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ABSTRACT

The baseline design for the target chamber and chamber components for the National Ignition Facility (NIF) consists of aluminum alloy structural material. Low activation composite chamber and components have important advantages including enhanced environmental and safety characteristics and improved accessibility due to reduced neutron-induced radioactivity. A low activation chamber can be fabricated from carbon fiber reinforced epoxy using thick wall laminate technology similar to submarine bow dome fabrication for the U.S. Navy. A risk assessment analysis indicates that a composite chamber has a reasonably high probability of success, but that an aluminum alloy chamber represents a lower risk. Use of low activation composite materials for several chamber components such as the final optics assemblies, the target positioner and inserter, the diagnostics manipulator tubes, and the optics beam tubes would offer an opportunity to make significant reductions in post-shot radiation dose rate with smaller, less immediate impact on the NIF design.

I. INTRODUCTION

The National Ignition Facility (NIF) is proposed by the Department of Energy, Office of Research and Inertial Fusion to demonstrate fusion ignition in the laboratory and study controlled fusion reactions.[1] These reactions are laser-driven inertial fusion of deuterium or deuterium and tritium containing shells with spherical symmetry.[2] The facility will be used to perform experiments in inertial confinement fusion (ICF) as an alternative to full-scale tests for the nuclear weapons program. Simultaneously, experiments can be designed as an alternate route to fusion energy leading to fusion break-even conditions and eventually power production.[3]

A conceptual design of the conventional facilities, such as the laser target area buildings, the support buildings, related site development, the laser facilities, and target area including the target chamber and components has been performed.[4] The target chamber baseline design consists of an aluminum alloy Al-5083 chamber surrounded by a ~50 cm thick concrete shield. Various chamber components, including the final optics assemblies (FOA), the target positioner/inserter and the diagnostics manipulators are also primarily aluminum alloy. Aluminum is an excellent choice with respect to cost, low development risk, ease of fabrication and modification and low long-term neutron activation. The short-term (15 h halflife) activation due to ^{27}Al(n,α) ^{24}Na reactions, however, will limit contact maintenance near the chamber for about a week after a single high yield shot.[5] Also, the aluminum chamber requires a ~0.5 m external concrete shield for neutron and γ radiation shielding.[4] Significant advantages could be gained by fabricating the NIF target chamber and its components from very low-activation composite materials. Environmental and safety characteristics could be enhanced and NIF experiment accessibility could be improved by reducing neutron-induced radioactivity of the NIF chamber and its components.

General Atomics performed a design study for Lawrence Livermore National Laboratory to investigate the potential advantages and feasibility of replacing the aluminum alloy NIF chamber and chamber components with composite materials.[5] The scope of this project excluded the design of the biological shield. Fabricating the target chamber and target chamber components out of modern, commercially available very low-activation organic matrix composite materials offers an attractive alternative that has advantages over aluminum. Materials with main constituents of H, C, O, and Si exhibit extremely low activation in NIF. Various forms of carbon fiber reinforced epoxy have developed into a mature technology with superior structural and mechanical properties at a lower density than aluminum.

II. CHAMBER DESIGN

A low activation chamber can be fabricated from carbon fiber reinforced epoxy using thick wall laminate technology similar to submarine bow dome fabrication for the U.S. Navy. A hemispherical design would result in the least number of joints as shown in Fig. 1. The two hemispheres can be joined by a scarf joint using adhesive bonding and composite fasteners. Port flanges can be fabricated from composite material and locked in place with O–rings. FOAs and other components can be mounted on these flanges.

Nuclear analysis was performed using the Monte Carlo Neutron Photon Transport (MCNP) code and FISPACT 4.1 activation code. The target chamber shield thickness was configured to satisfy the NIF operating neutron dose requirement. Computations did not include contributions due to residual target material. It was assumed that a cleaning mechanism would limit the accumulation of target material on the interior walls of the chamber. In terms of neutron induced radioactivity, the composite material offers lower doses than aluminum and requires no concrete shield for γ radiation shielding. The composite material itself acts as a neutron shield as well as a structural material.

Additional neutron shieling can be accomplished with externally placed, low density, borated composite tiles. The prompt neutron dose from the target is large and requires a biological shield which is integrated with the chamber building in the NIF conceptual design.[4]

Secondary γ radiation is produced from the decay of ^{24}Na, generated by the ^{27}Al(n,α)^{24}Na reaction, which is absent in the composite material. In addition to the aluminum chamber, the concrete shield itself is a major source of ^{24}Na production because of the Al content in the concrete.[6]

The contact dose rate on the exterior of the chamber after 24 hours even after a 100 kJ shot is 0.43 mrem/hr for the aluminum chamber with the concrete shield and negligible 0.001 mrem/hr for the composite chamber. At end of life the differences are more dramatic due to the absence of long lived radionuclides in the composite system. Fabrication costs based on U.S. Navy submarine bow dome technology is estimated to be $5.5 to $7 M. For an alternate foam core design costs are estimated to be $4 M which is similar to that of the aluminum alloy baseline design. These estimates exclude a necessary testing and risk mitigation program for the composite material. Also excluded are locating and drilling of ports, transportation and installation which would be comparable to those for the aluminum alloy design.

