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PRESSURE EFFECTS ANALYSIS OF NATIONAL IGNITION FACILITY CAPACITOR MODULE EXPLOSION EVENTS[1]

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ABSTRACT

Capacitors and power conditioning systems required for the National Ignition Facility (NIF) have experienced several catastrophic failures during prototype demonstration. These events generally resulted in explosion, generating a dramatic fireball and energetic shrapnel, and thus may present a threat to the walls of the capacitor bay that houses the capacitor modules.

The purpose of this paper is to evaluate the ability of the capacitor bay walls to withstand the overpressure generated by the aforementioned events. Two calculations are described in this paper. The first one was used to estimate the energy release during a fireball event and the second one was used to estimate the pressure in a capacitor module during a capacitor explosion event. Both results were then used to estimate the subsequent overpressure in the capacitor bay where these events occurred. The analysis showed that the expected capacitor bay overpressure was less than the pressure tolerance of the walls.

To understand the risk of the above events in NIF, capacitor module failure probabilities were also calculated. This paper concludes with estimates of the probability of single module failure and multi-module failures based on the number of catastrophic failures in the prototype demonstration facility.

INTRODUCTION

The National Ignition Facility (NIF) is a U.S. Department of Energy (DOE) inertial confinement laser fusion experimental facility currently under construction at the Lawrence Livermore National Laboratory (LLNL). The NIF mission is to achieve inertial confinement fusion ignition, contribute to the development of inertial fusion for electrical power generation, provide simulation capability for nuclear weapons effects testing, and to support basic science and technology.

The NIF will be an enormous facility, about 200 meters long by 85 meters wide. The NIF's laser system will have 192 beams that are arranged in 24 bundles of 8 beams each. Together the beams will produce about 500 TW of power (1.8 MJ over four billionths of a second). The laser light is in the ultraviolet spectrum at a wavelength of 0.35 μm. The beams will precisely compress and heat a one to three millimeters diameter target containing deuterium-tritium fuel to 100 million degrees. The result will be ignition for the first time in a laboratory. The NIF's construction began in 1997, and experiments may begin in 2003.

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A schematic layout of the NIF is depicted in Figure 1. The 24 laser bundles are grouped into 4 clusters of 6 bundles each. Clusters 1 and 2 are located in Laser Bay 1. They propagate from the Master Oscillator Room, through Laser Bay 1, Switchyard 1, Target Bay, and end at the center of the Target Chamber. Clusters 3 and 4 are located in Laser Bay 2. They propagate from the Master Oscillator Room, through Laser Bay 2, Switchyard 2, Target Bay, and end in the Target Chamber. The Capacitor Bays 1, 2, 3, and 4 store the power supply for laser Clusters 1, 2, 3, and 4, respectively.

The purpose of this paper is to evaluate the overpressure in the capacitor bay generated by a capacitor module explosion event and the impact of the overpressure on the capacitor bay walls. The evaluation is part of the NIF safety analysis.

