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Inertial Fusion Power Plant Concept of Operations and Maintenance

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ABSTRACT

Parsons and LLNL scientists and engineers performed design and engineering work for power plant pre-conceptual designs based on the anticipated laser fusion demonstrations at the National Ignition Facility (NIF). Work included identifying concepts of operations and maintenance (O&M) and associated requirements relevant to fusion power plant systems analysis.

A laser fusion power plant would incorporate a large process and power conversion facility with a laser system and fusion engine serving as the heat source, based in part on some of the systems and technologies advanced at NIF. Process operations would be similar in scope to those used in chemical, oil refinery, and nuclear waste processing facilities, while power conversion operations would be similar to those used in commercial thermal power plants. While some aspects of the tritium fuel cycle can be based on existing technologies, many aspects of a laser fusion power plant presents several important and unique O&M requirements that demand new solutions. For example, onsite recovery of tritium; unique remote material handling systems for use in areas with high radiation, radioactive materials, or high temperatures; a five-year fusion engine target chamber replacement cycle with other annual and multi-year cycles anticipated for major maintenance of other systems, structures, and components (SSC); and unique SSC for fusion target waste recycling streams.

This paper describes fusion power plant O&M concepts and requirements, how O&M requirements could be met in design, and how basic organizational and planning issues can be addressed for a safe, reliable, economic, and feasible fusion power plant.

Keywords: inertial, fusion, laser, engine, power, plant, operations, maintenance

1. INTRODUCTION

Parsons and Lawrence Livermore National Laboratory (LLNL) scientists and engineers developed pre-conceptual design solutions for using the laser based fusion technology being demonstrated at the National Ignition Facility (NIF) to provide power for commercial applications. Concepts of operations and maintenance (O&M) and associated design requirements also were developed for process control and long-term O&M for a power plant using this technology. The precision required for process control and the hazards involved in operating and maintaining systems and components containing tritium and lithium or that are highly activated presents unique O&M challenges. This paper describes O&M concepts and requirements, how these could be met in design, and how basic organizational and planning issues can be addressed to achieve safe, reliable, and economical operation of a fusion power plant.

2. OVERVIEW OF INERTIAL FUSION POWER PLANT CONCEPT

2.1 Plant System Description

The inertial fusion power plant (or 'plant') concepts presented in this paper are based on pre-conceptual design work using a laser inertial fusion process similar to that being demonstrated at the NIF project.[1,2,3] To use the laser fusion technology to achieve continuous power production will require injection of fuel targets (deuterium and tritium pellets) into a Fusion Engine Target Chamber (FETC), and tracking the location of the targets using a Tracking and Beam Reference System (TBRS), and aiming and firing of concentrated laser beams with a Beam Delivery System (BDS). Energy from the fusion products (predominantly neutron energy) heats liquid lithium circulated outside the walls of the fusion chamber. The closed loop lithium cooling system provides both tritium generation from fissioning lithium atoms and heat removal by absorption of the neutron energy from the fusion process and by heat transfer from the fusion chamber wall.

Multiple heat exchangers are used to avoid contact between the lithium cooling system and other cooling systems external to the Fusion Operations Building (FOB). The hot liquid lithium from the FETC cooling coils is circulated through a primary heat exchanger (located in the FOB) where it is cooled by a molten salt cooling system. The cooled lithium is returned to the FETC cooling coils and the hot molten salt is circulated through a tertiary heat exchanger (external to the FOB) which is cooled by a high pressure water system. The high pressure water is circulated through a Steam Generators (SGs) to produce steam to drive a turbine generator(s) (TG). The electrical power is sent to an auxiliary transformer which provides power to drive the laser systems and other plant "hotel" loads and to a main transformer which provides power to a substation connected to a power grid.

A key sustainability feature of the fusion power plant concept is the recycling of the tritium and deuterium fuel. After the target is consumed, the Chamber Gas Handling System (CGHS) recovers tritium and deuterium for recycling to a Tritium Processing / Target Fill (TPTF) building. The chamber pre-conceptual design uses xenon (Xe) as the fill gas. The total tritium inventory onsite is kept at a low level. A potential for breeding relatively large amounts of tritium for use at other plants is a feature of the sustainable nature of fusion power.

The plant pre-conceptual design includes redundant systems and components and design capacity margins to meet a target plant availability of greater than or equal to 92 percent. The plant would be designed to operate continuously except for regularly scheduled outages. Staffing for a commercial inertial fusion power plant would include on-shift personnel for security, O&M, and radiological control, and a day shift contingent of engineers, and quality assurance (QA) and administrative personnel. The total onsite staff required for O&M and other support functions is estimated to be approximately 400.

2.2 Plant Maintenance Cycles

Current pre-conceptual planning anticipates that the FETC at the center of the plant would operate continuously for a 5-year period. The FETC would then be replaced during a scheduled outage that would last 4 to 8 weeks. A spare FETC would be stored onsite in an associated Engine Maintenance Building (EMB). Other system components that require plant shutdown also would be replaced as required during the FETC outage window.

The complexity of the laser and FETC systems and the level of activation and contamination present in equipment located within the shielded area require an O&M concept to replace rather than repair these plant equipment items. Equipment would be designed for ease of removal of a complete module or assembly to limit hands-on exposure and system down time. Considerations such as this significantly re-balance the relative attractiveness of technological options for sub-systems such as the final optics assembly, and all aspects of the chamber environment. Equipment modules or assemblies would be replaced on a rotating cycle based on expected failure rates. For example, the pre-conceptual plant design includes an array of 384 lasers based on an 87.5 percent (7 in 8) reliability model. Assuming a 10,000 hour Mean Time-Between-Failure (MTBF), 8 laser boxes would be scheduled for replacement every week with onsite spares without interrupting the plant operation or causing any loss of net electrical output.

In a similar manner, other primary and secondary systems that support plant operation would be designed and configured based on predictive maintenance intelligence and periodic maintenance programs. Although still in development, some of the key systems that would be optimized for operation and maintenance reliability and overall plant availability include the following: FETC; BDS components; Target Injection System (TIS); lithium system components (note: liquid lithium is the current coolant assumed for the pre-conceptual plant design and O&M concepts, with alternative coolant fluids requiring further study); CGHS components; Tritium Processing Plant (TPP) equipment; Final Optics Assembly (or Final Beam Transport System); and Target Assembly Plant (TAP) equipment.

The following plant maintenance cycles were adopted for illustrative purposes and would be revised and optimized as the detailed design and O&M requirements are further advanced. The inertial fusion power would be specifically designed to provide the necessary component design life, system and component redundancies, and inspectability, modularity, and remote maintenance features to support the following O&M life cycle schedule.

