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NEUTRON ACTIVATION OF THE NIF FINAL OPTICS ASSEMBLIES AND THEIR EFFECT UPON OCCUPATIONAL DOSES

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ABSTRACT

During routine operations, the National Ignition Facility (NIF) will attain fusion yields as high as 1200 MJ/yr with individual experiments reaching 20 MJ. Neutron activation of components within the NIF Target Bay will result in occupational doses that must be understood and limited to ≤ 10 person-rem/yr. Previous work has shown that the final optics assemblies (FOAs) are the key to worker doses. The present work gives results for three-dimensional analyses including dose rates and worker doses. Results for modified FOA designs are also presented. Finally, a concept for a polyethylene shielding plug is discussed and shown to substantially reduce occupational doses.

I. INTRODUCTION

Construction of the NIF at Lawrence Livermore National Laboratory is currently underway. Initial operations will begin in Fiscal Year 2001 (FY01), and the facility will be completed in FY03. During peak operation, the NIF will attain D-T fusion yields of 1200 MJ/yr and produce 4.3×10^{20} 14 MeV neutrons per year. Individual experiments will attain fusion yields of up to 20 MJ (7×10^{18} 14 MeV neutrons). With such high yields, neutron activation will be important within the NIF Target Bay. Individual doses will be maintained ≤ 500 mrem/yr and the total occupational dose will be ≤ 10 person–rem/yr. Even once these limits have been met, NIF doses must be kept "as low as reasonably achievable" (ALARA).

During routine operation, target debris and ablated materials from the target positioner, first wall, beam-dumps, and diagnostics will be mobilized and have the potential to contaminate the debris shields. As a result, it is believed that the 192 debris shields will require change–out on approximately a weekly basis. Two-dimensional analyses with a preliminary design for the FOA have shown that the task of debris shield change–out will be responsible for the majority of dose received by workers. The dose rates experienced during this task are dominated by contributions from the FOA structure itself.

The present work details the results of 3-dimensional (3-D) neutron transport and activation calculations of the matured design for the FOA. Equilibrium dose rates, following years of radionuclide build-up during peak operation, are presented. Worker doses are presented for the baseline FOA as well as for modified designs. A concept for use of a polyethylene shielding plug reduces occupational doses substantially.

II. METHOD OF ANALYSIS

Analysis of the FOAs requires a set of computer codes and the creation of 3-D model for use with these codes. The following sections describe the computational process and the details of the FOA model that has been created for this work.

A. Computer Code System

A system of computer codes has been used to calculate the residual dose rates from NIF systems following yield operations. Calculations begin with the TART and TARTCHEK codes.[1] TART is a 3-D Monte Carlo neutron and photon transport code. It features a 175-group neutron structure that results in great speed when compared with other Monte Carlo codes. TARTCHEK is an interactive geometry visualization and error-checking code and is essential in the development of complicated, 3-D models. TART is used in conjunction with TARTCHEK to calculate energy-dependent neutron and photon pathlengths. Neutron pathlengths are converted into fluences and are used as an input to activation calculations. Photon pathlengths are converted into γ-ray fluxes and are used to estimate dose rates at a given location.

The TARTREAD code is used to read TART output and create input files for subsequent neutron activation calculations.[2] TARTREAD is an interactive code that prompts the user for selection of zones of interest, materials of choice, and an irradiation sequence. TARTREAD greatly simplifies the generation of activation input files.

Nuclide inventories have been calculated with the ACAB code.[3] A 1993 study sponsored by the International Atomic Energy Agency (IAEA) identified ACAB as one of only two codes that were "suitable and satisfactory" for detailed fusion calculations.[4] The present work utilizes an updated version of ACAB with expanded features including the ability to model pulsed irradiation accurately, to treat sequential charged-particle activation, and to treat actinides and fission products.

Gamma-ray dose conversion factors adopted by the American National Standards Institute have been used in this work.[5]

Residual dose rates, calculated with TART and ACAB, have been converted into worker doses assuming a fixed shot sequence. A year with 60 individual shots, each with 20 MJ of fusion yield, has been assumed. These shots are assumed to occur at intervals of 6 days with maintenance activities occurring between 5 and 6 days after the previous shot. In true operations, neither the fusion yield nor the spacing between experiments will be so precise. These assumptions, however, are consistent with the basic requirements for NIF operation.[6]

B. 3-D FOA Model

A 3-D model has been created for use with the TART code. This model has been generated from design drawings produced by the FOA design team. While not all aspects of the FOA design have been modeled in complete detail, the key components have been included. The FOA model includes approximately 500 geometric zones and uses 10 different materials.

