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CHAMBER DESIGN FOR THE LIBRA LIGHT ION BEAM FUSION REACTOR

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ABSTRACT

Scoping analysis was performed for LIBRA to determine the blanket design options that satisfy the tritium breeding and wall protection requirements. The blanket is made of banks of INPORT tubes of porous SiC and $\text{Li}_{17}\text{Pb}_{83}$ flowing in them. The reference design utilizes a 1.35 m thick blanket region backed by a 0.5 m thick HT-9 reflector. The lithium in the blanket and reflector is enriched to 90% ^6Li . This design leads to the shortest possible beam propagation channel. The TBR is 1.5 and the end-of-life dpa in the chamber wall is 200 dpa. In this paper we describe the design and configuration of the chamber as well as the tritium fueling and the response to the target explosion.

INTRODUCTION

LIBRA is a commercial inertial confinement fusion reactor conceptual design driven by light ions. The reactor produces 1160 MW of thermal power and 331 MW of net electric power. The 3.2 mg fusion targets are imploded by 4 MJ shaped pulses of 30 MeV Li ions at a repetition rate of 3 Hz. The target gain is 80, leading to a yield of 320 MJ.

The reactor chamber wall, made of the ferritic steel alloy HT-9, is protected from both neutron damage and the shock overpressure by an array of porous silicon carbide tubes with $\text{Li}_{17}\text{Pb}_{83}$ (LiPb) flowing through them. These INPORT tubes also recover the energy released from the target and breed enough tritium for the reactor to be self-sufficient in tritium. In this paper, the overall configuration of the reactor chamber will be described as well as the thermal hydraulics, chamber evacuation, chamber maintenance, and beam line protection. The neutronics analysis performed for the target and chamber will be discussed and the results of the scoping studies that lead to the reference chamber design will be presented. Tritium fueling and inventory will be discussed as well as the response of the INPORT tubes to the target explosion.

OVERALL CONFIGURATION

The LIBRA chamber is an upright cylinder with internal dimensions of 7.7 m height on axis and 6.0 m in diameter as shown in Fig. 1. The chamber is characterized by three distinct zones, the blanket, reflector and shield. The blanket in the vertical sides of the chamber consists of a 1.35 m thick zone of flexible porous SiC tubes, called INPORT tubes which occupy 33% of the available space and have LiPb circulated through them. A wetted surface on the tubes absorbs the surface heat load. The front two rows have 3 cm diameters and the remaining 9 rows have 10 cm diameters. The blanket is followed by a 50 cm reflector zone of HT-9. This reflector, which is cooled with LiPb, is the primary structural support for the INPORT units and is the vacuum barrier for the chamber. It is followed by a 2.5 m thick shield of He cooled reinforced concrete.

The roof of the chamber is covered with 10 cm thick wedge shaped woven SiC modules with LiPb flowing through them. Dripping from the roof is not an issue since a drop only travels ~ 0.5 m between shots, not far enough to intercept beams at any point. These modules are attached to a 25 cm thick HT-9 reflector cooled with LiPb. This reflector is welded to six equally spaced structural beams which, along with the integral central hub, constitute the primary support structure for the roof. Six independent shield segments fit between the beams to provide an effective shield thickness of 2.95 m. The final element in the roof is the vacuum flange made of HT-9 which is sealed to the vertical reflector to form the vacuum barrier for the roof. A pellet injector is located in the center of the roof, fitting through the central hub. This pellet injector is sealed to the top vacuum flange and can be removed independently for servicing.

The bottom of the cavity consists of a LiPb pool which is formed by the coolant flowing through the roof modules and the INPORT tubes. It drains through a 15 cm thick perforated plate made of HT-9, which acts as a reflector as well