1. Weekly and monthly – Scheduled equipment preventive maintenance, surveillance testing, and module and assembly replacement during plant operation
2. 1-year cycle – Short duration (1 to 2 weeks) outage for inspections, surveillance testing, preventive maintenance, and limited equipment replacement activities that cannot be performed during plant operations
3. 2-year cycle – Limited duration outage for replacement of modular components in the CGHS, TPTF, and lithium loops.
4. 5-year cycle – Long duration outage for FETC replacement
5. 10-year cycle – Major maintenance on the TG and secondary plant systems (concurrent with FETC replacement outage).

Additional details on major plant components and systems are included in the following sections.

3. MANAGEMENT, SAFETY AND TRAINING

3.1 Overall Organizational Structure

Each fusion power plant facility would be staffed with an appropriate number of onsite personnel required for routine operation and maintenance. A central organization would provide overall governance, management, and technical integration to support multiple commercial fusion power plants based on the same technology with similar design and licensing basis and common components, parts, and facilities.

The Central staff would include industrial and nuclear safety, licensing, Engineering, QA, Procurement, Emergency Management, Training, Human Resources, and Administrative personnel. This concept of centralized governance and organizational structure is intended to leverage resources and right-size individual plant O&M staffing requirements.

Each fusion power plant would have an onsite organization consisting of a Plant Manager and Superintendents and craft and non-exempt personnel for Security, Operations, Maintenance, Planning and Scheduling, Radiological Control, Systems Engineers, QA, and Quality Control (QC). On-shift personnel would include a Shift Manager, Control Room and plant Operators, select Maintenance craft, Radiological Control Technicians, a Shift Engineer, and a Shift QA/QC Inspector. The total onsite plant staff is estimated to be 250.

3.2 Maintenance Support Requirements

In addition to the conventional facilities associated with a thermal power plant (e.g., power conversion facilities) a fusion power plant includes specific technologies requiring a unique supply chain of vendors and contractors to provide the equipment and services needed for O&M support. Each power plant would include staffing to cover all key disciplines required for daily maintenance activities. Additional contractor radiological control and maintenance staff and equipment supplier (vendor) support would be required for scheduled outages in the 1, 2, 5 and 10-year cycles. Some systems such as the BDS and lasers would require daily service such as replacement of laser boxes. Other systems such as the TG(s) would be scheduled for major overhauls such as turbine rotor replacement on a 10-year cycle as specified by the manufacturer.

Personnel required for scheduled major maintenance would be centrally dispatched from the Central organization and supplemented by additional contractor craft and technicians.

Personnel hiring, training, and certification would be managed by the Central organization. The Central facility would provide adequate space for classrooms and would be appropriately equipped, including mockups of major plant components, to facilitate initial On-the-Job Training and requalification of the O&M and Radiological Control staffs. A Simulator also would be provided at the Central facility to mimic all plant monitoring and control capabilities in the

Plant Control Rooms and model the plant response for normal, abnormal, and accident conditions. Each plant would have a training facility and be equipped with workstations to support web-based training for required recurring training. The Safety and Health Engineering (S&HE) Department would be directly responsible for monitoring the safety metrics of the plant, investigating any reports of non-conformance with plant safety Standing Orders, and preparing recommendations for improvement of worker safety programs and training.

4. BUILDINGS, GROUNDS AND UTILITY SYSTEMS

4.1 Facility Descriptions

Figure 1 shows a pre-conceptual inertial fusion power plant site layout. The FOB is located centrally on the site layout and contains the fusion engine systems along with the laser systems and target delivery system required for fuel delivery, ignition, and energy capture. Facility area names and acronym descriptions are provided in Table 1. The O&M requirements for buildings, grounds, and utility systems were based on the facilities listed in Table 1.

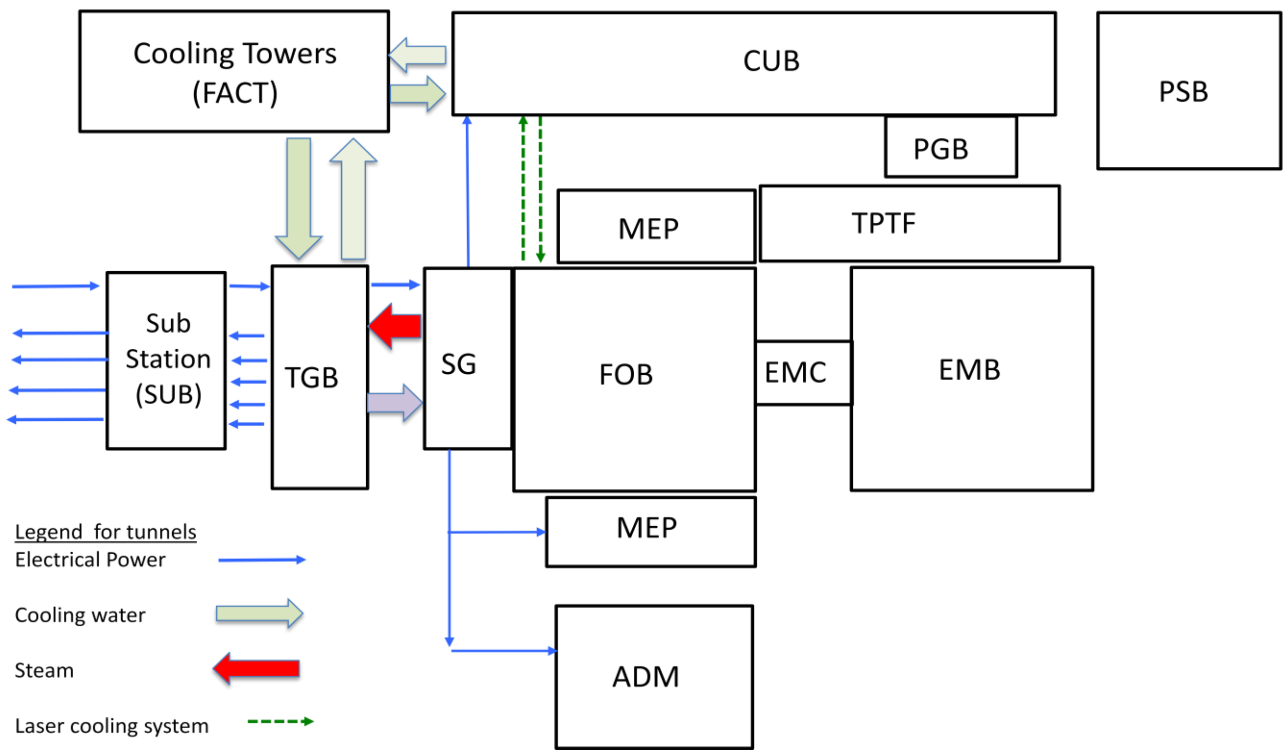

Figure 1. Pre-conceptual Inertial Fusion Power Plant Physical Layout

Table 1. Pre-conceptual Inertial Fusion Power Plant Facility Area Names and Functions

