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Fire Risk Analysis for the NIF Capacitor Containment Design

February 22, 1999

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Acknowledgment

We would like to thank Scott Doughty of the Applied Research Engineering Division for his help in setting up and conducting the dielectric fluid combustible performance screening tests.

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INTRODUCTION

Capacitor banks for pulsed power to NIF lasers are constructed as modules for a variety of logistic and safety reasons. One safety consideration requires that the capacitors be contained by enclosure surfaces to prevent shrapnel (potentially generated if the interconnecting bus conductors to the capacitors should fail) from damaging equipment and components nearby. This type of event can occur during catastrophic failure of capacitors due to internal case flashovers. If the flashover is of high strength, the capacitor case can rupture, resulting in the release of capacitor dielectric, and potentially, the ejection of materials of high kinetic energy. Simple shielding can contain the ejecta. However, since the capacitor dielectric fluids are moderately combustible, the shielding design must account for overpressure development if ignition of atomized dielectric should occur during the dynamic stage of capacitor failure. Thus, the flammable characteristics of the dielectric fluids need to be defined so that design of adequate module venting can be done.

The candidate dielectric fluids considered for the NIF program are castor oil, rape-seed oil, and dielectric fluid epoxide. Since these fluids are not commonly considered to be combustible hazards, there is a paucity of information about their flammable characteristics, particularly when they are atomized. Because these fluids are to be employed as dielectrics, they will necessarily have low vapor pressure, high viscosity, and high thermal stability. Moreover, since they are mixtures of organic molecules, their published flash-point data are approximate, and there will be distinct differences between closed- and open-cup values. Generally, the open-cup measurements will be of more practical significance. The most frequently reported flash-point values will be for unused fluids, which may be different from fluids that have served as dielectrics for long periods.

To determine the parameters of deflagration of atomized dielectric fluids and the potential for development of capacitor module overpressurization, it was necessary to perform screening tests to gain a sense of the combustible performance of the candidate fluids. Tests to measure the (1) flash ignition range, (2) burning rate, (3) surface quenching performance, (4) atomized ignition performance, and (5) vapor-phase ignition performance of these fluids were designed to produce practical and expedient results that would provide an adequate comparison of their relative properties and reasonable data with which to estimate risk parameters.

Analytical calculations based on available published data, pessimistic estimates of electrolyte release during capacitor failure, and current understanding of the module containment geometry were also done to estimate the potential for fire, deflagration, overpressurization, and required vent areas to accommodate the overpressurization in the capacitor bank containment. Results of calculations that pertain to the flammability of these fluids and data from the screening tests are in general agreement.

BACKGROUND

The capacitor modules typically contain 20 capacitors connected in parallel to a common bus by fiberglass reinforced steel inductors known as damping elements. The circumstance of exploding capacitors would most likely result from rapid generation of dielectric vapor or dielectric liquid thermal expansion caused by electrical breakdown between plates, or between plates and the grounded case, during periods of capacitor charging or discharge. Capacitors used in NIF modules are self-healing types, such that when minor discharge occurs between plates, the paths open and seal, and capacitance of the unit slightly decreases. However, there are other failure modes, which can result in capacitor flashover.[1] Because the capacitors are connected in parallel, all capacitors will discharge through the fault with maximum energy of ~1.7 megajoules.

Three internally developed mechanisms that have potential for dielectric release from the capacitors during catastrophic flashover are (1) rupture of the case from liquid pressure increase or internal vapor generation, (2) separation of the seal between the high-voltage terminals and case by liquid pressure buildup or internal vapor generation, and (3) arc penetration of the case during electrical breakdown between plates and the grounded case. If the dielectric is produced outside the capacitor in vapor phase or as a fine aerosol, and if arcing is occurring simultaneously with the release of dielectric, the conditions for ignition exist. Ignition is also possible if dielectric is above its autoignition temperature when the capacitor case or electrode interface fails due to thermal expansion of the dielectric.