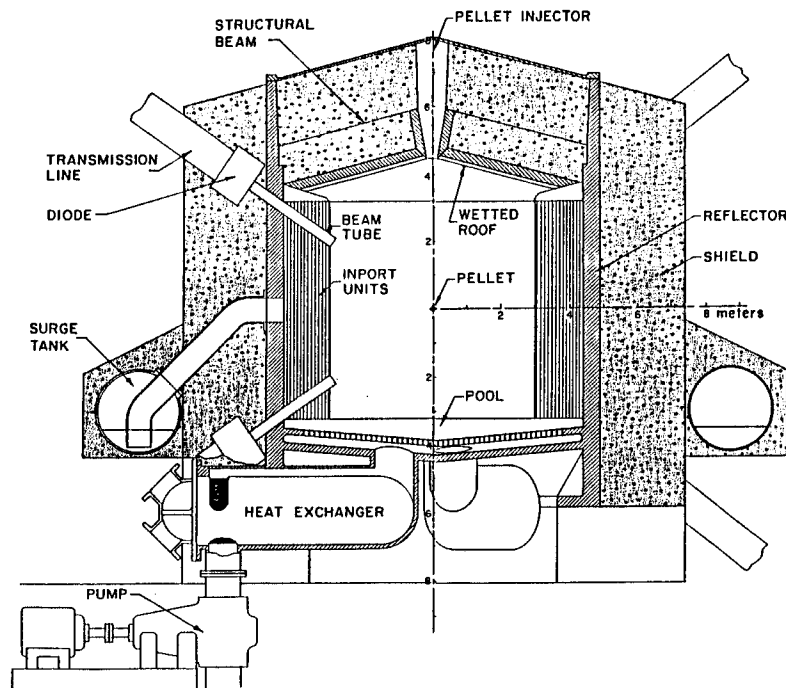


Fig. 1. Cross section of LIBRA target chamber.

as a shock damper. The LiPb then flows down a 20 cm thick splash plate into three ports leading to three heat exchangers located in the base of the chamber. After going through the heat exchangers, the LiPb is pumped back up to start another cycle through the chamber. In the heat exchangers, the LiPb is cooled with He gas which is then routed to steam generators and a conventional steam power cycle.

IMPORT TUBE MECHANICAL RESPONSE

An important chamber design issue is the inevitable motion of first-wall INPORTs resulting from the repetitive shock loading. Close-packing is desirable for screening purposes but physical contact would degrade the system. Motion control is made more difficult because of the INPORTs' large span without intermediate support. The mechanical response has been analyzed in considerable detail and the results have led to a feasible design.

Modelling includes tensile preload, axial tension gradient, damping, flow velocity and repetition rate. On each INPORT, the shock is applied in the radial direction with respect to the chamber. Although this driving force is planar, it is possible to develop out-of-plane, i.e., circumferential motion as well because of nonlinear coupling. The cross section essentially follows a complex orbital path, which continues as steady-state motion. However, by

adjusting physical parameters, particularly flow velocity and tension, the desired planar response will eventually persist even if circumferential disturbances are present initially. Such is the case in Fig. 2. The radial shock of 150 Pa-s is applied at 3 Hz to a unit with a length, diameter and wall thickness of 6.4 m, 3 cm and 2 mm, respectively, and a tensile load of 3000 N. The circumferential component approaches a steady-state value of zero while the radial component stabilizes to an oscillatory response ranging from 0 to 4 cm.

CHAMBER EVACUATION

The LIBRA chamber is designed to be self-pumped by the target explosion generated overpressure which expands into the suppression tank shown in Fig. 1, through 9 ducts equally spaced at the chamber midplane. A He gas equivalent to 100 torr at 300 K is needed for beam propagation and for stopping x-rays and ions. The gas temperature just prior to a shot is 800 K and the pressure is 260 torr. Immediately after a shot the temperature in the chamber rises to 9000 K and the pressure to 2900 torr. The temperature in the suppression chamber is maintained at 350°C and the pressure at 260 torr. After the shot, the gas in the reaction chamber undergoes an isentropic expansion through the LiPb lock into the suppression chamber, cooling itself in the process. Once the two chambers equilibrate in pressure, the LiPb lock will

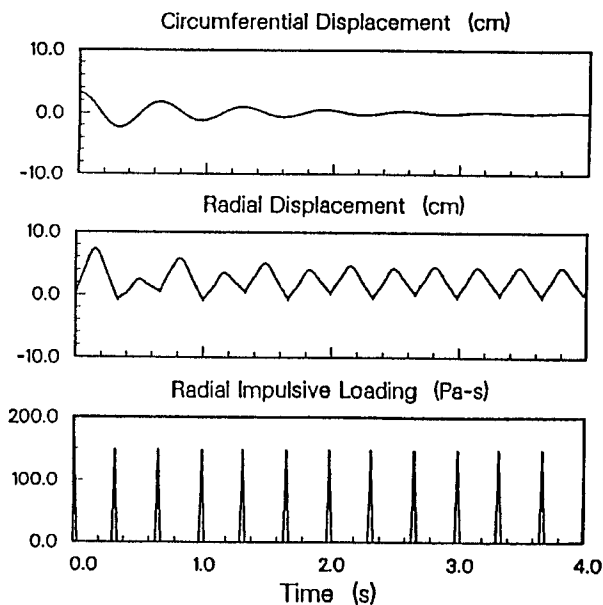


Fig. 2. INPORT displacement histories.