Acronym	Area Name	Functions
ADM	Administration Building	Contains the Central Control Room and staff offices for management and support services
CUB	Central Utility Building	Contains process gas storage and chiller arrays for cooling laser equipment levels in the FOB
EMB	Engine Maintenance Building	Contains spare fusion engine and areas where assembly and repair of fusion engines occurs
EMC	Engine Maintenance Corridor	Fusion engine chamber is transported from and to the EMB through the EMC (within the FOB)
FACT	Forced Air Cooling Towers	Exterior cooling towers for heat rejection from the turbine steam condensate loop and refrigeration located in the CUB; normally unmanned during operations

Acronym	Area Name	Functions
FOB	Fusion Operations Building	Three level structure with Fusion Engine at center on main level and two levels of laser equipment; portions of the FOB are accessed by O&M staff while other portions are separated by containment zones due to high temperatures, potential for radiation exposure, or both
GROUNDS	Grounds including Green (Cool) Rooftops	Security fencing, exterior lighting, landscaping, site improvements, water treatment plant, sewage treatment plant, fire-water storage, parking, storm water retention and drainage, and passive emergency back-up (e.g., hazmat spills, other exterior hazards)
MEP	Mechanical Equipment Plant rooms	Contain vacuum systems and other systems to support laser systems in FOB; accessible to O&M staff
PGB	Process Gas Building	Receives process gas from off-site; recycles used process gas back to process gas storage in CUB
PSB	Plant Support Building	Used for handling of spares and onsite maintenance tasks; includes warehouse, maintenance facilities, primary shipping, and receiving area
SG	Steam Generators	Provides steam generation capability
SUB	Electrical Substation	Provides power to the utility grid from the plant and is normally unmanned during operations; plant 'hotel' loads are powered via an "Aux Transformer" which gets its power either from the TG(s) (when plant is in operation), or from the grid via the substation (when plant is shutdown); power from the grid to the plant also supports start-up, operations, and emergency back-up systems
TAP	Target Assembly Plant	Located in the TPTF area; contains assembly equipment that fills target capsules with tritium and deuterium fuel and encloses the fuel capsules with hohlraum halves
TGB	Turbine Generator Building	Contains the TG(s) and local control room; normally unmanned during operations
TPP	Tritium Processing Plant	Located in the TPTF area; provides onsite processing and storage of the tritium
TPTF	Tritium Processing and Target Fill plant	Area housing the TPP and the TAP, detritation, and other supporting systems; note that TPP would contain the largest inventory of tritium; the TAP is located at grade for ease of handling and receiving of hohlraum target parts; this facility is zoned for containment and control of tritium fuel for the plant and is accessible by O&M staff and normally manned

4.2 Facility O&M

Plant systems and components would be operated only by qualified Plant Operators and be maintained under the control of the Shift Manager. A core staff of Operations, Maintenance, Radiological Control, Engineering, and QC personnel would be assigned to each shift to ensure safe and continuous operation of the plant. The Shift Manager would direct all Operator actions and authorize inspections, tests, or maintenance of plant equipment. The Shift Manager also would direct emergency operations until such time as the Emergency Operations Center is staffed and operational.

The Maintenance Department would be organized by the primary maintenance disciplines including mechanical, electrical, instrumentation / control, and information technology (IT). System maintenance is authorized by Work Packages approved by the Shift Manager and is directed by a Maintenance Foreman. Work flow would be planned and scheduled by a Work Control Unit supplemented with an appropriate plant maintenance work order software package (e.g., *Maximo*®). Preventative and predictive (where appropriate) maintenance programs are integrated into the conventional facilities maintenance.

4.3 Facility Logistics

Entry and exit to the plant is controlled at a secure entry point(s). Radiological Control Points and Radiation and Contamination Areas would be marked to control access into areas that contain radioactive materials. High Radiation Areas would be locked and alarmed. Flows of Equipment, consumables, spare parts, and replacement modules would be received at the PSB for manifesting, inventory control, storage, and subsequent drawdown when required. Flows of waste streams out of the plant would be controlled according to the type, toxicity, and risks associated with the waste product. Section 11 Hazardous Material Handling provides more details.

5. FUSION ENGINE AND CHAMBER GAS HANDLING SYSTEM

5.1 Fusion Engine and CGHS Description

Figure 2 shows a FOB cross-section of the three major elevation levels with the fusion engine chamber and other systems identified. The Effluent Chamber portion of the CGHS for reclamation of the target material is directly below the fusion chamber. Other CGHS systems not shown in the cut are the pre-cooler, compressor, compressor/manifold; Xe condenser, and reheater.

