net Electricity Output Types: The engine controllers shall be capable of outputting either AC or DC power to user loads.

Rationale: The selected power conversion equipment should be flexible depending on the connected user load.

Derived By: [105351] Electrical Supply

Linked From: EPS.5

[109181] Excess Electrical Power Shedding: Each engine controller shall be capable of shedding at least 5 kW of excess gross electrical power as heat at HFP conditions.

Rationale: All the electrical production must be able to be dissipated to the ECS for a no-load condition when the reactor is at full power.

Derived By: [105352] Excess Power Rejection

Linked From: EPS.6

[109182] Engine Heat Absorption Control: The engine controllers shall control the amount of heat absorption in the engines during all modes of operation.

Rationale: Power generation equipment will be used to absorb heat from the source.

Derived By: [105349] Heat Extraction from Reactor, [105355] PGS Controls

Linked From: EPS.8

3.4.1.2 ECS Functional Requirements

[109183] Engine Cooling Capacity: Each engine cooling loop shall be capable of extracting at least 20.45 kWth of heat from the corresponding engine when the reactor is operating at HFP.

Rationale: Each engine is capable of extracting 20.45kWth from the SCS. In the event that no power conversion is requested, the engine cooling loop should be able to remove all low-grade heat from the engine.

Derived By: [105352] Excess Power Rejection

Linked From: ECS.1

[109184] Excess Thermal Energy Extraction: Each engine cooling loop shall be capable of extracting at least 5 kWth of heat from the corresponding engine controller.

Rationale: If all the electrical production is shed as excess heat for a no-load condition, then the engine cooling loop should be able to extract the full amount from each train.

Derived By: [105352] Excess Power Rejection

Linked From: ECS.2

[109185] Cooling Loop Heat Rejection: Each engine cooling loop shall be able to reject at least 25kWth to the ambient air under any applicable climate conditions.

Rationale: 25kWth is derived from the total heat absorbed by engines (nominally 20.45kWth) plus heat due to pumps or other components in the loops.

Derived By: [105352] Excess Power Rejection

Linked From: ECS.3

[109186] Engine Cooling Loop Temperature Measurement: The engine cooling system temperature sensors used for measuring the temperature across the engine and/or controller shall be capable of measuring with an uncertainty of less than or equal to +/- 0.4ºC.

Rationale: The temperature across the engines is important input to the overall MARVEL heat balance / calorimetry equation per ECAR-6598.

Derived By: [113991] Power Conversion Monitoring, [105352] Excess Power Rejection, [105355] PGS Controls

Linked From: ECS.4

[109187] Engine Cooling Loop Flow Measurement: The flow meter used for power calibration in the engine cooling system shall have a measurement uncertainty of less than or equal to 1 l/min.

Rationale: The inner cooling loop flow rates are important inputs to the overall MARVEL heat balance / calorimetry equation per ECAR-6598.

Derived By: [113991] Power Conversion Monitoring, [105352] Excess Power Rejection, [105355] PGS Controls

Linked From: ECS.5

3.4.2 Subsystem and Major Components

Subsystem functional requirements are presented in Section 3.4.1. Other subLevel 3 Requirements are found in the following sections.

3.4.3 Boundaries and Interfaces

[109188] Engine Shutdown Receipt: The engine controller shall be capable of shutting the engine down upon receipt of a control signal.

Rationale: The engine shuts down by itself when the heat source is depleted. However, the design should include a way to shut down the engine when requested by the operator at any time.

Derived By: [105355] PGS Controls

Linked From: EPS.9

3.4.4 Code of Record

See the MARVEL Code of Record (COR) for the codes and standards applicable to the project.

[112252] ASME B31.3, “Process Piping,” 2022 Edition.

[112251] ASME B31.9, “Building Services Piping”, 2020 Edition.

3.4.5 Operability

No unique requirements are applicable to this section at this revision.

3.5 Specific Requirements

3.5.1 Radiation and Other Hazards

3.5.2 As Low As Reasonably Achievable [ALARA]

See Section 3.7.3.

3.5.3 Nuclear Criticality Safety

This section does not apply to this system.

3.5.4 Industrial Hazards

[109191] Coolant Loop Pressure Increases: The engine cooling loops shall include a means of limiting pressure to no more than 2.4 bar (34.8 psig).

Rationale: The coolant loops could experience pressure changes due to the amount of heat rejection required or temperature of the coolant. The manufacturer specifies a cooling loop limit of 3 bar. 20% margin is provided for safety.

Derived By: [105353] Power Generation Design for Operating Environment

[109192] Engine Cooling System Water Leakage within Upper Confinement: The engine cooling system shall be designed to prevent leaks within the reactor upper confinement space.