Another potential mechanism for dielectric release during operations is the event of a damping element failure during charging or discharge. Failure characteristics of flawed damping elements at high energy are said to be spectacular, producing incandescent shrapnel at high velocity. To reduce the intensity and magnitude of shrapnel release during damping element failure, designers encase the shunts with fiberglass shrouds. However, the energy released during shunt failure may still result in production of high-speed incandescent particles that could penetrate a capacitor case. Moreover, thermal energy transfer to the fiberglass shroud could cause its ignition, which in turn may provide an ignition source for released dielectric.

Experiences with past events of fires resulting from capacitor failure are sparse. The events seem to be minor, where evidence of fire or smoldering matter discovered is limited in size and intensity. Consequently, there is very little hard information to guide us in terms of defining quantities or dynamics of dielectric release. In addition, there is little known about the flammable characteristics of the candidate dielectric fluids. However, with the information on hand, we will posit scenarios of unknown probability for conditions of dielectric vapor release that, upon ignition, would result in deflagration. Note that the physical and flammable properties of these fluids are not favorable to the production of vapor, as shown in Table 1. The only way flammable fuel–air mixtures are likely is by atomization of the dielectric during high-pressure production from the capacitor. Since capacitor failure is by an electrical discharge fault, the percipient ignition source could exist at the dielectric discharge site. Thus, deflagration is unlikely. Equally unlikely are conditions for a large or persistent pool fire.

Table 1. Properties of caster oil, rape-seed oil, and dielectric fluid epoxide.

Dielectric	Castor oil MSDS OHS04358	Rape-seed oil MSDS OHS31599	Dielectric fluid epoxide Union Carbide, MSDS – 05/15/92
Chemical name	80-92% ricinoleic acid[1, 2] $C_{18}H_{34}O_3$	~50% eureic, ~32% linoleic ~15% oleic (acid)[1, 2] $C_{22}H_{42}O_2$	3, 4-epoxy cyclohexylmethyl- - 3, 4 epoxycyclohexylcarboxylate $C_{14}H_{20}O_4$
Molecular wt.	298 (ricinoleic acid)	310 (average above)	262.3 (MSDS)
Boiling point	313°C	NDA*	200°C (decomposes)
Freezing point	-10°C	17-22°C	-37°C
Specific gravity (SP, GR)	0.962 (at 15°C)	0.913-0.916	1.173
Viscosity	0.7 cp (at 25°C)	NDA	Slightly viscous
Vapor pressure	NDA	NDA	P < 0.01 mm Hg (at 20°C)
Flash point	229°C	163°C	118°C (closed cup), 204°C (open cup)
Auto ignition temperature	449°C	447°C	Decompose at 200°C
Vapor density (VD)	10.29 (calculate for air = 28.96)	10.7 (calculate for air = 28.96)	8.7 (from MSDS)
Comments	• Avoid contact with oxidizers • Will not polymerize	• Avoid contact with oxidizers • Will not polymerize	• Process hazards: spontaneous ignition of distributed hot mists and vapors • Hazardous polymerization may occur
Stoichiometry	$C_{18}H_{32}O_3 + 25O_2 + 94N_2 \rightarrow$ (product) 11.6 kg air: 1.0 kg fuel, fuel–air = 0.087	$C_{22}H_{42}O_2 + 30.5O_2 + 118.4N_2 \rightarrow$ (product) 12.7 kg air: 1.0 kg fuel, fuel–air = 0.079	$C_{14}H_{20}O_4 + 10O_2 + 37.6N_2 \rightarrow$ (product) 5.45 kg air: 1.0 kg fuel, fuel–air = 0.18
Specific volume liquid in liters to vapor in cu meters $= 0.83\left(\frac{SpGr}{VD}\right)$	1:78	1:71	1:112

* No data available.

GENERAL ANALYSIS

Capacitors in pulsed power modules contain substantial quantities of dielectric fluids. Past experience indicates that capacitors occasionally fail during charging cycles. When this occurs, observers note a flash, and upon investigation, discover dielectric residue on surfaces adjacent to the failed capacitor and scattered small areas of burning dielectric in the area of the flash. Where operators did not observe the capacitor failure, crews would find evidence of small fires and dielectric residue.