The FOA is divided into three major components or "spools." These are the Vacuum Isolation Valve (VIV), the 3ω Calorimeter, and the Integrated Optics Module (IOM). Figure 1 is a design drawing of the 3ω Calorimeter. Figure 2 is a plot showing the actual TART model for the VIV and 3ω Calorimeter. Many of the details of the calorimeter design have been modeled.

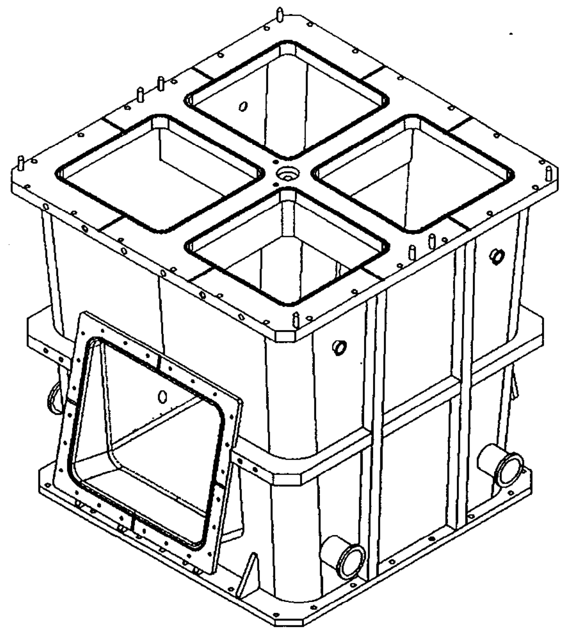

Figure 1. The 3ω Calorimeter is shown without the VIV or IOM spools.

Since the IOMs are symmetric about the centerline of the VIV, only one-quarter of the geometry was modeled. Figure 3 shows the major optical components within the FOA as well as the support structures.

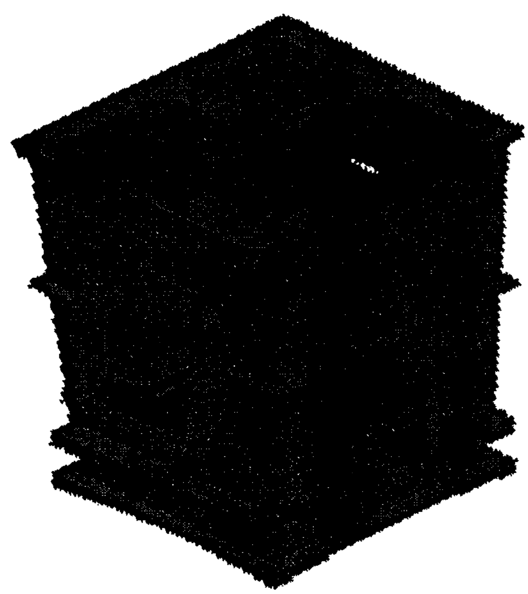

Figure 2. The VIV and 3ω Calorimeter spools are shown as modeled with the TART Monte Carlo transport code.

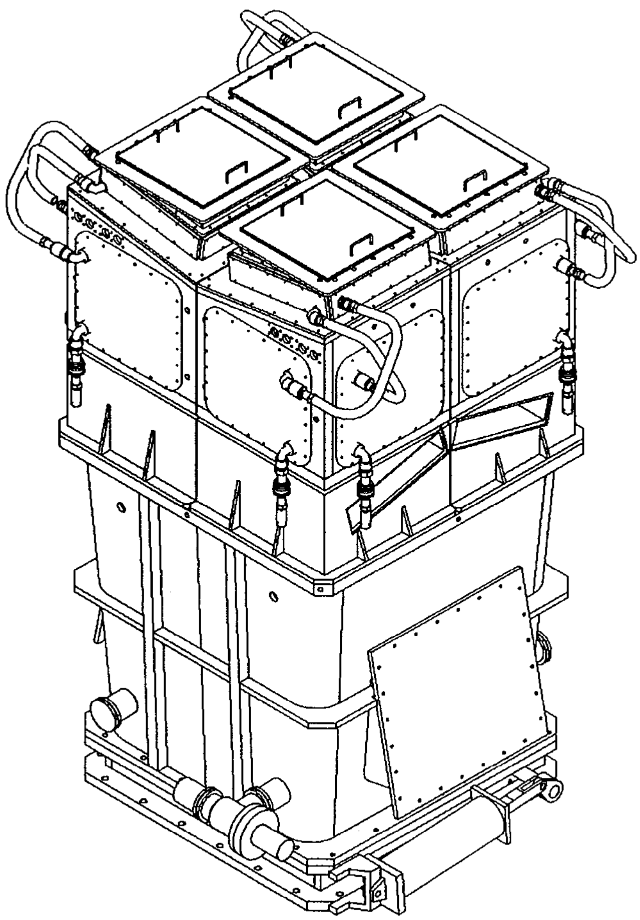

Figure 3. An entire FOA is shown as designed -- the VIV, 3ω Calorimeter, and four IOMs.