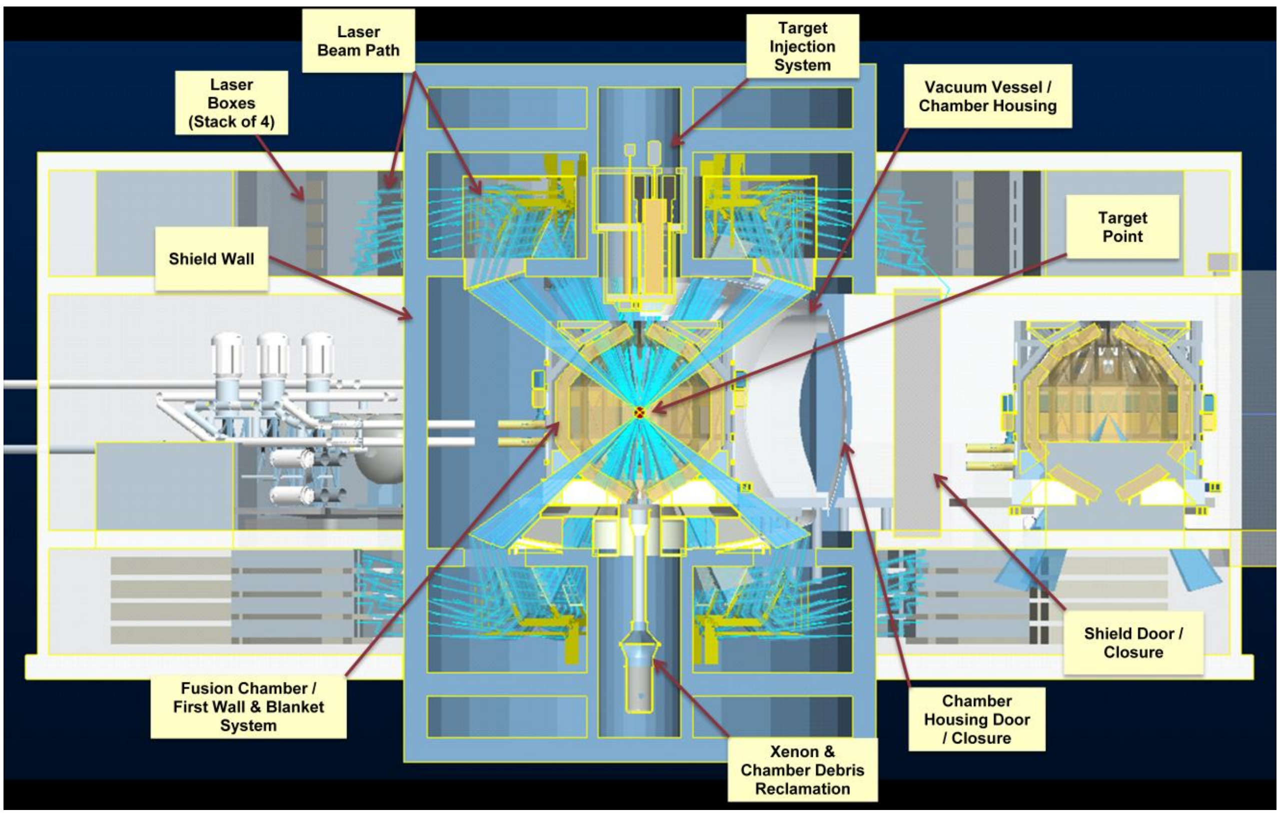

Figure 2. Pre-conceptual FOB Design Cut View Showing the Fusion Engine and Supporting Systems

There are three levels of fusion ‘confinement’: the inner most being the Target or ‘Fusion Chamber’ (note that it does not provide containment of fusion debris, only lithium); this is contained within a ‘Vacuum Vessel’ which is contained within a Fusion Engine ‘Chamber’ (FEC – actually denotes the surrounding concrete room). The FETC is mounted on a supporting frame and is designed as a roughly spherical chamber composed of 12 symmetrical segments that contain a First Wall System, consisting of an inner layer of lithium-filled tubes, and an outer Blanket System, consisting of lithium-filled channels to absorb the heat generated by the fusion reaction. The baseline design before optimization has each segment weighing 150 metric tons (MT) each for a total of 2,400 MT (without reflectors but including lithium coolant). The assembled FETC with reflectors but not including coolant weighs 1,500 MT. The entire FETC is removable. The FETC, CGHS, Target Injection System (TIS), and Laser System including the Final Beam Transport System are designed for some in-situ maintenance. All components within the FEC (FETC, FETC components, supporting frame and connecting lithium piping between the FEC and FETC walls) must be rotated out of service to the Hot Fusion Engine Chamber Storage Bay in the EMB during the replacement of the FETC.

The fusion chamber area and fusion chamber maintenance room would have an inert atmosphere and concrete surfaces lined with sealed-seam steel. The fusion chamber would be encapsulated but would not be actively cooled during transport onsite. It would be accessed for repairs more frequently than for replacement and would be disassembled for shipment and disposal by purpose-built unique Remote Handling and Maintenance Systems (RHMS) that can function in the activated environment. Final optics near the fusion chamber housing also are designed to accommodate remote handling for repair, maintenance, and replacement.

The fusion process generates heat to the walls of the FETC where a primary cooling system consisting of liquid lithium flowing through a directed flow (potentially tubular) First Wall System and a channeled Blanket System that circulates the lithium out of the FETC and the Fusion Engine vacuum vessel. The First Wall tubes are connected to a manifold at the back of each Blanket System module. A heat exchanger system provide heat transfer to a secondary cooling loop consisting of molten salt that transfers its heat to a high pressure water system and then to the SGs that provides steam for turbine generators that produce electrical power transmitted to the grid.

The fusion plant design includes various radiation shield wall design concepts to reduce O&M staff radiation exposure to As Low As Reasonably Achievable (ALARA) levels within allowable limits and limit radiation damage and heating of the main concrete shield wall outside of the main vacuum vessel from gamma radiation and neutrons are released in the FETC. Shielding design also provides absorption of radiation leakage back along the laser beam paths (i.e., beam ports) from the FETC to limit shield wall radiation damage and high heat loads, along with radiation scattering to other areas above the fusion chamber within the vacuum vessel.

The FETC and surrounding space enclosed in the FEC is filled with Xe as a background gas to absorb a portion of the radiation and provide a fluid to remove the products of the consumed fuel targets. The various gases, debris, and waste from the fuel targets including tritium are collected at the bottom of the FEC into a sump permanently installed outside the FEC at the bottom of the FOB. The CGHS equipment is located in a separate room on the main floor of the FOB and is accessed by maintenance staff in a controlled environment suitable for safe occupancy.

Molten target waste is stripped of remaining tritium and directed to an ingot casting and cooling area located in the EMB before storage and subsequent transport to the offsite target manufacturing facility for further processing and recycling. All other effluent and gases are routed to the CGHS for separation and distillation of each through carbon filters, hydride beds, reformers and other devices.

5.2 Fusion Engine and CGHS O&M

The FETC would require periodic replacement due to the progressive loss of structural integrity due to the high radiation levels inside the target chamber. The FETC maintenance concept is to remotely remove the FETC from the fusion chamber housing and replace it with a standby unit stored onsite. Due to the high level of activation of the materials, and the resultant high radiation levels, remote tooling would be required for FETC removal / replacement. Remotely operated disconnects would be provided for the lithium cooling system piping and for the FETC structural attachments to the FEC. A remotely operated FEC shield door would provide radiation shielding during operation and allow transfer of the FETC into and out of the FOB when the plant is shutdown. The used FETC would be size reduced within the EMB and the debris would be packaged for disposal as low-level waste (LLW).

During the planned FETC replacement outages, the following tasks would be performed:

1) Bypass the liquid lithium loops and purge remaining lithium in the FETC blankets, piping, and manifolds.
2) Disconnect the lithium piping to the FETC and disconnect the FETC from its supporting structure.
3) Remove the FETC from the FEC vessel and from the FOB through the FEC shield door using an EMC transporter.
4) Move the new FETC from the EMC into the FOB and reconnect the structural attachments to the FEC and the lithium piping.
5) Return the lithium cooling system to operation and resume plant operations.
6) Allow the activated FETC materials to decay in a Hot Bay Storage Room within the EMB until the radiation levels have been reduced to an acceptable level for further processing.

7) Bake-out of the components and parts of the FETC or its supporting structure and appurtenances by hot flowing argon to remove residual tritium and lithium.

8) Disassemble and size-reduce the FETC into manageable pieces.

9) Bake-out remaining tritium in the components.

10) Package, assay, and prepare waste manifests for interim storage or shipment of the FETC materials as LLW.

The plant pre-conceptual design concepts include unique RHMS for inspection and removal / replacement of equipment modules and assemblies in areas with high radiation levels, reactive materials (e.g. lithium), or high temperatures. Systems and components requiring RHMS include, but are not limited to: FETC, lithium cooling system components, and Final Optics components near the fusion chamber housing.