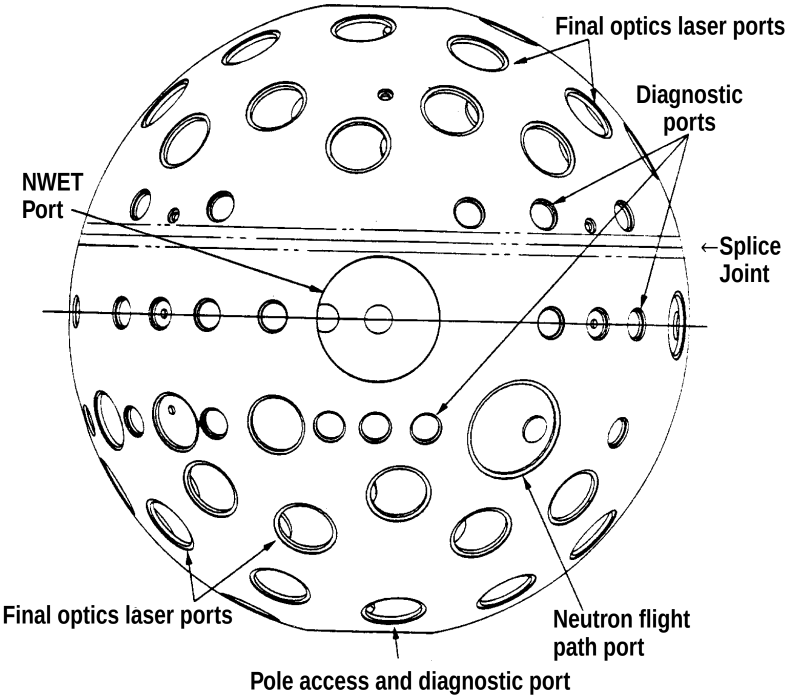

Fig. 1. Splice Joint Region Approximately 15 Degrees Above Equator.

A risk assessment based on Failure Modes, Effects and Criticality Analysis (FMECA) was performed for both the composite and aluminum alloy chambers.[7] The general conclusion is that the composite chamber represents only a slightly higher risk than the aluminum alloy chamber.

III. CHAMBER COMPONENTS DESIGN

Benefit would also be gained by making selected chamber components out of low activation composite materials. The FOAs require frequent contact maintenance to change the debris shields and are a large fraction of the planned person-rem dose for the NIF. The target positioner and inserter and the diagnostics manipulators are located close to chamber center and will receive a high neutron dose. These components have the potential for high pay-off if low activation composite materials can be used.

The main structure of the FOA's can be fabricated from carbon fiber epoxy. Internal structures such as lens and debris shield assemblies, shutter and focus lens drive can be fabricated from a variety of composite materials depending on design specific design considerations. A unique rectangular rolling seal assembly will replace a circular metal bellows. The main features of the composite design for the FOA are shown in Fig. 2.

Simplified computations of radiation shielding and induced activation were performed. The prompt neutron flux distribution was calculated with the three-dimensional MCNP code. These calculations utilized the most recent ENDF/B-Vl based cross section evaluations, MCNPDAT6. The neutron flux distributions were input into the FISPACT 4.1 activation code which was used to determine transmutation products and photon source rates as a function of time after the target implosion. Shot internals were assumed to be 2.5 days. Gamma source rates were subsequently input into MCNP to determine photon transport and contact dose rates. Neutron fluxes for both MCNP and FISPACT 4.1 computations were volume averaged over four FOA subvolumes or shells, each 0.5 cm thick for a total thickness of 2 cm.

Two cases were considered: (a) 2 cm thick carbon fiber composite FOA; and (b) 2 cm thick aluminum alloy FOA. Both FOAs were exposed to radiation due to the equivalent of a 100 kJ DT shot. The composite FOA satisfied the 0.65 mrem/hr contact dose rate limit specified in the NIF CDR within one hour after the shot. This does rate does not include contributions from the chamber and shield. Nearly all of the dose was due to ^{16}N (half life = 7 s), which decays rapidly. The aluminum alloy FOA also displayed rapid decay of activation, reaching the contact dose limit within several days. Nearly all of the dose was due to ^{24}Na (half life = 15 hr). These decay curves are shown as the dashed lines in Fig. 3. A much more significant difference becomes evident when considering the dose rate behavior at the end-of-life (EOL), shown by the solid curves in Fig. 3. EOL parameters are based on a reference NIF annual operating cycle yielding 385 MJ/yr for 30 years. This dose rate for the composite FOA shows very little change by the EOL, still reaching the unrestricted access limit within a few hours.