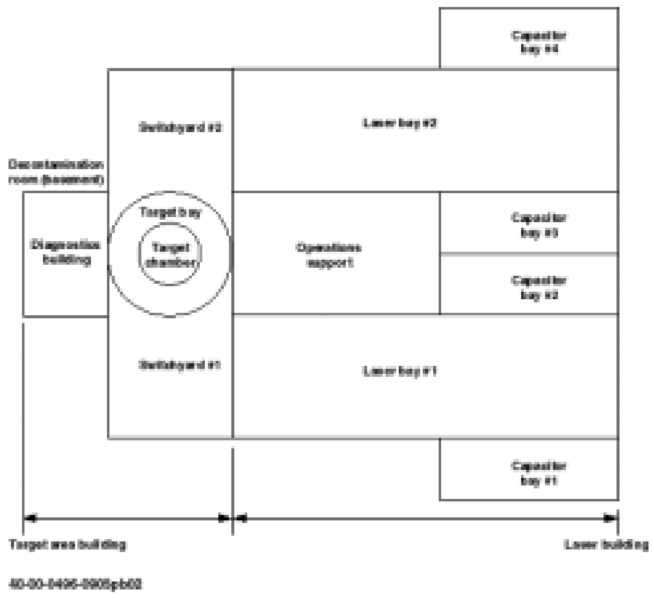

Figure 1. Schematic Layout of the National Ignition Facility

DESCRIPTION OF THE PROBLEM

The NIF power conditioning system consists of a large collection of capacitors, inductors, and resistors housed in 48 modules with associated switches, controls, distribution system etc., see Figure 2. Capacitors and power conditioning systems of the type required for NIF are known to fail catastrophically during charging or while the capacitors are in a charged state. Several such catastrophic failures have occurred at the First Article NIF Test Module (FANTM) at Sandia National Laboratories in Albuquerque. This is a prototype demonstration facility for the NIF equipment. Demonstration efforts with FANTM took place over a 10-month period in 1998 and 1999. During that time, five catastrophic failures occurred. These events resulted in pressurization of the module, and the generation of energetic shrapnel. In some cases, capacitor cases ruptured, spraying dielectric fluid into the module cavity; the oil mist ignited, generating a dramatic fireball.

In the case of the capacitor module explosion events, there exist two potential sources of overpressure from these explosions. First, the rapid dumping of electrical energy (about 2 MJ) into components, such as a resistor, can result in overpressure. Second, if the dumping of electrical energy leads to failure of a capacitor case, then a dielectric oil mist can be created. An electrical arc can subsequently ignite the air-oil mixture, leading to a chemical deflagration. The rapid reaction, increase in temperature, and generation of reaction products result in overpressure.

During these capacitor explosion events, the rapid deposition of energy leads to localized heating and pressurization over a very short time period. The pressure buildup will rapidly reach a peak quasi-static pressure, which will then decay over time. This quasi-static pressure will result in damage to materials and components inside the module, and will also present a threat to the capacitor bay that houses the modules. Various methods were utilized to estimate the maximum quasi-static pressure in a capacitor module, and subsequently in the associated capacitor bay. These included calculations based on observed evidence after events at FANTM, as well as theoretical calculations. Two of

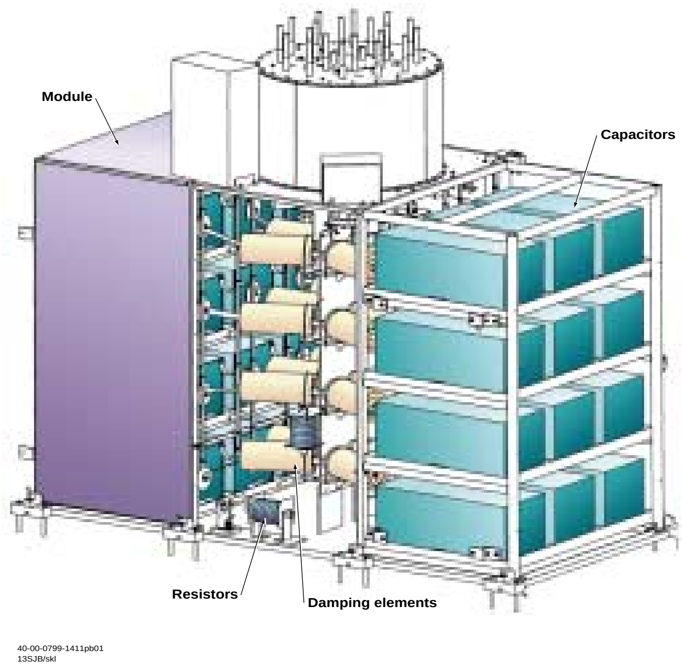

Figure 2. Schematic of a Capacitor Module
(Scale: 1 in. = 52.6 in.)

the approaches are described in this paper, and where possible, implications for the module and for the capacitor bay are discussed. Issues related to shrapnel are not covered in this paper, but are addressed in detail in the full report (LLNL, 1999).

$$m_{air} = 11.6\, m_{oil} \qquad (2)$$

PRESSURE ANALYSIS

This section briefly describes two approaches utilized to estimate the energy released in a capacitor bay or the pressure generated in a module. The subsequent overpressure in the associated capacitor bay are also evaluated. These two calculations are both derived from video evidence taken during explosive events at FANTM. The calculation details are described in (LLNL, 1999).

