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H. Khater, L. Dauffy, S. Sitaraman, S. Brereton

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EVALUATION OF PROMPT DOSE ENVIRONMENT IN THE NATIONAL IGNITION FACILITY DURING D-D AND THD SHOTS

Hesham Khater, Lucile Dauffy, Shiva Sitaraman, and Sandra Brereton

Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, khater1@llnl.gov

Evaluation of the prompt dose environment expected in the National Ignition Facility (NIF) during Deuterium-Deuterium (D-D) and Tritium-Hydrogen-Deuterium (THD) shots have been completed. D-D shots resulting in the production of an annual fusion yield of up to 2.4 kJ (200 shots with 10^{13} neutrons per shot) are considered. During the THD shot campaign, shots generating a total of $2x10^{14}$ neutrons per shot are also planned. Monte Carlo simulations have been performed to estimate prompt dose values inside the facility as well as at different locations outside the facility shield walls. The Target Chamber shielding, along with Target Bay and Switchyard walls, roofs, and shield doors (when needed) will reduce dose levels in occupied areas to acceptable values during these shot campaigns. The calculated dose values inside occupied areas are small, estimated at 25 and 85 µrem per shot during the D-D and THD shots, respectively. Dose values outside the facility are insignificant. The nearest building to the NIF facility where co-located workers may reside is at a distance of about 100 m from the Target Chamber Center (TCC). The dose in such a building is estimated at a fraction of a µrem during a D-D or a THD shot. Dose at the nearest site boundary location (350 m from TCC), is caused by skyshine and to a lesser extent by direct radiation. The maximum off-site dose during any of the shots considered is less than 10 nano rem.

I. Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory will be the world's largest and most powerful laser system for inertial confinement fusion. NIF is a 192 laser beam facility that will produce 1.8 MJ, 500 TW of ultraviolet light. NIF consists of three buildings; Laser and Target Area Building (LTAB), Diagnostics Building (DB), and Optics Assembly Building (OAB). As shown in Fig. 1, the main laser systems are installed in two laser bays inside the LTAB. Each laser bay delivers 96 beams into one of two Switchyards. Sets of turning mirrors in each Switchyard (SY) redirect the beams into the Target Bay (TB). Additional sets of optics in the TB will align and focus the beams onto the target in the center of the Target Chamber (TC). The 192 beams enter the TC through 48 indirect-drive beam ports. Laser beams then enter a metal can (hohlraum) and create thermal x-rays that heat the surface of the fusion capsule.

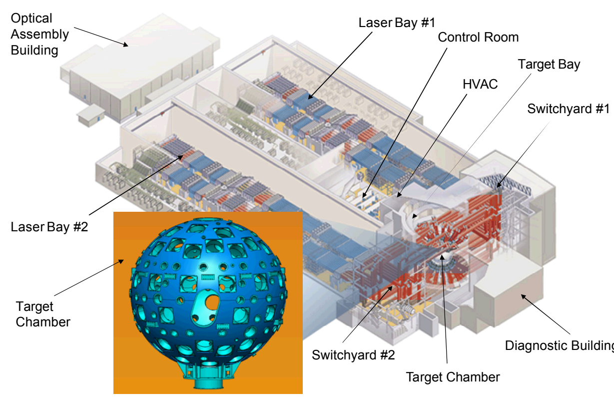

Fig. 1. Layout of the NIF facility.

The Target Bay has a semi-cylindrical design with an inner radius of 50', 6'-thick concrete walls and 4.5'-thick concrete roof. There are six main floor levels within the TB at elevations of -33'-6", -21'-9", -3'-6", 17'-6", 29'-6" and 50'-6" and two diagnostics mezzanines at elevation of 7'-10" and 40'-0" with respect to the ground level. The TC is located in the middle of the TB with its center at elevation of 23' from the ground level. Twenty TB doors connect the TB and the two SY. A total of 174 and 48 utility penetrations are present in the TB and SY walls, respectively.