The modules that are currently under design for the NIF project contain 20 capacitors, each of which contains large volumes of dielectric fluids (estimate ~15–25 gallons [56.78–94.63 liters]). The damping elements between the capacitors and the central bus bar can potentially fail catastrophically, generating shrapnel that has the potential to damage critical components of the experiment. For this reason, the capacitor modules racks have metal panel perimeter shields. In effect, the shields provide containment for the capacitors, which could experience overpressure if a dielectric release from a failing capacitor should produce a persistent vapor or aerosol volume that is ignited.

Ignition of dielectrics is possible when vaporized or atomized and mixed with air at appropriate fuel–air mixtures if a simultaneous ignition source is present. If the liquid is superheated to its autoignition temperature, it will ignite on contact with air. Transient pressurization of an enclosure occurs when a premixed fuel–air volume is ignited. The pressure rise is directly proportional to (1) the fuel–air mixture ratio, (2) the mixture volume relative to the enclosure volume, and (3) the ratio of flame temperature to ambient temperature before ignition. Theoretical values for maximum pressure rise from ignited hydrocarbon fuel–air mixtures that fill a confined space are of the order of 7 atmospheres (100 psi [7.03 kg/sq cm]). If only a portion of the space is filled by the fuel–air mixture, the pressure rise is proportional to the ratio between the volume of the fuel–air mixture and the total volume of the enclosure. Low-volatility fluids with high flash-ignition ranges and high viscosity are unlikely to form large vapor volumes with air, unless they are explosively dispersed.

The dynamics of capacitor failure that result in dielectric release are not defined. Because the power potential that can be concentrated at the fault site within the capacitor is huge, and because the dielectric completely fills the capacitor volume, any temperature increase or vaporization process has the potential to cause excessive pressurization and potential failure of the capacitor case or electrode attachment. The amount of dielectric released by this process will be dependent on fault location and failure mode of the case. If the case failure site and discharge faults are proximate, ignition of the dielectric spray should occur simultaneously with dielectric release from the capacitor. This should produce a "flame thrower" effect during the ejection period. This event would result in minimal-to-no pressure increase in the module. In this case, we assume that electrical arcing or internal case flashover is the ignition source. If instead, the discharge fault superheats the dielectric or dielectric vapor to local temperatures above the fluid autoignition temperature, the same flame thrower event should occur at the capacitor failure site. Note that flaming dielectric aerosol should self-extinguish upon contact with cold metal surfaces, and the only place flaming should persist is where liquid could pool or on surfaces of low thermal conductivity.

Penetration of capacitors by particles produced from a failing damping element should not cause dielectric vapor or aerosol generation. However, shattered and ignited fiberglass shroud materials may provide wicking sites for dielectric pools on horizontal surfaces. Appropriate design of horizontal surfaces should negate this concern.

The Materials Safety Data Sheets (MSDSs) and materials handbooks publish some properties for castor oil, which consists mostly (80–92%) of ricinoleic acid ($C_{18}H_{34}O_3$); rape-seed oil, a mixture of eurcic acid, linoleic acid and oleic acid ($C_{22}H_{42}O_2$); and dielectric fluid epoxide, ($C_{14}H_{20}O_4$). These data are summarized in Table 1. Review of these properties indicates fairly inert and viscous fluids of low flammability, i.e., high flash- and boiling-ranges dictate low volatility. Thus, substantial thermal or mechanical energy must be applied to the fluids before they can be made susceptible to ignition. Electrical failure of capacitors can provide local sites of intense energy that could conceivably cause limited vaporization or aerosol generation of these fluids. If the vapor or aerosol can mix with air before falling out or condensing and if an ignition source is active at the same time, some overpressurization of the module enclosure could occur.