Method #1: Fireball Calculation

The first calculation utilizes evidence from the video of FANTM Event #1, which occurred on 9/11/98. On the video, there appears to be a large fireball created during the event as shown in Figure 3.

The size of the fireball is estimated to be no greater than 3m in diameter. The analysis assumed that a 3m diameter spherical fireball containing oil and oxygen at the stoichiometric ratio burned to completion:

$1.66\ C_{18}H_{34}O_3 + 41.5\ O_2 \rightarrow$ combustion products,

Figure 3. Fireball exiting the capacitor module during FANTM Event #1

The purpose of this analysis is to estimate the energy release from the oil burning of the fireball. The result will then be used to estimate the overpressure in the capacitor bay where the event occurred. The energy release, E, can be expressed as:

$$E = m_{oil} \langle H \qquad (1)$$

where m_{oil} is the amount of oil in the fireball that would be burned, H is the heat of combustion of castor oil and is equal to 37.1 MJ/kg. The mass of oil, m_{oil}, can be evaluated as follows:

At the stoichiometric mixture, the ratio of mass of air to that of oil is 11.6 to 1, i.e.,

In addition, the sum of the volume of air and that of oil vapor inside the fireball is equal to the volume of the 3m diameter fireball, V (=14.1 m^3), i.e.,

$$V_{air} + V_{oil} = V$$

$$m_{air} \langle \frac{RT}{M_{air}\,P} + m_{oil} \langle \frac{RT}{M_{oil}\,P} = V \qquad (3)$$

where the ideal gas equation (PV = mRT /M) is applied. M is the molecular weight (M_{air} = 28.8 g/g-mole, M_{oil} = 298 g/g-mole); P is the room pressure (P = 1 atm); and T is the temperature of the fireball which was taken to be the flame temperature of the dielectric castor oil and was estimated as 2000 °K (Staggs, 1999).

Equations (2) and (3) can be used to solve for m_{oil} and yield m_{oil} = 211g. Equation (1) then gives E = 7.8 MJ. Thus in the fireball scenario, 211 g of oil would burn, releasing 7.8 MJ of energy. Adding the 2 MJ of electrical energy results in a total of 9.8 MJ of energy being released (this is conservative, since much of the electrical energy would be consumed in creating the conditions allowing for combustion of the oil, i.e., atomizing the oil).

The capacitor bay air volume is approximately 8.12 x 10^3 m^3. Assuming the energy release of 9.8 MJ is absorbed as internal energy of the nitrogen and oxygen in the capacitor bay air, the temperature rise (ΔT) of the air in the bay can be determined by the following expression:

where N_{O2} and N_{N2} are the number of moles of oxygen and nitrogen in the capacitor bay air, respectively; Cv_{O2} and Cv_{N2} are the constant volume heat capacities of O_2 and N_2, respectively. Using the ideal gas equation, the result of ΔT from Eq. (4) was used to estimate the pressure rise. The evaluation yielded an overpressure of 9.9 psf (pound per square foot) in the capacitor bay. This is a conservative estimate of the bay pressure because ideal conditions are assumed in the

$$E = N_{O2}\, Cv_{O2}\, \Delta T + N_{N2}\, Cv_{N2}\, \Delta T \qquad (4)$$

fireball, and energy absorbed by the equipment in the capacitor bay is ignored. The 9.9 psf is below the pressure tolerance of the bay walls of 30 psf.

Method #2: Swinging Doors Calculation

The second calculation utilizes evidence from the video of FANTM Event #5, which occurred on January 28, 1999. At the time of the event, the module configuration consists of the following (see Figure 4):

$$P(t) = (P_{qs} + P_o)\exp(-c\frac{A_{tot}}{V}t) - P_o \qquad (5)$$

- Two 4'x4' west-facing swinging doors: a bottom-half door (BHD) and a top-half door (THD).
- A 1'x3' small west-facing flapper door (WFD) which is attached to the top-half door.
- A large, 4'x8' central east-facing door (CED), on the opposite side of the module to the swinging half doors.
- A small 1'x3' east-facing flapper door (EFD) which is attached to the bottom of the central east-facing door.