The NIF operation is divided into four different phases.[1] Phase I includes laser operations with up to 192 beams and 100 hohlraum shots (with no fusion targets) per year. The main radiation hazard in this phase is caused by x-rays generated due to 3ω (ultraviolet) laser interactions with different target materials. Phase II includes all Phase I operations and a maximum of 200 Deuterium-Deuterium (D-D) shots per year with maximum yield of 10^{13} neutrons/shot. Phase III includes

Phase II operations plus a combination of Tritium-Hydrogen-Deuterium (THD) shots and Deuterium-Tritium (D-T) shots for a maximum annual yield of 30 kJ ($1x10^{16}$ neutrons/year). The THD shots are limited to a maximum of $2x10^{14}$ neutrons/shot. Finally, Phase IV, which represents the full NIF operations, includes Phase III operations and D-T shots with routine 20 MJ yield per shot, and a maximum annual yield of 1200 MJ.

This paper summarizes results of analyses performed to evaluate the potential radiological hazard posed by neutrons generated due to D-D and THD fusion shots during Phases II and III of the NIF operation. Evaluation of the prompt dose levels inside and outside the facility shield walls is presented for the two campaigns. Similar analysis for hazard associated with Phase I of NIF operation has been separately published.[2] Results for prompt dose analysis expected during D-T shots in Phases III and IV will be separately presented.

II. NIF Facility Modeling for Prompt Dose Analysis

A detailed 3-D model of the NIF facility has been developed using the MCNP radiation transport code.[3] The Target Chamber (TC) is made of a 10-cm-thick aluminum wall surrounded by 40-cm of borated concrete. The TC includes, 48 indirect-drive and 24 direct-drive laser beam ports as well as 120 diagnostic ports. All diagnostic and direct-drive ports are assumed to be unshielded and only covered with ~ 2"-thick port covers made of aluminum alloy. Indirect-drive ports are connected to fully modeled Final Optics Assemblies (FOA). The Target Bay (TB) shielding walls are made of 6'-thick concrete, and the typical thickness of a concrete Switchyard (SY) wall is 3'–3".

A total of 19 primary TB doors connect the TB and the two Switchyards. An additional TB door "TOTIM" connects the TB and the Diagnostic Building (DB). The analysis presented in this paper assumes that none of the TB shield doors (except for the 6'-thick concrete door "TOTIM") have been installed in the facility during D-D shots. An additional shield door will be installed at the 17'-6" floor level prior to the start of THD shots. Additionally, there are 29 secondary doors at points of entry into the Switchyards, including the two facility elevators. This analysis assumed that none of the secondary shield door will be in place during D-D or THD shots. All remaining primary and secondary shield doors will be installed prior to Phase IV of NIF operation. The detailed TB model used in this analysis is shown in Fig.2. The figure shows details of TC with all diagnostics and direct-drive ports covered with the aluminum port covers. It also shows the 48 FOAs and all TB floors including floor penetrations.

Calculations are performed to identify the level of radiation streaming through the following penetrations in the TC, TB, and SY walls:

1. 48 indirect-drive beam ports in TC;
2. 24 direct-drive beam ports TC;
3. 120 diagnostic ports in TC;
4. 2 diagnostic penetrations in TB wall;
5. 175 utility penetration in TB wall;
6. 48 utility penetrations in Switchyard walls.

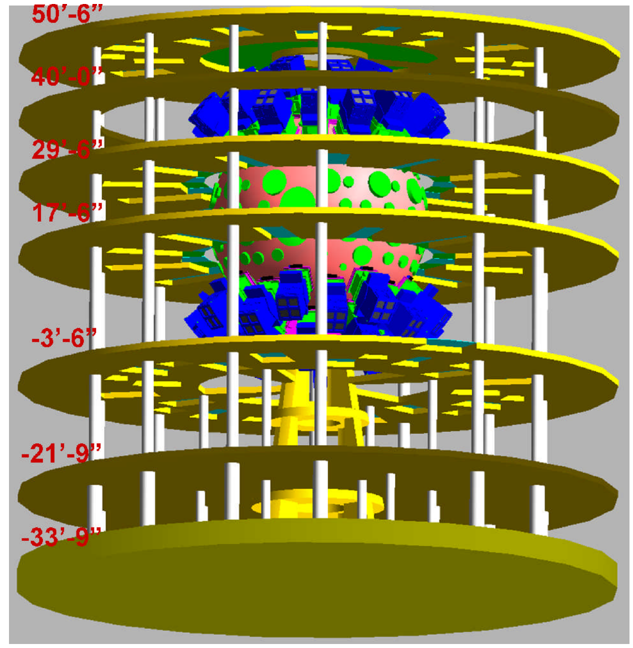

Fig. 2 MCNP model of the NIF Target Bay.