Figure 4 is a view of the IOM in which the walls of the IOM and the optics cell have been removed so that the details can be seen. On the right side of the figure are the debris shield and diffractive optics cassettes. In the center are the final focus lens and the frequency conversion crystals.

Figure 4 is also a good example of the methods that have been used in the present work. Details that are likely to affect the outcome of the analysis have been modeled in great detail. Those components that are unlikely to make significant contributions to the total dose rates, however, have been modeled in a more approximate manner. Figure 5 shows an approximate model for the motors within the optics cell. The shape of the optical components also has been approximated.

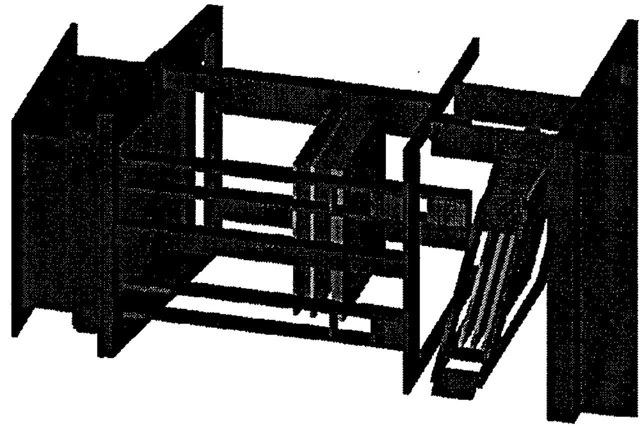

Figure 4. In this cut-away view of an IOM, the walls have been removed to reveal the six optical components and the vacuum window.

III. RESULTS

Residual dose rates have been calculated immediately after a final, 20 MJ yield following 10 years of NIF operation at 1200 MJ/yr. Figure 5 is a plot of the gamma-ray dose equivalent rate that would be experienced by a worker standing next to the FOA in a position to remove and replace one of its debris shields. The dose rates include contributions from nearby equipment such as the target chamber and gunite shielding.

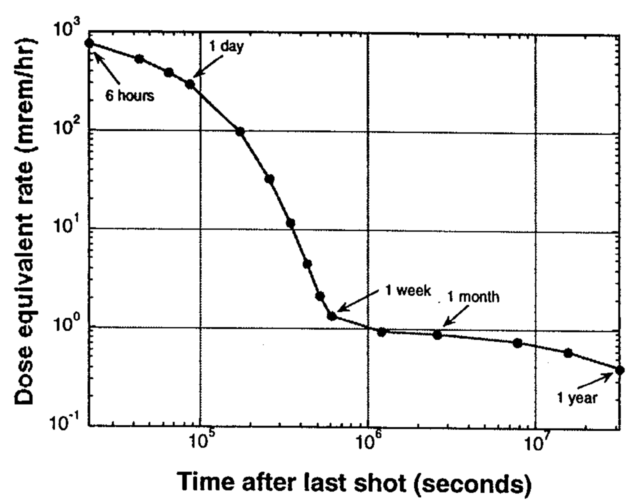

Figure 5. The residual dose rate near a single FOA remains above 1 mrem/hr for more than 7 days.

Immediately after a high-yield experiment, the residual dose rate is nearly 1 rem/hr. At a time of 5 days after the experiment, when workers would be replacing debris shields, the dose rate would be about 4.5 mrem/hr. Since debris shields (all 192 of them) need to be replaced weekly and will require 15 person-minutes per debris shield, this would result in an annual occupational dose of over 11 person-rem. Once all 48 FOAs and other tasks considered, the occupational dose climbs to 27.3 person-rem/yr.

In an effort to reduce the occupational doses, major contributors to the total dose rate have been identified. During debris shield change-out, dose rates are dominated by contributions from the VIV and 3ω Calorimeter. These components could be constructed with alternate, low-activation materials such as carbon composite. Estimates are that such construction would be 3-5× more expensive than conventional construction from an aluminum alloy.[7] Replacement of the VIVs would cost $4.3-7.2M ($30k each for aluminum construction). Such a retrofit would reduce occupational doses by approximately 11.5 person-rem/yr at a cost of $19-31k per person-rem saved. Normal ALARA guidance calls for the expenditure of only $2.5k per person-rem saved. If the 3ω Calorimeter spools were replaced instead, the occupational dose would be reduced by 3.7 person-rem/yr. This would cost $2.2-3.6M ($15k per unit times a factor of increase of 3-5) resulting in a cost-benefit ratio of $30-49k per person-rem saved.

Implementation of both of the above modifications would reduce the total annual occupational dose to approximately 12.2 person-rem. This reduction would require an expense well above that justified from an ALARA standpoint.