The FANTM Event #5 involved an explosion. As a

$$\theta(t) = \int_0^t \omega(\tau)d\tau \qquad (6)$$

result, the top-half door, the bottom-half door, and the two flapper doors all swung open, and the central east-facing door

$$\omega(t) = \int_0^t \Gamma(\tau)d\tau \qquad (7)$$

moved away from the module. The swinging positions of the doors were recorded on video film taken during the explosion at 30 frames per second, i.e., 33.3 msec between two consecutive frames. By looking at each of the frames, the swing angles of the bottom half-door, the top half-door, and the small flapper door could be roughly estimated. The objective of this calculation was to estimate the peak quasi-static pressure inside the module by attempting to reproduce the positions of the swinging doors as a function of time, as shown on the video. These swing angles were used for comparison with theoretical calculations and conclusions on the peak quasi-static pressure could then be drawn. The calculations are described in detail in (LLNL, 1999).

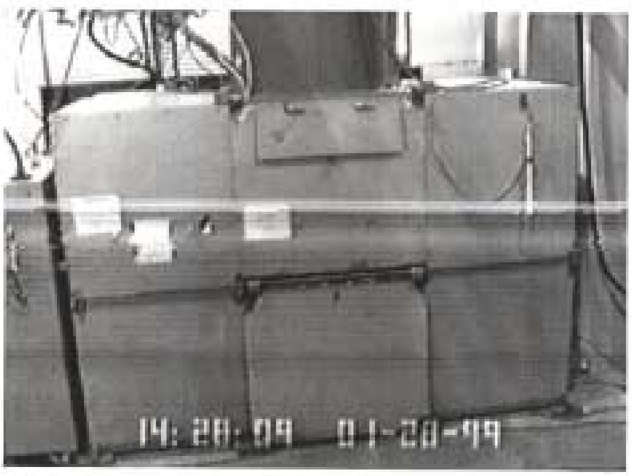

Figure 4 View of capacitor module for FANTM Event #5 (the bottom-half door and the top-half door at the center as well as the small flapper door at the top could all swing open)

After an explosion in an enclosed or partially vented containment, the pressure buildup will rapidly reach a peak quasi-static gas pressure, P_{qs}, which will then decay exponentially as a function of time. The expression is given below (DOE, 1992):

where P_o is the ambient pressure, A_{tot} is the total venting area of the containment, V is its volume, and c = 2378 ft/sec.

The swing angle θ of the bottom-half door can be expressed as:

and

where ω(t) is the angular velocity of the bottom-half door, $\Im$ is its moment of inertia, and Γ(τ) is the torque acting on the bottom-half door due to the pressure and gravity. $\Im$ and Γ are expressed as:

$$= \frac{1}{3} m\, h^2$$

$$\Gamma(t) = \frac{1}{2} P(t)\, h^2\, w - \frac{1}{2} m\, g\, h \sin\theta(t)$$

where h and w are the height and width of the bottom-half door, respectively. The venting area, $A_{BHD}(\theta)$, produced by the bottom-half door as it swung open can be expressed as:

Note that $A(\theta) \le h\, w$.

Similar equations also hold for the top-half door and the two small flapper doors.

The travel distance, D, of the 4'x8' central east-facing door can be expressed as:

$$D(t) = \int_0^t v(\tau)d\tau \qquad (9)$$

$$A_{BHD}(\theta) = h^2 \sin\theta(t) + 2h\, w \sin\frac{\theta(t)}{2} \qquad (8)$$

and

$$mv(t) = \int_0^t F(\tau)d\tau \qquad (10)$$

where v(t) is the velocity of the central east-facing door, m is its mass, and F(t) is the force acting on the door due to the pressure and the friction after the door breaks away from the module. F is expressed as:

$$F(t) = P(t)h'w' - \mu_k W \qquad (11)$$

where h' and w' are the height and the width of the central east-facing door, respectively; W is its weight; and μ_k is the kinetic friction coefficient.

The venting area, $A_{CED}(D)$, produced by the central east-facing door as it moved away from the module, can be expressed as:

Equation (12) indicates that there will be no venting through the floor.

The total venting area in Eq.(5) is the sum of the individual venting areas, i.e.,

$$A_{TOT}(t) = A_{BHD}(t) + A_{THD}(t) + A_{WFD}(t) + A_{EFD}(t) + A_{CED}(t) + A_{FIX}(t) \qquad (13)$$

where A_{FIX} is the fixed venting area (= 2 ft^2) provided by the 1 inch gap around the bottom of the module.