The neutron cross section data were taken from the FENDL-2.1 cross section database.[4] Photon cross sections are derived from the ENDF/B-VI.8 data library. Effective dose values are calculated inside the NIF facility using the ICRP-74 Anterior-Posterior (AP) neutron fluence-to-dose conversion coefficients.[5] On the other hand, effective dose values outside the facility shield walls are calculated using the ICRP-74 Isotropic Geometry (ISO) neutron conversion coefficients. Finally, an isotropic source of neutrons is assumed at the target center. The D-D neutron source consists of 98% 2.45 MeV (D-D) and 2% 14.1 MeV (D-T) neutrons, and a total 0f 10^{13} neutrons per shot. On the other hand, a detailed THD neutrons source spectrum was generated based on a 1.6% Deuterium ratio and a total number of neutrons of $2x10^{14}$ neutrons per shot.[6] Mesh tallies are used to produce prompt dose maps of the entire facility. Dose values outside the TB doors (at locations with highest doses) are also calculated.

III. Prompt Dose during D-D Shots

Prompt dose values are calculated inside the TB, outside all primary TB doors, and outside all secondary doors leading to SY1 and SY2. No access is allowed to the inside of the TB or the two SYs during shots. Figure 3 shows the expected dose values during a D-D shot at the 17’-6” floor level. This floor level experiences the highest level of radiation due to neutrons streaming out of the chamber through the large number of diagnostics ports located near the TC waist. The dose values range from a maximum of 110 mrem inside the TB to 6 mrem outside the two unshielded primary TB doors (in the unoccupied SYs). Keep in mind that these primary shield doors will not be installed until Phase IV (ignition campaign). The dose inside the unoccupied Elevator 1 (elevators are disabled during shots), is 2 mrem. The dose in the normally occupied DB is a fraction of mrem. Dose values that are < 1 μrem are not assigned a color on the maps.

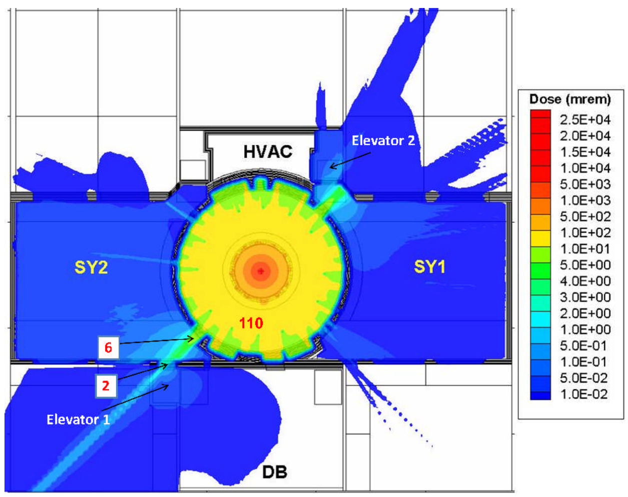

Fig. 3. Prompt dose map of the 17’-6” floor level during D-D shots.

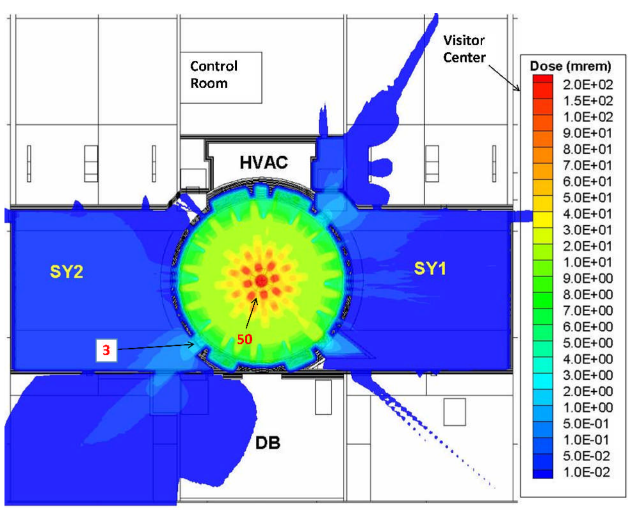

Fig. 4. Prompt dose map of the -3’-6” floor level during D-D shots.