The integrated fusion process systems would be fully automated and monitored and controlled by the Control Room. Subroutines would be used to automatically sequence system startup / shutdown and normal operational evolutions. All automated operational sequences would be initiated by Control Room permissive interlocks and Operator inputs. The target injection process would automatically stop, thereby stopping all fusion reactions in the event of failure of any of the fusion chamber systems, the lithium cooling system, or any of the confinement systems within the FOB or in the TPTF. Residual heat in the fusion chamber and in the FETC itself would be removed by operation of the lithium cooling system. No post-shutdown safety controls are expected to be required since there are no post-shutdown fusion reactions and no "decay heat" to be removed, and the dispersible radioactive material inventory within the fusion chamber is limited to relatively small amounts of deuterium and tritium.

The CGHS equipment and components are designed to the greatest extent feasible, to be 'maintenance free' between the planned 1, 2, 5, and 10-year maintenance cycles. Equipment or components that are expected to require maintenance during the life of the plant would be designed as "plug and play" modules to limit the plant downtime. Equipment and components that are located in high radiation or high temperature areas or within the lithium cooling system area would be provided with a specially designed RHMS for remote removal and replacement. Other components such as compressors and pumps that have shorter lifecycles and are not activated by the high radiation levels within or adjacent to the FEC would be located in an accessible area of the main level of the FOB (i.e., MEP areas) where regular maintenance can be performed. All systems that are necessary for plant operation would be designed with full or partial redundancy so that no single failure or inspection or maintenance activity would result in an interruption of plant operations.

6. BEAM DELIVERY SYSTEM (BDS)

6.1 BDS Description

The inertial fusion plant would include 384 lasers arrayed on two FOB levels. The 384 beams are concentrated into 48 laser illumination beam groups. The laser beam paths are argon filled tubes connected to an array of optical controls including lenses, telescopes, mirror frames, gas, and vacuum vessels to focus and increase the concentration to the required energy level as depicted in Figure 3. Pinhole rooms with vacuum atmospheric controls are oriented to focus the aggregated beams on the FETC center point and minimize neutron leakage back into the FOB. Special RHMS would be required for components beyond the first Pinhole Room indicated by the dashed vertical line in Figure 3. Integration of the BDS with other plant systems is shown in previous Figure 2.

Laser systems would be enclosed in environmentally controlled boxes shipped into and out of the site on a periodic maintenance schedule for major repairs, refurbishment, and upgrades to improved technologies. Robotics for replacement of the laser system support structure would be located in areas adjacent to the equipment to be replaced. Systems replacement would be in large pieces to the extent possible that would then be repaired or disposed of off-site.

6.2 BDS O&M

Digitally programmed and controlled pulses of energy are focused onto the injected targets fusing the tritium and deuterium fuel providing the heat energy to the lithium heat transfer system. The Operators overseeing the laser systems are located in the Control Room within the ADM.

The BDS includes lasers and the optic devices housed within 8,000 Line Replaceable Units (LRUs). The LRUs are large metal frames that hold lenses, mirrors, or glass that can be easily installed in a Beamline or removed for maintenance.

The lasers and optics devices have an estimated MTBF of 10,000 hours. Eight laser boxes would have to be replaced each week to avoid a forced outage due to loss of all reserve laser system capacity. The BDS components such as optics, frequency converters, mirrors and related components also would be rebuilt, upgraded, and tested before return to spares after they are removed as part of the routine rotating replacement schedule. Other maintenance activities that cannot be performed during plant operations would be performed during one of the 1, 2, 5, and 10-year major maintenance cycle outages. Local site maintenance personnel would be supplemented with the resources coordinated from Central during major maintenance.

The laser master oscillator splits the laser light into 384 beam lines. Maintenance on these components would be done as part of the routine laser component replacement program, and is not expected to require significant effort or design considerations to support O&M. The laser beam boxes would be designed so that one of the groups of eight which feeds a single beam port can be down without affecting plant availability. The individual beam boxes are designed to be fabricated and tested off site and delivered to the plant and stored in a Laser Reception Hall. A small stockpile of approved laser boxes (estimated at 16) stored in the PSB would be used to rapidly replace a beam box that has failed or that shows signs of eminent failure. The beam boxes would be transported from the PSB to the FOB through an outside pathway, and then brought to the laser floor using one of the two FOB elevators. The laser support system which holds the beam boxes is designed so that minimal or no adjustment of the beam box location would be necessary, and the connection of the beam box to its supporting electrical lines and cooling pipes would be rapid, as would be the connection of the beam box to the beam delivery system. The laser beam box area is calculated to have sufficiently low radiation levels that the replacement of the beam boxes would not have to be done using remote control devices.

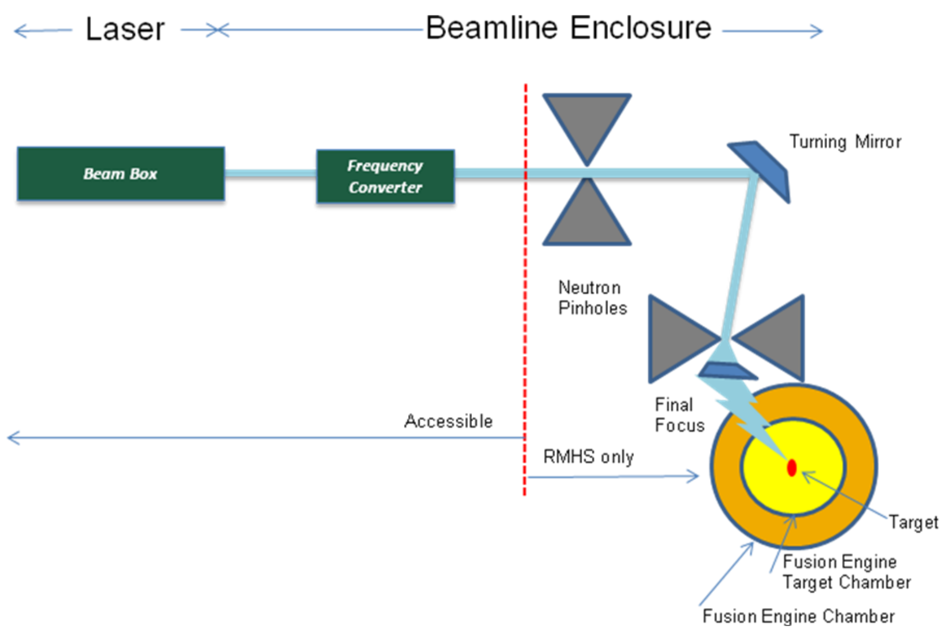

Figure 3. Beam Delivery System Concept

Maintenance of the BDS and the final optical transport system would likely be done with the same RHMS that is co-located with the two systems in the upper chambers inside the shield wall. Design of these two systems and the replacement mechanisms requires further work but it is expected that these mechanisms could be used to grip an individual optical component, which are designed to be smaller than 0.7 m on a side, lightweight, and thin, move it without any interruption of a beamline, and remove it through the shield wall via a specially designed portal. The installation of replacement optical components would be done in inverse fashion. It is expected that the optical components removed from inside the shield wall would be activated, and therefore, must be transported in a shielded container. They would be transported via FOB elevators to an area in the EMB which is used for radioactive waste disposal. They would eventually be transported off site as part of the waste disposal process, along with other radioactive waste.