prevent any further communication between them. The post-expansion gas temperature in the reaction chamber will be higher than it was prior to the shot, and that fraction within the INPORTS' area will quickly cool to the average temperature of the LiPb. As the chamber gas cools down to the initial temperature of 800 K, the pressure falls below 260 torr and fresh He gas is injected to maintain the pressure at the prescribed pre-shot value. Although further trade study and analysis is needed, we have found that a suppression tank volume of ~ 65% that of the chamber is needed. A steady state pumping speed of 1.5×10^5 ℓ/s is required for evacuating the suppression chamber at a repetition rate of 3 Hz. The only vacuum pumps suitable for operating under these conditions are oil-free mechanical pumps.

BEAMLINE MAGNETIC PROTECTION

There are 18 beam lines, 9 equally distributed at the top and 9 at the bottom, inclined at an angle of 34° to the horizontal. To prevent the beams from shorting to the blanket, they are transported between the INPORT units through magnetically insulated tubes shown in Fig. 1. The beam tubes are integrated with the INPORT units so that there will be no unprotected surfaces.

It has been determined that a magnetic field of 3.2 T is needed within a 20 cm bore beam tube. A coil made of a molybdenum alloy TZM and insulated with BeO and SiC has been proposed. Such coils will have 123 turns, an OD of 0.34 m and ID of 0.2 m. They will be 2.9 m long and will require 11.3 kV and will dissipate

a total of 26.5 MW. The coils will be cooled through the insulation by the LiPb and the energy will be recovered in the power cycle. Although this scheme appears viable, beam protection still is a critical issue.

NEUTRONICS ANALYSIS

Neutron target interactions in ICF reactors result in neutron spectrum softening, neutron multiplication, and gamma production. Therefore, the first step in the chamber neutronics analysis involves performing detailed target neutronics calculations. Neutronics calculations have been performed for the LIBRA target using the one-dimensional discrete ordinates code ONEDANT.³ The target has 3.2 mg of DT that is compressed to a ρR value of 2 g/cm^2 at ignition. The fuel is surrounded by CD_2 pusher and Pb tamper. The calculations were performed using spherical geometry and 30 neutron - 12 gamma group cross section data based on the ENDF/B-V evaluation. A uniform 14.1 MeV neutron source was used in the compressed DT fuel zone.

The total energy deposited by neutrons and gamma photons in the target was calculated to be 1.754 MeV per DT fusion. Only 0.11% of this energy is deposited by gamma photons. About 70% of the energy is deposited in the DT fuel zone and 1.025 neutrons are emitted from the target for each DT fusion reaction. The average energy of neutrons emitted from the target is 11.64 MeV. For each DT fusion reaction, 0.013 gamma photons are emitted from the target with an average energy of 3.85 MeV. The energy spectra of the emitted neutrons and gamma photons are shown in Fig. 3. Performing an energy balance for the target indicates that 0.37 MeV of energy is lost in endoergic reactions per DT fusion. For the LIBRA DT fuel yield of 320 MJ, the target yield was calculated to be 313.3 MJ. The neutron and gamma yields are 216.9 and 0.9 MJ, respectively, while the combined x-ray and debris yield is 95.5 MJ.

A one-dimensional scoping analysis was performed to determine the blanket design options that satisfy the tritium breeding and wall protection requirements. The ONEDANT code was used with the chamber modeled in one-dimensional spherical geometry. A point source emitting neutrons and gamma photons with the spectra given in Fig. 3 was used at the center of the 3 m radius cavity. The results were normalized to a DT yield of 320 MJ and repetition rate of 3 Hz. The blanket is made of banks of INPORT tubes with 0.33 packing fraction. The tubes consist of 2 vol% SiC and 98 vol% LiPb. A 0.5 m thick reflector consisting of 90 vol% HT-9 and 10 vol% LiPb is used behind the blanket.