For a given initial peak quasi-static pressure, the impulse due to the torque (Eq. 7) acting on the swinging doors with respect to their hinges can be evaluated as a function of time by considering the gas pressure and the gravitational force. Similarly, the impulse due to the force (Eq. 10) acting on the central east-facing door can also be evaluated as a function of time by considering the gas pressure and the friction. The result can then be used to determine the angular velocity of the swinging doors and the velocity of the central east-facing door; which in turn, can be used to calculate the swing angle and the travel distance, respectively. Finally, the swing angle and travel distance thus obtained can be used to determine the venting area as a function of time and the associated pressure decay. The calculation can be carried out step by step using the finite difference method with a spread sheet.

The angular displacement of the swinging doors depends on the peak quasi-static pressure, which is the only parameter in the calculation. The calculation considered several peak quasi-static pressures, such as 10, 11, and 12 psig. The results indicate that the angular displacements of the bottom half-door, the top half-door, and the flapper door can be best reproduced by a peak quasi-static pressure of 11 psig.

The calculated swing angles for a peak quasi-static pressure of 11 psig are depicted in Figure 5. Figure 5 also shows the swing angles of the bottom and top half-doors estimated from the video as a function of time (data are taken from (Smith, 1999)). Figure 5 indicates that the swing angles of the bottom and top half-doors shown on the video are consistent with a peak quasi-static pressure of 11 psig. It should be noted that the video data of the positions of the bottom and top half-doors within the first 0.1 second have large uncertainty (video was overexposed); therefore, the comparison within the first 0.1 second is less significant. The maximum swing angle calculated for the bottom half-door is 179°, which is within the range of the ultimate angle of 160° to 180°, as determined by the video (see Smith (1999)). The calculation shows that the quasi-static pressure drops to the ambient pressure in about 9 msec.

For a peak quasi-static pressure of 11 psig, the calculation estimates that the small flapper door reaches 48^o at 33.3 msec and 100^o at 66.6 msec. This is consistent with the video data from frames 1 and 2. The calculated total venting area of the

$$A_{CED}(D) = D(t)\,(2h' + w') \quad (12)$$

module increases from 2 ft^2 at 0 seconds to 7.4 ft^2 at 9 msec (the increasing venting area is provided by the swinging doors and the movement of the central east door). At that point, the quasi-static pressure is reduced to the ambient pressure. A similar venting effect may be provided by a fixed venting area less than 7.4 ft^2.

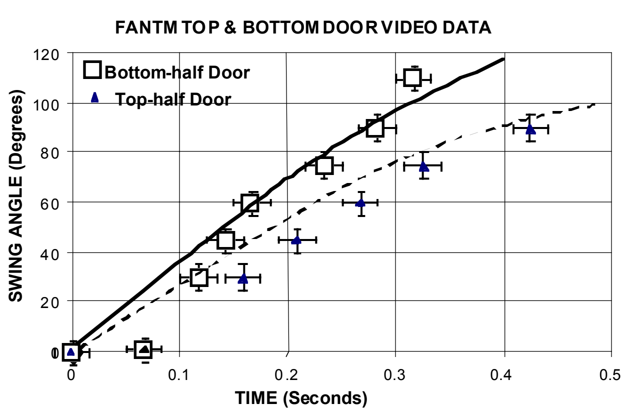

Figure 5 Comparison between theoretical calculations (at P_{qs} = 11 psig) and video data for the swinging doors
Solid curve represents calculated results for the bottom-half door, dotted curve represents calculated results for the top-half door.
(Video data are taken from (Smith, 1999))

Next, the overpressure in the capacitor bay resulting from the expansion of the 11 psig module pressure out into the bay volume was estimated. The air volume inside the module is approximately 4.75 m^3, the air volume of the capacitor bay is approximately 8.12 x 10^3 m^3; based on the ideal gas law the overpressure in the bay was obtained as 0.93 psf. This would not present a structural threat to the bay walls.