Final optic components located in 'pinhole' rooms in a vacuum controlled environment require maintenance using RHMS. Final optics are expected to have a sufficiently long lifecycle that replacement would normally occur at the annual maintenance cycle.

The primary BDS maintenance activity is the removal and replacement of the laser boxes when equipment faults occur or when periodic maintenance requires removal and replacement. Laser box connections and supporting systems include direct current (DC) power; data fiber optic feed; propylene glycol chilled water; and clean helium gas providing 5 atmospheres of pressure. Onsite maintenance of the supporting systems would be required.

6.3 BDS Logistics

All beam box maintenance would be performed off site by commercial vendors certified and coordinated by Central. When new or refurbished laser boxes are received onsite an Acceptance Test Procedure (ATP) is performed to ensure that the equipment is ready for service and meets all performance requirements. The laser boxes are then placed into racks in the laser box storage area in the PSB. Each laser box has a total weight of about 10 metric tons. Mobile extraction and lifting equipment would be operated by staff.

7. TARGET INJECTION SYSTEM AND TRACKING BEAM REFERENCE SYSTEM

7.1 TIS and TBRS Description

The TIS is located in the FOB above the FEC vessel and FETC while the TBRS's are mounted in a stable pocket of the FOB structure. The TBRS laser tracking beams and receivers are arrayed horizontally to record the time and transverse the location of the passing target. Target timing and velocity are determined from tracking data.

The TIS receives the fuel targets from the TPTF building by mechanical and pneumatic conveyance. The targets are cooled to pre-ignition requirements by helium cryogenic equipment. The helium Target Injection Gun (TIG) accelerates the target to the speed and location required in the center of the FETC. A rotating shutter is used to shield the target in the injector from gamma radiation and neutrons generated from the previous fusion 'shot'. The TIS design includes redundancy to increase reliability. Multiple gas TIGs are vertically mounted on the turret allowing quick replacement and increased reliability. Pressurized helium forces the target down the barrel clamped at the muzzle to minimize vibration. Electromagnetic steering corrects any remaining residual errors in the flight path. Modular design of the TIS would minimize onsite maintenance and optimize reliability. Spare TIGs are resourced by Central and would be available for delivery and installation within 24 hour.

The TBRS measures the trajectory, velocity, and tilt of the target to ensure optimal position before ignition. The injector delivers the target to the FETC center within the laser Field-of-View (FOV). The TBRS is in a closed loop coordinated automatically to feed back target positioning for the BDS to accurately intersect the targets at ignition.

7.2 TIS and TBRS O&M

Operation of the TIS is digitally programmed and controlled with performance monitoring at the Central Control Room. The TBRS is interlocked with the final aiming and firing of the concentrated laser beams for precision operation and reliable ignition of the fuel targets. Since the TIS components are integrated into a modular unit, no major maintenance is planned onsite. The entire assembly includes redundancies and engineered components that are designed and manufactured by vendors to meet performance requirements. The TBRS is inspected and calibrated whenever there is a rotation of the FETC. There are opportunities at the 1, 2, 5, and 10-year maintenance cycles to perform required replacement of modular components.

7.3 TIS and TBRS Logistics

The fuel targets are transported from the target fuel area of the TPTF building by the target transport system to the TIS. The tubular structure is filled with cooled helium and includes an inner wall transporting the fuel targets by pneumatic, electromagnetic, and mechanical drive components. The inner tube is filled with a cryogenic supply of helium gas. TIS modules would be transported from the FOB via a corridor to the freight elevator. From there, the module is transported to the EMC for inspection and if necessary detritiation of inner components before packaging and shipping out of the plant. New modules are received at the PSB, inspected, and tested. The module is then transported through the corridor to the FOB equipment elevator and then installed for operation. Coordination and logistics support are provided by Central and the commercial vendors contracted and certified to provide the equipment, parts, and service.

8. POWER GENERATION AND SUBSTATIONS

8.1 Power Generation and Substation Description

Heat from the liquid lithium is transferred to a molten salt secondary cooling system and then to a tertiary water cooling medium. The water is transferred to SGs to produce steam to drive the TG(s). The steam, condensate, and support systems are similar to other large steam cycle electrical power plants. Six steam pipes from each of the SGs supply the high pressure turbine(s) in the TGB. The steam drives the various stages of the TG(s) which in turn delivers electrical energy to an electrical substation located near the TGB: The substation transmits power to the grid and back into the plant to power to all plant 'hotel' loads (primarily the laser systems).

Steam supply to the TG(s) is monitored and controlled at the Central Control Room with valves and actuators through digitally programmed instructions. Steam piping is built to last for the life of the plant. Inspections and repairs if needed would be conducted during the 1, 2, 5, and 10-year major maintenance outage cycles.

Heat transfer is accomplished through three SGs (heat exchangers) in the FOB to the TG(s) located in the TGB with associated equipment based on a Supercritical Rankin cycle. Power generated by the TG(s) is stepped up to the grid voltage via a main transformer the substation. The substation is controlled using a Supervisory Control and Data Acquisition System (SCADA) operated by the electric utility for coordination with grid operations. Maintenance would be performed by contractors and vendors.

The tertiary side cooling system is a "closed loop" system that uses evaporative cooling towers (FACTs). Closed loop cooling water systems are required in most locations to meet environmental permitting requirements. Operation of the cooling water system including FACTs, the circulating water pumps, chemical treatment system, makeup water system, and blow-down system is controlled at the Central Control Room by the Digital Control Systems (DCS) that coordinate operation with the TG(s) components including the condensate return loop.

8.2 Power Generation and Substation O&M

The TG(s), FACTs, interconnecting piping, and related equipment are monitored and controlled by the DCS dedicated to the operation of the TG(s) and steam plant. After the TG(s) has been warmed up and brought to full speed, it is synchronized with the grid and connected to export power to the grid. The Operator then increases the steam flow rate to increase power output. The DCS controls the target injection rate as required so that the fusion chamber power matches the heat transport requirements of the lithium and molten salt coolant loops which in turn are matched to the steam output of the SGs and the electrical output of the TG(s). Normal diagnostics and monitoring of TG(s) performance are conducted as specified by the TG manufacturer. Normal operation would be remotely controlled from the Central Control Room in the ADM building. Local monitoring and control panels are located throughout the plant to provide control and indication of local systems and equipment.

The substation is normally unmanned during operations and digitally programmed and controlled by SCADA systems. Power from the grid back to the plant is operationally under the supervision of the Central Control Room. Substation power transmission to the grid is operationally under the supervision of the electric utility and grid operations Power Control Center (PCC) for the geographic region.