Figure 4 shows prompt dose values at the ground level. The -3’-6” floor level is considered the ground level for the TB, SYs and DB. Dose inside the TB at this level is about half its value in the 17’-6” floor level. The dose in the occupied DB remains on the order of 1 μrem. Much lower (insignificant) dose values are expected in the control room and the visitor center. Dose maps of other floor levels showed lower dose values than shown in figures 3 and 4. Prompt dose values outside the facility at near-by building and at the nearest site boundary (at 350 m from TCC) are 30 and 0.4 nano rem, respectively.

The final two dose maps shown for the D-D shots are for the -21’-9” and 50’-6” floor levels. These are the two floor levels where laser beam pass through the TB wall. The TB wall thickness increases at these 2 floor levels from the nominal 6’ to12’. The reason for increasing the concrete thickness is to allow for additional collimation of neutrons passing through the laser beam ports and hence reduce the radiation environment in the two SYs as well as the rest of the facility. There are 12 indirect-drive and 2 direct-drive laser beam penetrations at each of the two floor levels. Each penetration is 3’-9” wide and 4’ high. Since the current NIF configuration does not utilize direct drive ports, a 1’-thick concrete block was placed inside each of the direct-drive penetrations at each floor level.

As shown in Fig. 5, the radiation streaming through the laser beam penetrations results in low dose values (< 0.05 mrem) during the proposed D-D shots. A higher dose value of 0.7 mrem is calculated outside the TB doors. This low dose value confirms that shielding the TB doors is not needed for NIF operation during D-D shots. A dose value of 3 mrem is shown inside the Neutron Spectrometry (NS) room. This room is unoccupied during the shots. The reason for the higher dose at this location is that a section of the 6’-thick concrete wall that is facing the room is not schedule for installation until the start of the ignition campaign with higher yield D-T shots. Finally, the maximum dose inside the TB during the shot at this floor level is ~ 7 mrem. Notice that higher dose values shown on the map in red color represent the dose inside the laser beam tubes which are not accessible.

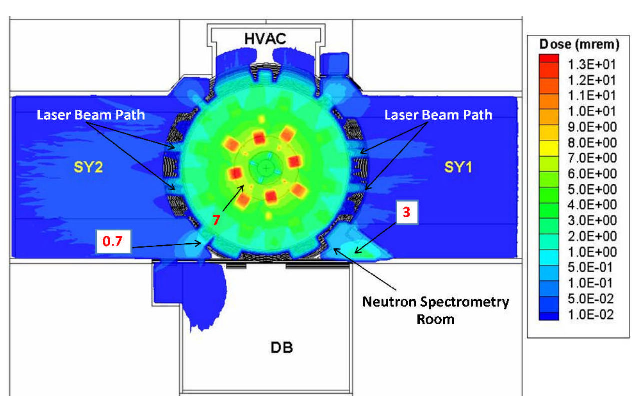

Fig. 5. Prompt dose map of the -21’-9” floor level during D-D shots.

Dose map of the 50'-6" floor level, Fig. 6, exhibits a similar trend as the -21'-9" level. The radiation streaming through the laser beam penetrations also result in low dose values (< 0.05 mrem). The dose expected outside the TB doors is in the order of 0.5 mrem per shot and the dose inside the TB is about 5 mrem. As a final observation, it is important to notice that the dose values in the normally occupied DB are negligible even without secondary shield doors which are scheduled for installation before the start of Phase IV of NIF operation.

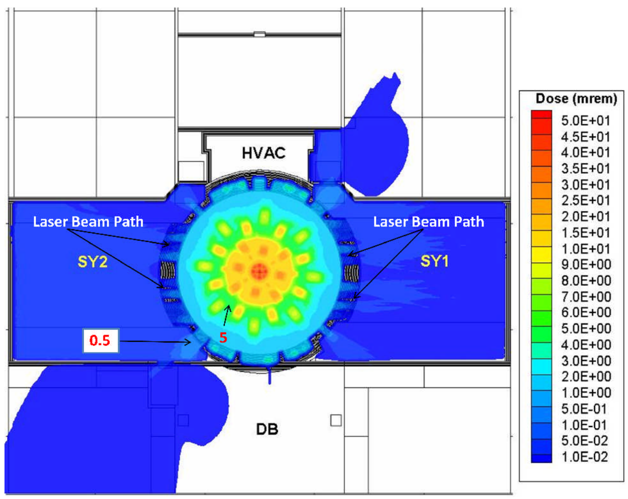

Fig. 6. Prompt dose map of the 50'-6" floor level during D-D shots.