A minimum tritium breeding ratio (TBR) of 1.1 is required to achieve tritium self-sufficiency. In addition, the INPORT tubes are required to protect the first metallic wall.

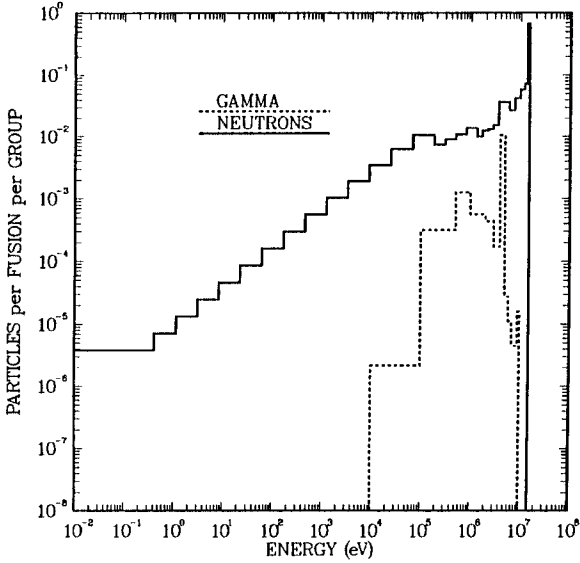


Fig. 3. Energy spectra of neutrons and gamma photons emitted from the LIBRA target.

The peak end-of-life dpa in HT-9 is required not to exceed 200 dpa, implying that for 30 Full Power Years (FPY) of operation, the peak dpa rate should not exceed 6.6 dpa/FPY. The design should also aim at maximizing the energy multiplication (M) due to its impact on the cost of electricity. In addition, the blanket thickness needs to be minimized to minimize the length of the channels used for beam propagation.

The calculations were performed for different blanket thicknesses (Δ_B) and lithium enrichments (% ^6Li). The results are mapped in Fig. 4. The TBR values take into account the neutron multiplication in the target. For a fixed lithium enrichment, increasing the blanket thickness results in increasing TBR, decreasing M and decreasing damage rate. Increasing the lithium enrichment for a given blanket thickness results in increasing the TBR, decreasing M, and decreasing the dpa rate. In order to satisfy the tritium breeding and wall protection requirements, the design point should be in the box indicated in the upper left corner of the graph. In order to satisfy the other design goals of minimizing the blanket thickness and maximizing M, it is clear that the design point should be at the right or lower boundaries of the box. The intersection of the boundaries of the box with the curves that correspond to different enrichments give the options that satisfy the design requirements. While all these options allow the reflector to be a lifetime component, different values of TBR and M are obtained. To minimize the length of the beam propagation channel, a 1.35 m thick blanket with 90% ^6Li enrichment is used in LIBRA. This yields local (one-dimensional) TBR and energy

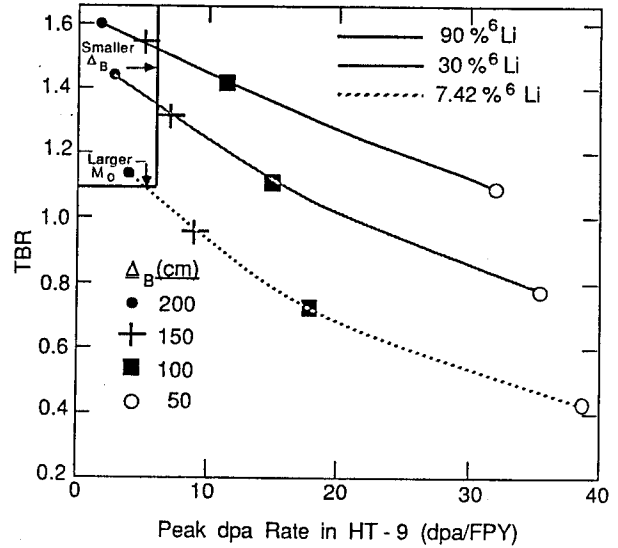


Fig. 4. TBR vs. damage rate for the blanket design options considered.

multiplication values of 1.5 and 1.18, respectively. The peak dpa and helium production rates in HT-9 for this design are 6.6 dpa/FPY and 3.5 He appm/FPY, respectively. Since spherical geometry has been used in the calculations, the damage rates given above represent the worst conditions at the midplane of the cylindrical chamber.