Maintenance staff levels to support the TG(s) and substation systems would be optimized similar to other steam-driven electrical generation power plants. Maintenance is performed in accordance with the component manufacturers' requirements. Diagnostic systems provide predictive maintenance tools to anticipate potential failures before they occur.

Major maintenance for the TG is performed at 8 to 10-year cycles. The turbine housing is disassembled and rotors and blades inspected and replaced as recommended by the turbine manufacturer. Major maintenance staffing would be resourced and coordinated by Central.

9. TRITIUM PROCESSING AND TARGET FILL

9.1 TPTF Description

The TPTF is located adjacent to the FOB. The target-fill automated assembly equipment is located at one end, and the tritium processing equipment at the other end, with all interfaces in between. Control of the radioactive hazard is a primary consideration in the design and maintenance of ventilation and detritiation systems. Primary and secondary back-up detritiation systems would be required for safety and reliability. This area also is connected to a 1MW back-up diesel generator for continued operation of some systems and safe-shutdown of others.

Tritium is collected by the CGHS and Blanket Tritium Extraction System and routed from the FOB to the TPP for processing. Additional intermittent tritium streams are received from the vacuum chambers at the BDS pinhole rooms and the detritiation system at the EMB. Hydrogen, deuterium, and tritium are extracted for isotope separation by a Hydrogen Purification System (HPS). Waste products are passed on to an Effluent Detritation System (EDS).

An Isotope Separation System (ISS) produces D2 and T2. The fuels are sent to a Storage and Delivery System (SDS). The storage sub-system includes a series of segregated and independent hydride storage beds. The delivery sub-system includes pumps, valves, and control devices. The EDS receives H/D/T from the ISS, tritium from the lithium processing off-gas, and waste products from the HPS. The process effluents include tritiated water returned to the ISS, water, and stack gas. An Analytical System receives samples from the SDS, ISS, EDS, and HPS. The samples are analyzed for conformance with plant operational and licensing requirements including tritium accountancy.

Primary and secondary confinement systems include pipe-work, gloveboxes, ventilation, and air detritiation. Leakage detection and fire / explosion protection systems also are required. Air detritiation is achieved by molecular sieve bed dryers or wet scrubber columns. Water detritiation is required to treat effluent from a fire protection event that releases water into an area containing radioactive material.

Target fueling and assembly is automated and digitally controlled. Multiple assembly lines and redundant components are anticipated to ensure reliability and support overall availability to the plant. A highly automated and reliable system is required to produce over 1 million fueled targets per day.

Rugby-shaped lead (Pb) hohlraum halves and empty capsules are received in trays from an off-site manufacturing facility. Storage for 7 days of production of inert components is provided outside the secondary containment perimeter of the Target Fill assembly area. The DT fuel is delivered from the TPP. Helium used in the production process is delivered from the CUB. DT layering and nano-porous aero-gel foam substrate loading of DT fuel capsules is accomplished in each assembly line by high-yield diamond ablators adopted for the current point design. Laser Entry Hole (LEH) shields are installed after injection of the DT fuel capsules. The completed fueled hohlraums are steered by mechanical, electromagnetic, and pneumatic methods through a target delivery conveyor system confined with helium gas and delivered to and received by the TIS at the top of the FOB.

Multiple assembly lines would provide adequate redundancy and reliability to allow each assembly line to be taken out of service for periodic maintenance. Since this production method would include a throughput of over 1 million fuel targets per day it is anticipated that a full-time onsite maintenance staff would be required to maintain the assembly line components at the maintenance shop in the PSB.

9.2 TPTF O&M

The TPP would be digitally programmed and monitored at the Central Control Room in the ADM building. A secondary control room in the TPTF is required for backup and emergency conditions. Each of the systems comprising the TPP is of modular design with redundancies for equipment with lifecycles matched to the 1, 2, 5, and 10-year major maintenance cycles. Modular subsystem spares and major maintenance would be performed offsite by commercial vendors resourced and certified by Central. The primary onsite staffing requirement would be for the maintenance of the secondary containment systems including leakage detection, fire/explosion detection systems.

An onsite maintenance staff is required to monitor and check performance of system components; operate RHMS for removal and replacement of subsystem modules; remove and replace high efficiency particulate air (HEPA) filters to the heating, ventilating, and air conditioning (HVAC) system; maintenance of the detritiation systems; and other maintenance that must be performed onsite on a repetitive and frequent basis. Containment, encapsulation, casketing and manifesting of any activated waste materials would be performed at the TPP area before shipping off site from the PSB shipping area

As currently envisioned, the target assembly would be a highly automated and reliable industrial process. For example, each machine would be capable of producing 50,000 targets in 24 hours, and with 42 machines in 6 or 7 assembly lines, the overall production capacity is 2.1 million assembled fuel targets. This yields a 50 percent stand-by capacity in case an assembly line is taken out of service for replacement of one of the production units. Staff would be present during the production as an additional monitoring resource for the instrumentation and controls required for the critical and precise assembly operation.

Since this production method would include a throughput of over 1 million fuel targets per day it is anticipated that a full time onsite maintenance staff would be required to maintain the assembly line components at the maintenance shop in the PSB. Additional offsite resources and coordination would be provided by Central for assembly line modular units that cannot be serviced onsite.

9.3 TPTF Logistics

The TPTF is located adjacent to the EMB for ease of transit of hazardous materials that cannot be contained and packaged directly in the tritium processing and target assembly areas. These materials and components would be transported by RHMS and would transit from the TPTF area to the EMB through a lateral corridor and access to the EMC.

Primary deliveries to the TPTF would be at a receiving area grade and adjacent to the Target Assembly area. Storage for a 7 day production of target components would be maintained. Allowances would be made in the design to account for adequate buffer of assembled / fueled targets. Shipping from the TPTF area would be limited to pre-packaged and casketed hazardous materials including any surplus of tritium provided to other fusion power plants for start-up feed stock

10. REMOTE HANDLING AND MAINTENANCE SYSTEMS

10.1RHMS Description

The fusion process generates neutrons and gamma radiation that activates components located in the FEC and FETC. Components of the BDS, CGHS, and lithium heat transfer systems also become activated in the course of normal operations. Maintenance equipment under operator supervision would perform both routine and unplanned maintenance activities in areas of the FOB, EMB, and TPTF.

The RHMS includes all mobile or fixed equipment that is under operator control for the purpose of accessing areas of the power plant that for safety reasons cannot be occupied by humans. RHMS must be capable of operating in the high temperature and inert gas atmospheres.

10.2RHMS O&M

Piping systems for the various fluids, gases, and vacuum systems would require diagnostic systems to locate and assess the level of repair required. Specialized equipment would be mobilized for leak repairs where feasible.

Electronic equipment may not be used in areas subject to high neutron flux. Mechanical, hydraulic, and pneumatic powered RHMS would be used during fusion system operations.