IV. Prompt Dose during THD Shots

Several THD shots are scheduled to take place during Phase III of NIF operation. The scheduled shots will use a deuterium fraction of 1.6% and generate a total of $2x10^{14}$ neutrons/shot. Most of the neutrons are generated by D-T reactions with about 15% produced by the T-T reaction. The amount of D-D neutrons is quite small. Due to the expected higher dose associated with THD shots in comparison to the D-D shots, an additional TB shield door will be installed at the 17'-6" floor level prior to the start of Phase III of NIF operation. The 3'-thick concrete door will be installed at the entry point between SY2 and the TB. Results presented in this section will not address the second part of Phase III where a total neutron yield of 10^{16} will be generated by D-T shots.

As in the D-D case, prompt dose values are calculated inside the TB as well as outside primary TB and secondary doors leading to SY1 and SY2. No access is allowed to the inside of the TB or the two SY during shots. Dose map of the 17'-6" floor level is shown in Fig. 7. A maximum dose of 2000 mrem is expected inside the TB (unoccupied area) during a THD shot. The dose outside a primary TB door (also unoccupied area) is 135 mrem and 0.3 mrem in case of the unshielded (SY1 side) and shielded (3'-thick concrete on SY2 side) doors, respectively. The TB shield door on the SY2 side is needed to mitigate radiation streaming through the door and hence reduce dose values in Elevator 1 and outside the DB. Walls of Elevator 1 and the DB building are made of thin sheetrock which does not provide effective shielding for neutrons. On the other hand, radiation streaming through the TB door on the SY1 side is stopped by the 2'-thick concrete wall separating SY and the Laser Bay.

Smaller dose values are expected outside the two 36"-diameter diagnostics penetrations. The dose outside the Neutron Activation Diagnostics (NAD) and the Neutron Imaging Diagnostics (NID) is ~ 2 mrem. Concrete blocks that are 1'-thick are placed inside each diagnostics penetration when it is not in use. Future plans for using these diagnostics penetrations will include design of beam dumps to contain the beam when the shielding blocks are removed.

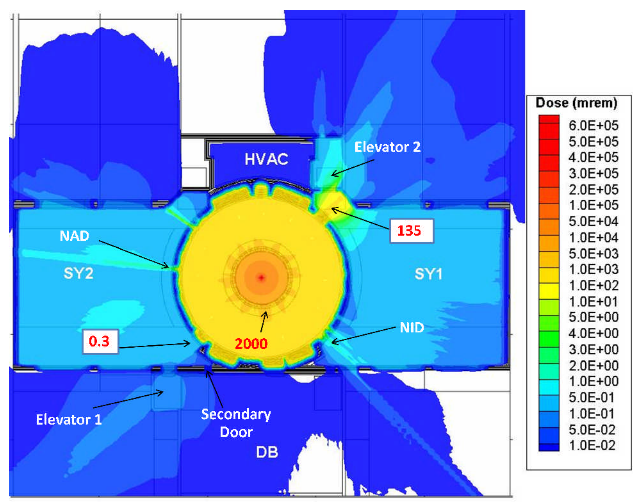

Fig. 7. Prompt dose map of the 17'-6" floor level during THD shots.

Similar to D-D shots, the dose inside the TB at the ground floor level (-3'-6") is about half its value at the 17'-6" floor level. As shown in Fig. 8, the dose inside the TB is ~ 1000 mrem (unoccupied area). Outside the unshielded TB doors, the dose drops to ~ 50 mrem (also unoccupied area) and drops further to ~ 0.7 mrem outside the DB. The area outside the DB is not normally occupied during the shots but a passer-by could be present. The dose in the occupied DB is below 0.1 mrem during the shot. Doses in the control room and visitor center remain in order of 1 μrem per shot. Prompt dose values outside the facility remain small for THD shots. The dose in a near-by building and the nearest site boundary are 500 and 7 nano rem per shot, respectively.