Rationale: Water should not be able to spray on top of the reactor head, as it could come in contact with leaked primary or secondary coolant.

Derived By: [115351] Power Generation Design for Dynamic Effects

[109193] Engine Cooling System Water Leakage into IHX: Accidental leakage of water from the engine cooling loop into the IHX pressure boundary shall (1) be able to be detected and (2) not challenge the PCS pressure boundary.

Rationale: Water will boil when in contact with the hot secondary coolant and produce steam that has the potential to damage structural components. Detection is necessary to allow corrective action to be taken by the operator.

Derived By: [115350] Reactor Structure Design for Dynamic Effects

Linked From: ECS.6

[115358] Engine Cooling System Water Leakage impact to PCS and RCS: Any postulated leakage from the ECS shall not challenge the PCS pressure, nor shall it challenge operation of the RCS components.

Rationale: The PCS and RCS are safety-related systems, so the ECS must be designed to avoid impairing or compromising their safety functions.

Derived By: [115351] Power Generation Design for Dynamic Effects

3.5.5 Operating Environment and Natural Phenomena

[109196] Temperature Environment of Stirling Engines: Portions of the engines in contact with the secondary coolant shall be capable of maintaining their structural integrity at a maximum temperature of 530°C.

Rationale: Equipment must be designed to function in the environment in which it is installed. The secondary coolant is expected to reach 530°C in an unprotected loss of heat sink (ULOHS) scenario where all four engines simultaneously lose their heat removal capability per ECAR-6332.

Derived By: [105353] Power Generation Design for Operating Environment

[109197] Temperature Environment of Power Generation Equipment in TREAT: Power generation SSCs installed on the TREAT Facility operating floor shall be capable of operating in an ambient environment between 0°C and 32°C.

Rationale: Equipment must be designed to function in the environment in which it is installed. The equipment will need to function in the normal TREAT Facility temperature ranges.

Derived By: [105353] Power Generation Design for Operating Environment

[109198] Temperature Environment of Power Generation Equipment Outdoors: Engine cooling equipment installed outside the TREAT Facility building envelope shall be capable of operating at outdoor temperatures between -28°C and 35°C.

Rationale: Equipment must be designed to function in the environment in which it is installed. The equipment will need to function in the temperature ranges experienced at the INL site found in Section 5.1 of STD-139-23 3000.

Derived By: [105353] Power Generation Design for Operating Environment

[115359] Seismic Impact on Safety SSCs: The PGS components shall not affect functions of SR or NSR-AR SSCs during a seismic event.

Rationale: SSCs that impact the functioning of safety-related SSCs during a seismic event must also be classified as safety-related. In order to avoid seismic qualification of the PGS, the system must not impact safety SSCs.

Derived By: [115379] Power Generation System Seismic Design

3.5.6 Human Interface Requirements

No unique requirements are applicable to this section at this revision.

3.5.7 Specific Commitments

No unique requirements are applicable to this section at this revision.

3.6 Engineering Discipline Requirements

3.6.1 Civil and Structural

See TFR-2576, MARVEL Reactor Structure, for structural requirements.

3.6.2 Mechanical and Materials

No unique requirements are applicable to this section at this revision.

3.6.3 Chemical and Process

No unique requirements are applicable to this section at this revision.

3.6.4 Electrical Power

[109202] External Power Connection: The engine controller shall include a means of being powered by an external power supply.

Rationale: The engine control should not rely on the power coming from the engine alone. It requires an external power source to start.

Derived By: [105355] PGS Controls

[109203] Power Output Measurement: The engine controller shall be capable of measuring both gross and net electrical power received and sent from the system.

Rationale: The amount of power produced by the PGS equipment should be able to be measured and recorded to confirm efficiency of the subsystem.

Derived By: [113991] Power Conversion Monitoring, [105351] Electrical Supply

[109204] Uninterruptible Power to Engine Cooling Motors: An uninterruptible power supply (UPS) shall supply 30 minutes-worth of uninterruptible power to the engine cooling system for pumps and fan motors.

Rationale: The engine cooling system requires an electrical power source to provide active engine cooling. This source must on be uninterruptible power to ensure cooling can be provided for a limited time on a loss of power until the TREAT standby power supply kicks on.

Derived By: [105354] Power Generation Availability

[109205] Standby Power to Engine Cooling UPS: The UPS for the engine cooling subsystem shall be provided power by a standby-backed T-REXC power supply.

Rationale: A standby-backed power supply ensures that the UPS can seamlessly transition over to a new power source when available to prevent the batteries from running out and interrupting the power supply to the connected load.