SCREENING TESTS OF DIELECTRIC FLUID FLAMMABILITY

To better understand the relative difference in flammability of the dielectric fluids, screening tests were designed to determine (1) ease of ignition, (2) burning rate, (3) cold surface quenching for bulk fluids, and (4) ignition characteristics of sprayed fluids and fluid aerosols. Specifically, three areas of testing were conducted to determine the burning characteristics of each fluid. Testing was conducted to determine the flash and/or flame point, the rate at which each fluid would burn, and the combustion of a sprayed/aerosolized fluid. Other aspects of this testing included the effect on the burning duration of ignited fluids poured on metal surfaces, burning gases passing through metal screening, and ignition of fluid aerosols immediately after spraying events.

Flash- and Flame-Point Tests

The candidate dielectric fluids are mixtures of hydrocarbon compounds that do not have unique flash and fire points. Consequently, these tests were designed to determine the temperature conditions that would cause ignition without sustained flame and the point when sustained burning would occur. Because of ambient influences, these values will be higher than the values obtained with standard flash- and flame-point test methods.

In these tests a durable, small stainless steel metal cup assembly with an internal temperature sensor, shown schematically in Figure 1, was used to contain the fluid. The cup assembly was placed on top of an adjustable hot plate. A type "K" bare-beaded thermocouple was supported above the pan with the sensor end approximately

1 mm beneath the top of the fluid and 1 cm from the edge of the pan. The temperature of the pan was monitored using the internal sensor, and the temperature of the fluid was monitored with the bare-beaded thermocouple. The bare-beaded thermocouple was also used to stir the fluid (see Figure 2) to insure uniformed heating. A hand-held torch was used as a pilot flame to ignite the gases.

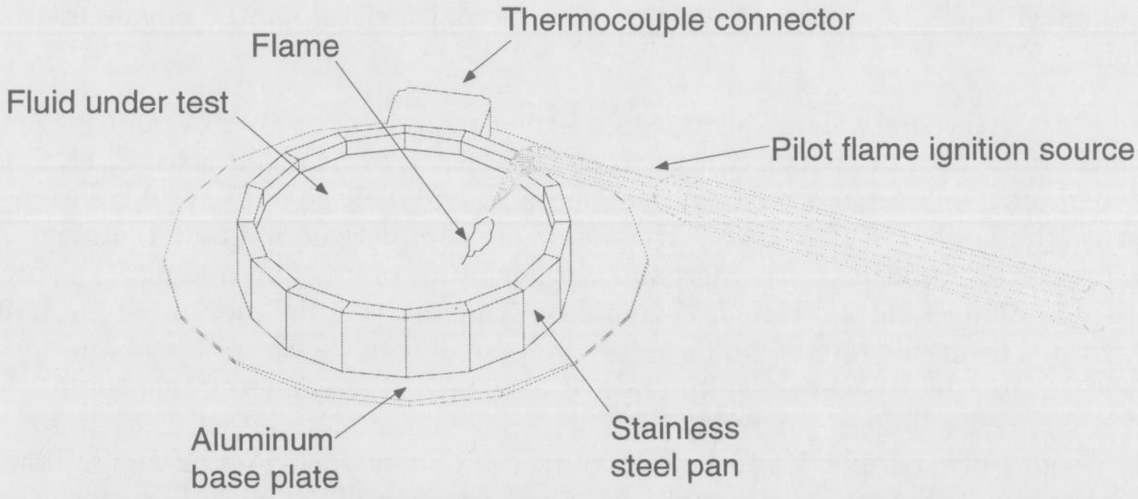


Figure 1. Schematic of testing assembly to determine flash points and flame points of dielectric fluids.