Analyses of the radiation levels in the -21'-9" and 50'-6" floor levels show that neutron streaming through the laser beam penetrations in the TB wall result in doses in the SYs that are < 1 mrem per shot. As shown in Fig. 9, in case of the -21'-9" floor level, the maximum dose outside the unshielded TB door is 20 mrem (unoccupied area). There is no DB floor at the -21'-9" floor level but the dose outside the secondary door connecting the DB corridor to SY2 is 0.2 mrem per shot. During a shot, the dose inside the unoccupied NS room climbs to about 70 mrem. As mentioned before, dose values in the NS room will drop significantly during higher yield shots after installation of the remaining open section of the TB wall.

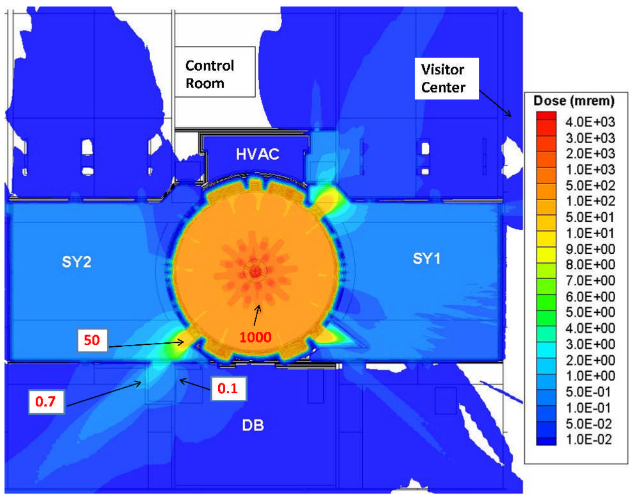

Fig. 8. Prompt dose map of the -3'-6" floor level during THD shots.

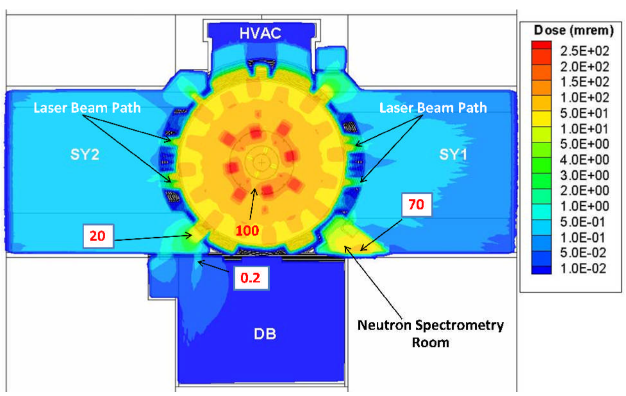

Fig. 9. Prompt dose map of the -21'-9" floor level during THD shots.

The radiation levels on the remaining floor levels are somewhat similar to what has been shown already. For example an examination of the dose values calculated for the 29'--6" floor level showed that the maximum dose inside the TB is in the same order as what was calculated at the -3'-6" floor level. Finally, dose values expected in the -33'-6" floor level are the lowest in the NIF building.

V. SUMMARY

Detailed analyses of dose values within and outside the NIF facility during D-D shots and THD have been completed. Dose values during a single D-D shot generating 12 J of fusion yield (10^{13} neutrons) were calculated at different locations from the TCC inside and outside the facility. A total of 200 D-D shots per year are expected during Phase II of the NIF operation. The dose values in normally occupied area are small and the results confirmed that there is no need for additional primary TB shield doors (in addition to the existing "TOTIM" door). No secondary shield doors are needed for this phase of NIF operation. The neutron yield during THD shots is factor of 20 higher than the D-D yield and the resulting dose values are higher by about the same ratio. Primary TB and secondary shield doors are also not needed for the THD shots, except for an additional 3'-thick concrete shield door that will be installed at the SY2 side of -3'-6" floor level. All of the calculated dose values easily meet the DOE requirements in regard to personnel safety. In conclusion, the dose values inside and outside the NIF facility during D-D and THD shots are small and do not pose a hazard to workers, visitors or the public.

ACKNOWLEDGMENTS

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