Since the baseline blanket design, with 1.35 m thick zone of INPORT tubes, results in a relatively large TBR in the chamber sides, a smaller local TBR is allowed in the reactor roof. A scoping analysis for the roof has led to a 10 cm thick LiPb protective layer with 2% SiC fabric followed by a 25 cm thick HT-9 reflector cooled by 10% LiPb. The local TBR in this zone is 0.8 and the peak dpa rate in HT-9 is 50 dpa/FPY. The roof structure has to be replaced every 4 FPY. Since only ~15% of the source neutrons go to the roof, this design will yield an overall TBR that exceeds the minimum requirement by an adequate margin. The impact of neutron streaming on TBR is negligible due to the small solid angle subtended by the penetrations. Furthermore, the sensitive components in the diodes are not in direct line of sight of neutrons produced in the target. Detailed three-dimensional neutronics calculations are underway.

THERMAL HYDRAULICS

The thermal hydraulics in LIBRA is modeled after the earlier heavy ion beam study HIBALL.² In this paper we do not address evaporation or recondensation which has as been extensively treated in previous studies.⁴ With the

exception of the shield, which is He gas cooled, the entire chamber is cooled with LiPb. As a safety feature, no water cooling is used anywhere in the chamber. A single LiPb loop is employed in the reactor. It integrates the cooling of the reflector with the cooling of the roof and the INPORTs, and performs its function in the suppression tank as well. The LiPb inventory is minimized by having the heat exchangers built into the base of the chamber thus obviating the need for extensive heavy piping.

The roof is cooled by LiPb first flowing through the reflector and then entering the SiC modules at predetermined radial locations. This coolant then flows down the vertical sides of the chamber through rear INPORTs. The integrated energy received from the roof, from the low nuclear heating in the rear INPORTs and during its residence in the bottom pool raises the temperature of the LiPb from 340°C to 500°C. LiPb is also ducted into the remaining INPORTs independently of the roof coolant experiencing the same temperature rise. The 500°C LiPb draining from the pool is then routed to the front of the heat exchangers, such that it can exchange heat with He gas in a counter flow configuration. From this point the LiPb is pumped back up to start a new cycle through the chamber. A fraction of this flow is pumped into the suppression tank where it serves to cool the hot gases exhausted from the chamber as well as to trap any LiPb vapor that did not condense in the chamber. The temperature of the LiPb in this tank is maintained at an average value of 350°C. From the suppression tank the LiPb is used to cool the reflector. The pertinent thermal hydraulic parameters are given in Table 1.

Table 1. Thermal Hydraulics Parameters

Total thermal energy in the chamber (MW)	1160.5
LiPb inlet temperature (°C)	340
LiPb outlet temperature (°C)	500
LiPb mass flow rate (kg/s)	5.07×10^4
Estimated pressure drop (MPa)	2.0
LiPb pumping power (MW)	10.8
He gas inlet temperature (°C)	300
He gas outlet temperature (°C)	480
Steam temperature (°C)	450
Power cycle efficiency (%)	38

TRITIUM FUELING, BREEDING AND INVENTORY

Hollow polymeric shells are filled in a pressure chamber containing 23 MPa of molecular DT at the rate of 3 Hz. The fuel gas enters each evacuated shell via a small hole which is subsequently sealed. The targets are overcoated mechanically with Pb foil. Batches of targets are stored under helium pressure in a cryogenerator as the temperature is reduced to the triple point of DT, 19.8 K. The targets remain

at this temperature for 2 hours while a uniform thickness of solid DT forms on the interior surface of the shell due to the thermally induced sublimation of the DT resulting from the beta-decay of tritium.⁵ Subsequently, the prepared targets are stored at 4.2 K where the internal DT pressure is 4×10^{-10} Pa. A one-day's supply of fuel targets is maintained to minimize tritium inventory.

The LiPb within the reactor cavity contains the tritium formed during breeding plus the unburned DT from each target explosion. The tritium concentration in this liquid alloy is controlled by the diversion of 6.3 m³/s of the alloy to a Tritium Removal System (TRS).² The TRS is evacuated and the breeder alloy is dispersed as small droplets, 240 μm dia., which fall to the bottom of the chamber in 1 s. During this transit time, tritium effuses from the droplets until a residual tritium partial pressure of 1.3×10^{-5} Pa is achieved. By this technique, the average tritium concentration in the alloy is only 1.4×10^{-4} wppm.