PROBABILITY ANALYSIS

The expected NIF capacitor module explosion rate was estimated based on data from FANTM at Sandia National Laboratories, Albuquerque. At the end of the test program in July of 1999, a total of 17112 shots had been conducted. During the test program, there were 5 incidents of various types. The last failure occurred in January of 1999. After that, an additional 9545 shots were fired without incident.

The failure rate for the module can be calculated in a number of ways:

(1) Based on the total data set:

$$\frac{5\ \text{explosions}}{17112\ \text{shots}} = 2.9\text{x}10^{-4}\ \text{explosions/module-shot}$$

(2) Based on the data up until January of 1999:

$$\frac{5\ \text{explosions}}{7567\ \text{shots}} = 6.6\text{x}10^{-4}\ \text{explosions/module-shot}$$

(3) Based on the data after January of 1999:
The predicted failure rate, P, for 0 failures after n trials is:

$$P = 1 - (1 - CL)^{1/(n+1)}$$

where CL is the confidence level.
At 95% confidence, the failure rate would be:

$$P = 1 - (1 - 0.95)^{1/(9545+1)}$$
$$= 3.1\text{x}10^{-4}\ \text{explosions/ module-shot}$$

Because modifications were made to the capacitors and other components throughout the test program, the second half of the data is perhaps more representative of the situation. Therefore at the 95% confidence level, the capacitor failure rate would be 3.1 x 10^{-4} per module per shot.

In a NIF capacitor bay, there will be 48 operating modules involved in a shot and the shot charge period will last two minutes. To determine the probability of two events occurring simultaneously in a shot, the number of combinations of two modules must be determined. This is described by:

$$C(2,48) = \frac{48!}{46!\,2!} = 1128$$

Thus, there are 1,128 ways one can combine 48 modules into pairs of two modules. The probability of two explosions per shot would be determined from the probability of each module exploding individually, times the number of combinations of two modules. Mathematically, this would be expressed as:

$$P(2\ \text{explosions}) = 1128 \times (3.1\text{x}10^{-4})^2$$
$$= 1.1\text{x}10^{-4}\ \text{two-explosions/shot}$$

In the above evaluation, it was assumed that the explosion events are independent. That is, that an explosion involving one module will not cause another module to explode and they are not triggered by a common event.

Simultaneous explosions are of interest from the standpoint that their pressure pulses in the capacitor bay could overlap. The duration of the capacitor bay overpressure is estimated based on the expected air leakage rate, see details in (LLNL, 1999). For there to be a potential overpressure issue from simultaneous explosions, it was determined that two explosions would have to occur within 22 seconds of each other. During a two minute shot charge period, the chances of two explosions occurring within 22 seconds of each other would be 22/120. Thus, the chances of two events occurring within any 22 second time window would be:

$$P_2 = P(2\ \text{explosions within a shot charge period}) \times 22/120$$
$$= 1.1\text{x}10^{-4} \bullet 0.18$$
$$= 2.0 \times 10^{-5}\ \text{two-overlap-explosions/shot.}$$

Note that during a two minute shot charge period, the probability of three events occurring simultaneously within any 22 second time window is described by:

$$P_3 = \frac{48!}{45!\,3!} \langle\, (3.1\text{x}10^{-4})^3 \langle\, \left(\frac{22}{120}\right)^2$$
$$= 1.7\text{x}10^{-8}\ \text{three-overlap-explosions/shot}$$

The above estimated probabilities of occurrence could be used to evaluate the risk associated with multi-module failures during NIF operations.

CONCLUSIONS

Capacitors and power conditioning systems required for the National Ignition Facility (NIF) have experienced several catastrophic failures during prototype demonstration. Based on the analysis described here, it was estimated that for a capacitor event, only a few hundred grams of dielectric fluid would be consumed in a fireball, or an internal pressure on the order of 11 psig could result inside a module. The estimates of energy release and module pressure were then used to estimate the potential overpressure in the associated capacitor bay after an event. Note that the two evaluations describe two different types of capacitor events, thus they yield different overpressures. It was shown that both expected capacitor bay overpressures from the two analyses were less than the pressure tolerance of the walls of 30 psf. In addition, the estimated overpressures from the analyses of other capacitor catastrophic failures (not reported here) were also less than 30 psf. Based on this, it does not appear necessary to provide any pressure relief for the capacitor bay.

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