An alternate concept for reducing occupational doses has been proposed and evaluated. Auxiliary shielding, internal to the FOA flange may be used to reduce the neutron flux in the FOA. Specifically, a polyethylene "plug" will be inserted within the flange tube in front of the VIV spool. Figure 6 shows a cross section of what such a plug might look like. It would, of course, require a rectangular opening in its center to allow the laser beams to pass through. Additionally, the plug would need to be clad within some type of casing for protection against x-rays, stray laser light, debris, and for vacuum considerations (out-gassing).

Use of the polyethylene plug would provide a substantial dose reduction. Figure 7 shows the dose rates for each of the concepts that have been analyzed for decay times of 4 to 6 days. The polyethylene plug yields a dose reduction equal to that for a composite VIV. Implementation of the polyethylene plug is expected to be relatively inexpensive and probably less than $10k per port. This results in a cost-benefit ratio of $3k per person-rem saved. This is approximately equal to the ALARA guidance.

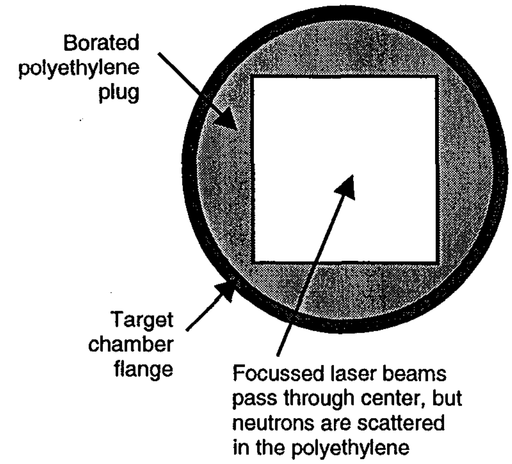

Figure 6. The polyethylene plug would be a right circular cylinder with a rectangular penetration to allow the laser beams to pass through its center.

If only the "baseline" polyethylene plug were to be implemented, the total annual occupational dose would be 19.5 person-rem/yr. Additional shielding may be placed within some portions of the VIV itself, and the plug design still must be optimized. Table I summarizes the options that have been considered and the occupational doses that would result. The table also estimates values for an optimized polyethylene plug.

IV. CONCLUSIONS AND FUTURE WORK

Due to the need for frequent access to the area around the FOAs and significant dose rates in this area, the total annual occupational dose would be unacceptably high for the baseline FOA design. Several material replacements and a shielding material addition were analyzed and have been shown to provide substantial reduction in the occupational dose. None of these options, if implemented independently, would reduce the dose to the limit of 10 person-rem/yr. The option offering the biggest return for the cost is the polyethylene shielding plug to be located within the FOA flange tube. Optimization of this shielding plug should decrease the occupational dose close to acceptable levels. An optimized plug, in conjunction with minor material replacements and operational procedures, will decrease the occupational dose to the limit.

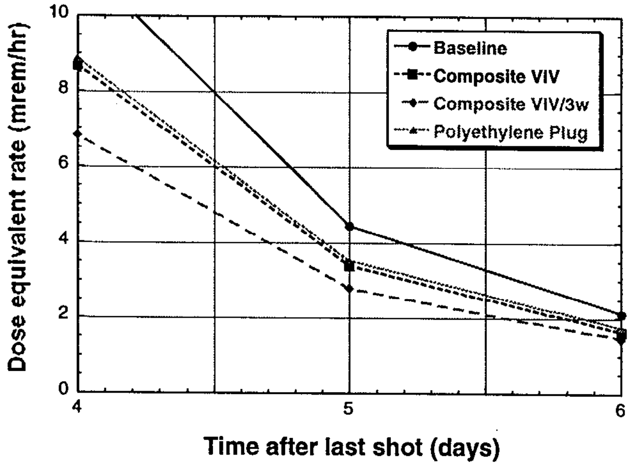

Figure 7. Use of a polyethylene plug would reduce dose rates near the FOAs to about the same level as if the VIV is replaced with a low-activation composite.

Future work will concentrate upon optimization of the polyethylene plug and continuing the search for low-activation materials that might be used in a cost-effective manner. Time and motion studies will continue to be developed in order to increase the understanding of the tasks that must be performed within the NIF Target Bay and how the doses associated with these tasks might be decreased. Other work will focus upon methods of auxiliary shielding.

Table I. The total doses show that more work is needed.

Case description	Total dose rate near FOAs at t=5 d (mrem/hr)	Total annual occupational dose (person-rem/yr)
Baseline	5.15	27.3
Composite VIV	3.43	15.9
Composite VIV & 3w Calorimeter	2.56	12.2
Polyethylene shielding plug	4.18	19.5
Optimized polyethylene plug*	3.5	14.0

*Estimated

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