During FETC shutdown and rotation RHMS would be used to disconnect and transport the FETC, its supporting structure, and other components located in the FEC containment vessel. The installation of replacement equipment in the FEC containment vessel would similarly be installed, connected, inspected, and tested with RHMS.

The Final Optics System (FOS) includes components such as the final focusing lenses, vacuum windows, relay telescopes lenses, and mirrors that would require replacement in a high temperature environment. The TIS also would require that removal, replacement, and repair tasks be performed by similar RHMS.

RHMS and components also would require a periodic maintenance program for repair, replacement and in some cases waste disposal due to activation of equipment materials and components.

Maintenance performed in the EMB by RHMS includes transport, lifting, disassembly, sawing, cutting, grinding, assembly, welding, testing, baking, and waste packaging. A tritium recovery area and system also would be located in the EMB.

Final optic components would be replaced while maintaining operation of neighboring beam lines. Equipment in these locations would be operating in a Class 100 environment in a temperature range of 600 to 800 C. Equipment would be capable of repeatable precise component insertion in the presence of neutrons and radiation. Laser beam path optics also would be removed while adjacent to other operational laser beam path equipment.

All RHMS, components, and hardware are subject to its own maintenance and replacement cycle. Minor maintenance such as replacement of consumable parts or modular components or repairs would be conducted onsite in the PSB. Major maintenance would be conducted off-site by vendors and contractors certified for the particular equipment types or by Central as appropriate.

10.3 RHMS Logistics

Activated materials or components that must be removed from a fusion power plant would be packaged and contained at the nearest location of operations feasible. Alternatively, materials and components that cannot be packaged at the source must be transported through the EMC to the EMB. It is anticipated that many of the RHMS items and components would be subject to this requirement and appropriate transit pathways would be included in the programming and design requirements for the power plant facility.

11. HAZARDOUS MATERIAL HANDLING

11.1 Hazardous Material Handling Description

The inertial fusion power plant design would provide the containment of and protection from hazardous materials in the processes and waste streams generated from plant O&M processes. The most hazardous materials include tritium, lithium, target waste, refrigerants, HEPA filters, chemicals, waste water, transformer oils, batteries, etc. All materials entering the plant facilities would be manifested and inventoried at a central receiving area located conveniently between the PSB, CUB, and ADM. All processes would be automatically monitored by DCS's linked to the Central Control Room. Process chemistry would be analyzed as appropriate to the system and associated risks both for safety as well as optimal operational economies.

Administrative controls would be implemented to ensure safe handling, processing, packaging, storage, and shipment for disposal of hazardous materials. These controls include audits of physical inventories, process systems, analytical procedures, and back-up systems for emergency conditions. Larger components such as the FETC would be transited in containment areas such as the EMC to protect against injury to plant workers or release of hazardous materials to the environment.

All plant O&M processes would be designed to mitigate and reduce risks to an ALARA standard. Radioactive waste streams would be minimized by optimal lifecycles of qualified materials and other engineering and O&M practices and techniques.

12. RADIATION SAFETY AND LICENSING

12.1 Radiation Protection Program

Inertial fusion power plant design would be in accordance with best engineering practices with engineered features (passive and active) that provide direct and effective control and management of radiation risks. Containment and shielding structures, specialized ventilation systems, and back-up safety systems would be integrated in a reliable and safe design to protect the workers, public, and the environment.

Sources of radiation in an inertial fusion plant include:

1) Tritium fuel in the cycle of target assembly through fusion ignition and recycling
2) Neutrons, X-rays and gamma rays emitted during, or immediately after, the fusion ignition of the DT fuel targets in the fusion engine chamber
3) Fusion engine and other plant components that become activated from the presence of radioactive sources
4) Long-lived radionuclides produced as a result of fusion target ignition
5) Tritium that is produced from neutron irradiation of the lithium coolant

Protection of plant O&M staff against radiation exposure is a primary safety function. A job hazards analysis (JHA) would be performed before performing work in any area of the plant. A radiological analysis also would be performed before work in all radiologically controlled areas. Appropriate controls identified as part of the JHA and radiological analysis would be documented in a Radiological Work Permit (RWP). The RWP would be incorporated into the Work Package for maintenance and would be discussed as part of the Pre-Job Briefing.

Radiation and contamination surveys would be performed on a regularly scheduled basis to establish and confirm control boundaries for Radiation Areas, High Radiation Areas, Locked High Radiation Areas, Contamination Areas, High Contamination Areas, Airborne Contamination Areas, High Airborne Contamination Areas, etc. Surveys would be performed immediately before and during work in areas not routinely surveyed. Survey results would be used for work planning and for incorporation into the RWPs and Pre-Job Briefings.

RWPs would specify the required Personnel Protective Equipment (PPE) and dosimetry required for O&M staff entry into Radiologically Controlled Areas. Radiological Control Technicians (RCTs) would be assigned on shift and would monitor work in progress to verify that radiological conditions do not change during the performance of work. RCTs also would monitor worker stay times and conduct surveys as required to ensure that workers do not exceed exposure limits established in the RWPs

Chemical safety would be managed in much the same way as Radiation Safety. Periodic surveys would be performed in all areas containing hazardous materials and controls established to prevent access without the appropriate PPE. Chemical hazards would be assessed as part of JHAs as well as radiological and industrial hazards. Controls would be established as part of the work planning process and incorporated into Work Packages. Industrial Hygienists would perform surveys and monitor work in progress to verify compliance with work controls.

12.2Licensing

The O&M concepts developed as part of design and engineering work for inertial fusion power plant pre-conceptual design assume that primary jurisdictional and regulatory framework would be normalized for the commercial licensing and operation of such power plants. The Operator of each power plant would be required to apply for and obtain a license from the Nuclear Regulatory Commission (NRC) to construct and operate the parts of the facility that generate radionuclides or that contain quantities of radioactive material which if released could pose a hazard to the general public. Although there are no existing regulations governing commercially operated fusion power plants, it is expected that the licensing process and conditions of operation would be similar to those currently in place for other non-reactor nuclear facilities which require a “specific license”.

A licensing process similar to that used for “Fuel Cycle Facilities” would seem to be most appropriate given the limited radiological inventory and risk to the public. Such a licensing protocol would require a license application including an Integrated Safety Analysis (ISA), Safety Analysis Report (SAR), and Environmental Report (ER). The ISA and SAR would identify Items Relied on for Safety (IROFS) which then would be required to prevent or mitigate postulated accidents that could otherwise exceed NRC limits for off-site exposure. Structures, systems, and components (SSCs) identified as IROFS would be subject to specific quality requirements to provide a higher level of confidence that the SSC would perform its’ safety function when required. A graded QA program similar to that specified in Part 70, Subpart H of Title 10 of the Code of Regulations would be required to implement an inertial fusion power plant. This QA program would be described in the license application, and implementation of this program as well as other administrative programs described in the License Application (LA) would be subject to NRC oversight.

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