Derived By: [105354] Power Generation Availability

3.6.5 Instrumentation and Control

[109206] CAN Bus Commands: The engine controller shall be capable of receiving and implementing CAN bus commands from the control system.

Rationale: The engine controller and control system communicate via CAN bus protocol. The control system will send start up commands to the engine controller during integrated system startup.

Derived By: [105355] PGS Controls

Linked From: EPS.7

3.6.6 Computer Hardware and Software

No unique requirements are applicable to this section at this revision.

3.6.7 Fire Protection

No unique requirements are applicable to this section at this revision.

3.7 Testing and Maintenance Requirements

3.7.1 Testability

No unique requirements are applicable to this section at this revision.

3.7.2 Inspections, Testing and Surveillances

[109207] Power Generation Health Check: The engine controller shall be capable of performing a diagnostic health check prior to engine startup.

Rationale: The health check ensures that all pre-requisites are met for system operation.

Derived By: [113991] Power Conversion Monitoring, [105356] Power Generation Inspection and Testing

Linked From: ECS.7

3.7.3 Maintenance

[109208] Engine Cooling Loop Filling and Draining: The engine cooling loops shall include a means of filling and draining.

Rationale: Filling and draining is required for startup / commissioning, maintenance and replacement, and eventual decommissioning.

Derived By: [105357] Power Generation Maintenance and Replacement

[109209] Engine Removability: Engine components shall be remotely removable from their installed location on the reactor.

Rationale: This is required for engine maintenance and/or replacing it with high grade heat exchanger. Preliminary activation results indicate that hands-on maintenance will be impractical and remote removal features will be necessary for ALARA considerations.

Derived By: [105357] Power Generation Maintenance and Replacement

3.8 Other Requirements

3.8.1 Security and SNM Protection

This section does not apply to this system.

3.8.2 Response to Alarms

[109210] Engine Health Notification: The engine controller shall be capable of notifying the control system upon detection of an engine health check failure condition.

Rationale: Any engine fault condition should be communicated to the control system so that operators can take corrective action.

Derived By: [113991] Power Conversion Monitoring, [105355] PGS Controls

Linked From: ECS.7

3.8.3 Special Installation Requirements

[109211] Engine Hoisting Compatibility: The engines shall have hoisting provisions that are compatible with the TREAT Facility crane.

Rationale: The engines will be hoisted by the TREAT Facility crane during installation, replacement, and eventual decommissioning.

Derived By: [105357] Power Generation Maintenance and Replacement

3.8.4 Reliability, Availability, and Preferred Failure Modes

[115078] Independent Engine Cooling Loops: The engine cooling loops shall be independent from each other.

Rationale: The cooling loops must be independent to preclude the common failure mode that is not included in the accident analyses.

Derived By: [105352] Excess Power Rejection

3.8.5 Quality Assurance

The INL Quality Assurance Program is applicable to all activities affecting quality including design, procurement, fabrication, construction, receiving, installation, inspection, testing, and operation activities. More specifically, construction QA requirements will be specified on Form 540.10C, Subcontractor Requirements Manual (SRM) Applicability - Construction. Fabrication QA requirements for INL-performed fabrication will be specified on Form 431.55, Fabrication Services Work Request, as well as associated drawings and referenced specifications. Conformance to technical and quality assurance requirements will be verified by in-process inspections during fabrication, construction, and installation activities. Such inspections will be outlined in the applicable specifications, drawings, and procurement documents including the INL forms noted above. Final acceptance of procured and in-house fabricated components will be accomplished as defined by fabrication work control documents (including drawings and instructions) and procurement documents (including statements of work, specifications, and drawings), as applicable. Final acceptance of assembled systems will be verified through acceptance testing.

4. APPENDICES

Appendix A, Source Documents

Appendix B, System Drawings and Lists

Appendix A, Source Documents

FOR-684, "Transient Reactor Test (TREAT) Facility Micro-Reactor Experiment Cell (T-REXC)," Rev. 0, Idaho National Laboratory

FOR-868, "Microreactor Applications Research Validation and Evaluation (MARVEL) Project", Rev. 0, Idaho National Laboratory.

PDD-13000, "Quality Assurance Program Description", Rev. 10, Idaho National Laboratory.

SAR-420-ADD-1, "Addendum to Support the Microreactor Applications Testbed," Rev. 0, Idaho National Laboratory

STD-139-23 3000, "Comfort Heating, Ventilation, and Air Conditioning (HVAC) INL Engineering Standards", Rev. 2, Idaho National Laboratory.

TFR-2576, "MARVEL Reactor Structure (MRS)," Rev. 0, Idaho National Laboratory

Appendix B, System Drawings and Lists

See the Affected Documents List in EC-1757 for a full listing of MARVEL PGS drawings.