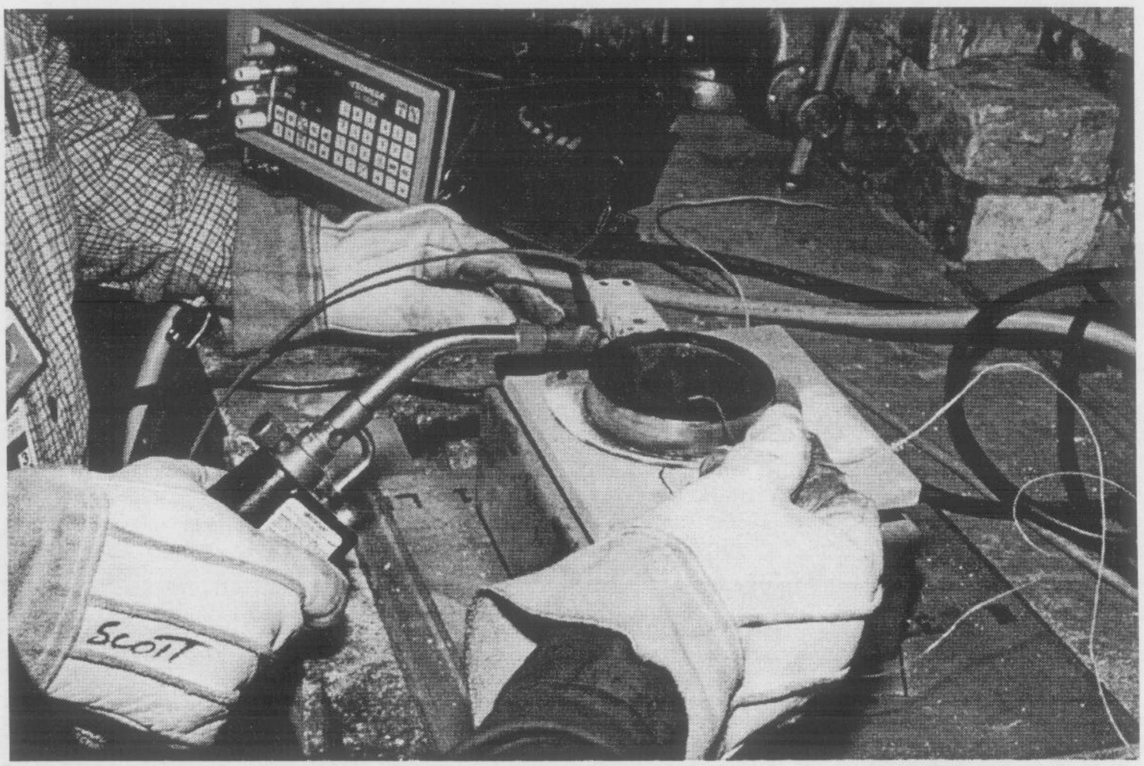


Figure 2. Bare-beaded thermocouple used to stir the dielectric fluid to ensure uniform heating in flame-point and flash-point tests.

In preparation for each test, the hot plate and pan assembly was leveled to insure that the fluid evenly contacted the lip of the pan. The pan was then filled to within 1 mm of the lip with the test fluid. The temperature of the pan and fluid was then slowly increased until a light vapor could be seen coming off the surface of the liquid. The pilot flame was then directed over the fluid within 1 cm from the surface. The flash-point temperature of the liquid was recorded when the vapors started to briefly ignite or flash. The flame-point temperature was recorded when sustained burning occurred. In each of these tests, the flash and flame temperatures were different. Table 2 lists the results of these tests.

Table 2. Flash- and flame-point ignition tests.

Material	Flash point	Flame point
Castor oil	613.4°F (323°C)	656.6°F (347°C)
Rape-seed oil	617.0°F (325°C)	680.0°F (360°C)
Epoxy resin	356.0°F (180°C)	388.4°F (198°C)

After each test and while the fluid was still burning, the fluid was poured over a 150-mm-diameter cylinder of aluminum. In each case, the fluid spread across the aluminum cylinder, quickly cooling and extinguishing the flames against the surface of the cylinder.