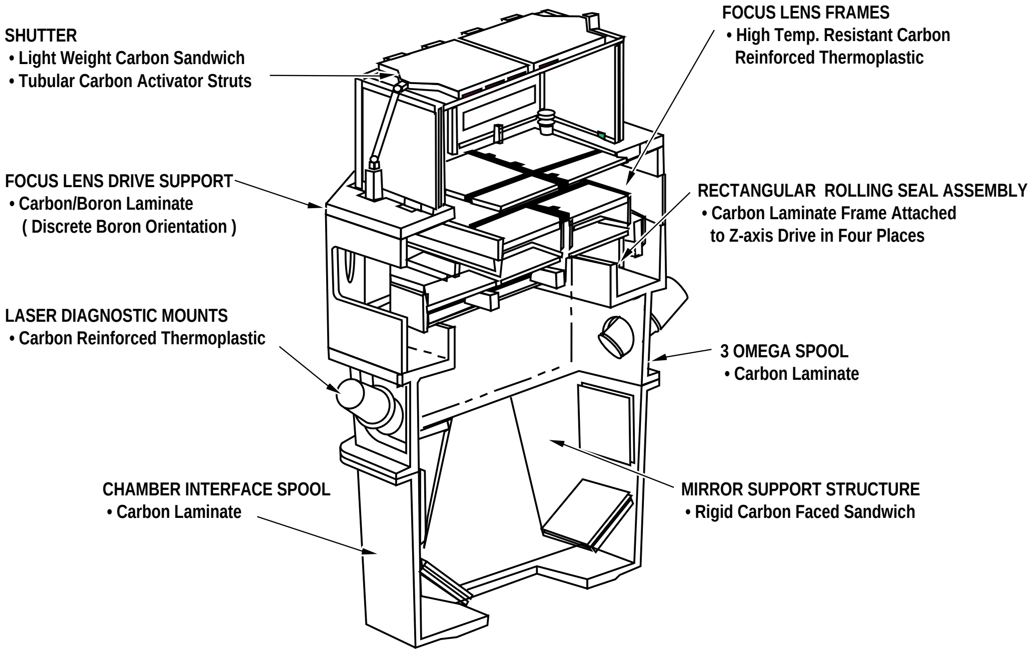

Fig. 2. Composite Final Optics Assembly Concept.

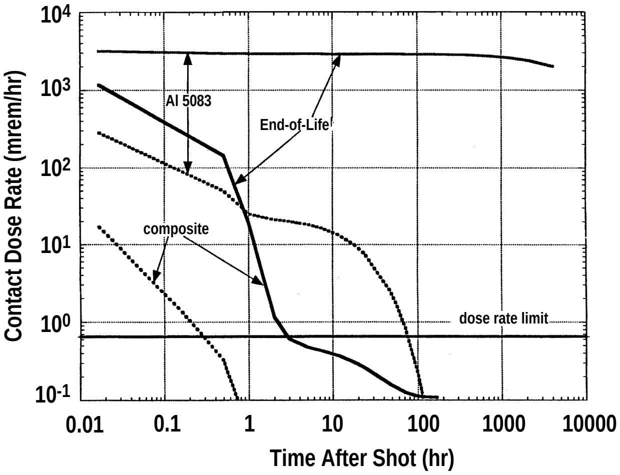

Fig. 3. Composite FOA satisfies NIF dose rate requirements through out operating lifetime. Dashed lines are activation after first 100 kJ shot. Solid lines are activation after 30 years of operation. EOL Al alloy dose rate is dominated by ^{54}Mn.

However, the results suggest that contact dose for the aluminum alloy FOA will evolve substantially by EOL. The evolution of the dose rate shows contributions by two important isotopes. The early phase is dominated by decay of ^{24}Na (half life = 15 hrs). This is also seen in the dose rate behavior after the initial 100 kJ shot. However, underlying the EOL dose rate is a more important contribution by ^{54}Mn (half life = 312 days) which accumulated over the operating life from neutron reactions with the small iron content in the Al-5083 alloy. After 2300 hrs, the EOL dose rate is dominated by ^{54}Mn and remains significantly above the unrestricted access limit.

The target positioner and inserter and diagnostics manipulators can be fabricated from high modulus carbon fiber reinforced epoxy. Due to increased stiffness and lower density compared to aluminum the diameter can be reduced from 50–75 cm to 20–30 cm. The proper X, Y, Z and rotational positioning in the nose of the target positioner can be accomplished with pneumatically operated motors and actuators for a substantial weight savings of the tip.

The optics beam tubes can be fabricated from a low cost fiber glass epoxy material system or extruded high density polymeric material.

IV. CONCLUSIONS

The results of this study show that low activation composite materials could be of practical use for target chamber components on the NIF. An all composite target chamber is technically feasible, would significantly reduce the post-shot radiation dose rate, and would cost only slightly more than the reference aluminum alloy design to fabricate. However, it entails increased design, implementation, and manufacturing risk. Use of low activation composite materials for several chamber components such as the final optics assemblies, the target positioner and inserter, the diagnostics manipulator tube, and the optics beam tubes would offer an opportunity to make significant reductions in post-shot radiation dose rate with smaller, less immediate impact on the NIF design. We recommend that serious consideration be given to adopting very low activation composite materials for these chamber components on NIF.

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