In order to limit the loss of tritium to ~10 Ci/d at the steam generator, tritium removal is accomplished also, from the helium circuit. Tritium which permeates into the helium circuit is converted to the oxide form by the use of either an oxidized coating or a palladium coating on the heat exchanger with excess oxygen in the helium.⁶ The tritium oxide is adsorbed on a desiccant in the helium circuit.

The α-emitter ²¹⁰Po is generated by nuclear reactions with Pb and its Bi impurity.⁷ Because of its short half-life, 138 days, ²¹⁰Po is not a waste disposal problem; however, it could become a radioactive hazard during an accident if the coolant system ruptured. Po will effuse from the small fuel droplets during their transit through the TRS until a steady-state inventory of several 10's of kCi remains in the coolant. The probability of all of the Po escaping is low because leaking LiPb will eventually freeze and retain the Po. During normal operation the effused Po vapors from the TRS must be collected on efficient filters, which contain several MCi of ²¹⁰Po.

The solubility of tritium in the SiC fibers as a function of the concentration of tritium in the breeder alloy has not been determined, although the solubility of gaseous D₂ has been measured for SiC powders.⁸ The fibers contain excess carbon and oxygen and the oxygen probably reduces the solubility for tritium. The solubility of tritium in the fibers, 9 wppm at 500°C, was based, therefore, upon the form of SiC which has the minimal solubility for D₂, yielding an inventory of 150 g of tritium. The corrosion resistance of SiC to liquid Pb is good and similar preliminary results have been obtained for LiPb. A schematic tritium flow diagram is shown in Fig. 5.

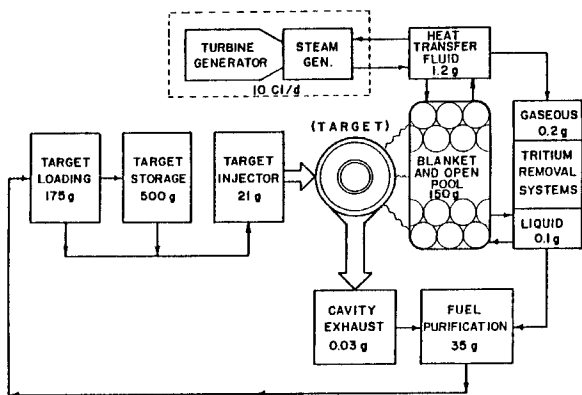


Fig. 5. Tritium flow diagram with component tritium inventories.

REACTOR CHAMBER MAINTENANCE

The roof reflector and SiC modules, the INPORTs and the magnetic protection beam tubes are not lifetime components and thus will have to be periodically replaced. A scheme for dismantling the roof of the chamber to provide access to the replaceable components has been developed. The pellet injector is removed first, followed by the vacuum flange, the six individual shield segments and finally by the structural beam/reflector/wetted surface protection coming out as a single unit. The heaviest component is ~ 100 tonnes. Once the roof components are removed, the INPORTs as well as the beam tubes can be extracted and replaced. The heat exchangers are designed such that the tube bundles can be removed radially outward. All maintenance will be performed by remote control.

SUMMARY

The chamber of the LIBRA light ion beam reactor utilizes LiPb in a self-cooled mode. The chamber wall is protected by INPORT tubes of SiC in which LiPb flows. The LiPb provides a wetted surface for surface heat absorption. The chamber is self-pumped by the target explosion generated overpressure into a suppression tank. As a safety feature, no water cooling is used anywhere in the chamber with the shield being helium cooled. Analysis of the mechanical response of the INPORTs to sequential impulses has been made. It has been found that by selectively adjusting the physical parameters, the INPORTs can be tuned to produce planar motion only, allowing for a close-pack design without dynamic interference. The neutronics analysis indicated that tritium self-sufficiency and adequate wall protection can be achieved using a 1.35 m thick zone of INPORTs. While the side and bottom chamber walls will be lifetime

components, the roof structure has to be replaced every 4 full power years. The roof is designed for disassembly to provide access for maintenance of internal components. The tritium inventory is less than 1 kg and the tritium leakage rate is kept below 10 Ci/d. Target survival and beam line protection are still viewed as critical issues.

ACKNOWLEDGEMENT

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