Burn-Rate Tests

To define burning rates for the dielectrics, 100 to 120 grams of each test fluid were placed in a 150- by 75-mm pyrex dish placed on top of a hot plate. The hot plate and dish were placed on top of a Mettler model PS 30 balance, and the balance was tared. As shown in Figure 3, a bare-beaded type "K" thermocouple, supported above the dish, was placed in the fluid approximately 1 mm from the top level of the fluid.

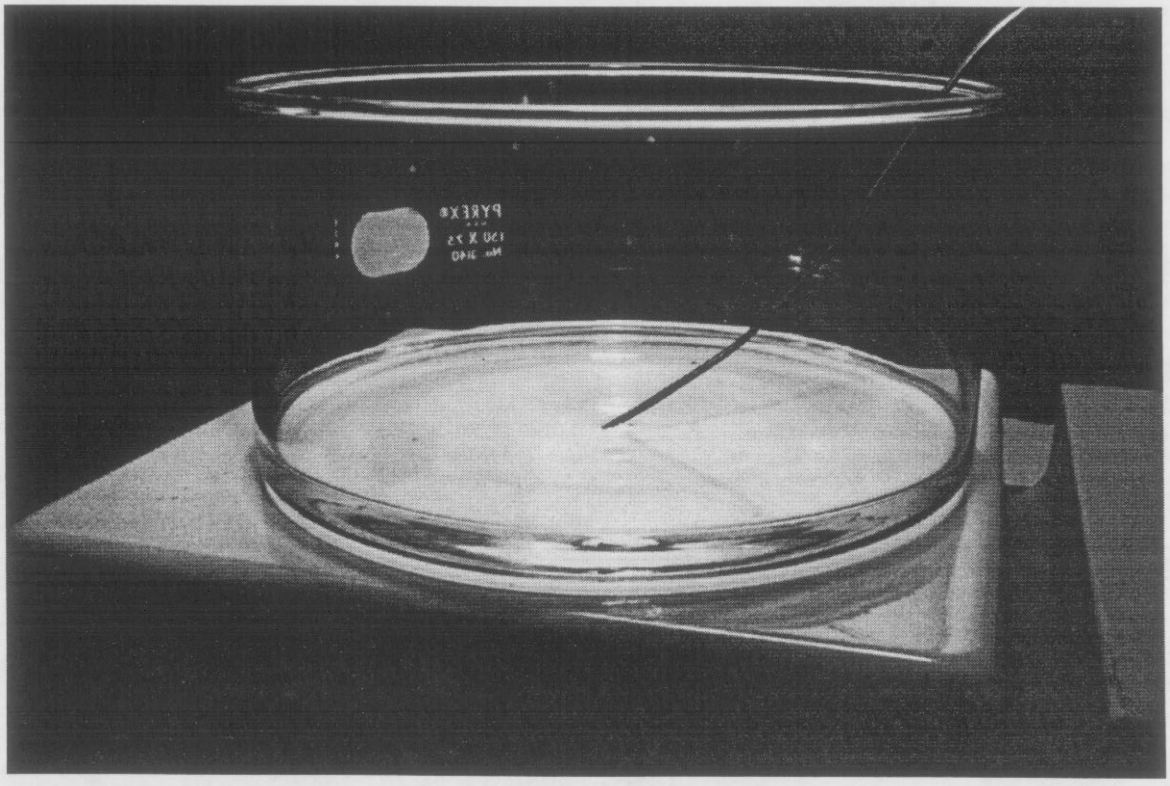


Figure 3. Burn-rate test of a dielectric fluid in a pyrex dish on a hot plate with a bare-beaded type "K" thermocouple placed in the fluid 1 mm from the top level of the fluid.

The temperature of the fluid was increased to its flame point, ignited, and allowed to free burn (see Figure 4). Weight measurements were recorded at one-minute intervals for a period of ten minutes. Approximately 50% of the fluid was consumed during each test. The graph in Figure 5 shows the comparison of the mass loss rates for each fluid.

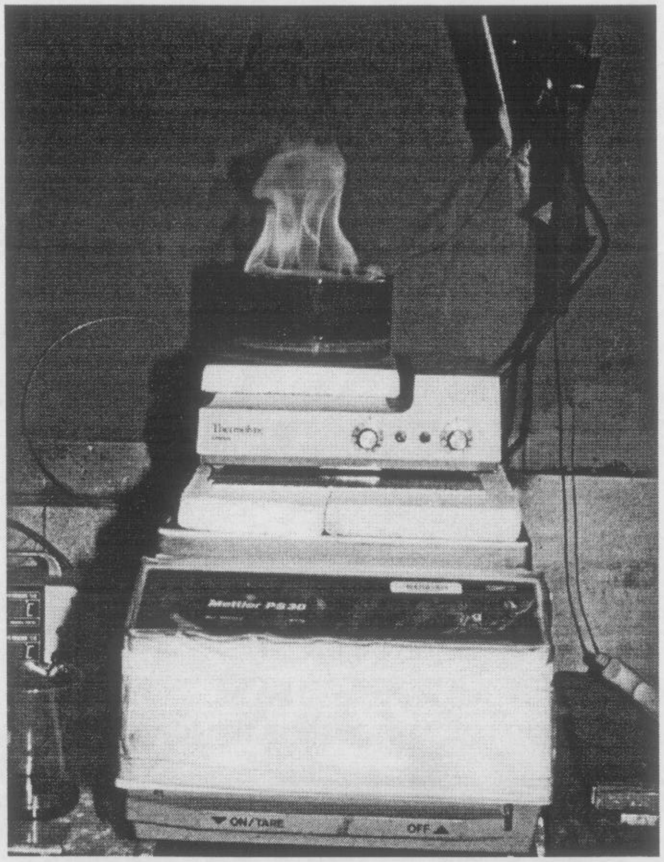


Figure 4. Dielectric fluid allowed to burn during a burn-rate test.

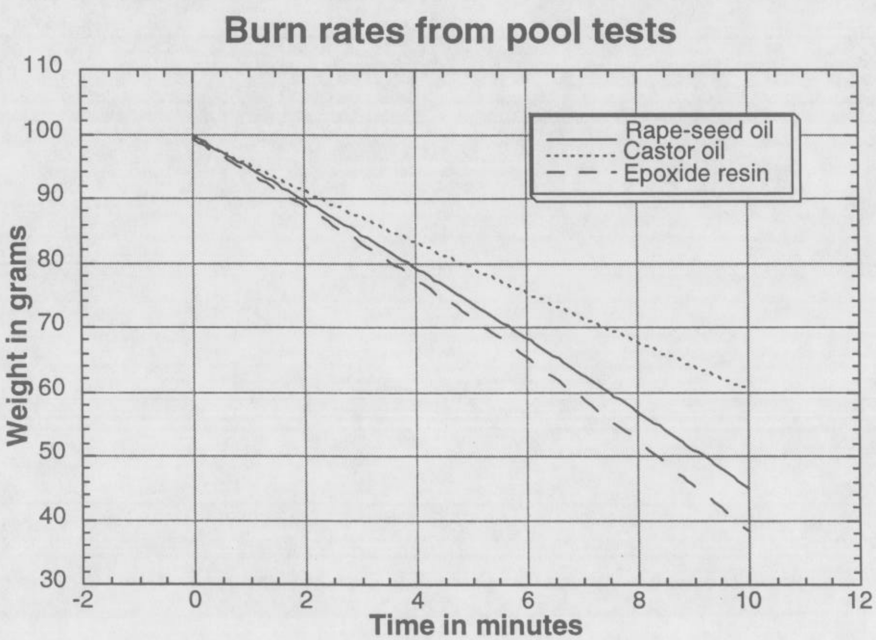


Figure 5. Comparison of mass loss rates for each dielectric fluid during burn-rate tests.

During each test a perforated metal sheet with 0.125-in.-diameter (0.3175-cm-diameter) hole providing a 40% open area was placed on top of the dish (see Figure 6) to see if the flame plume would pass through the grid. In each test, the flame plume did not pass through or burn above the screen.

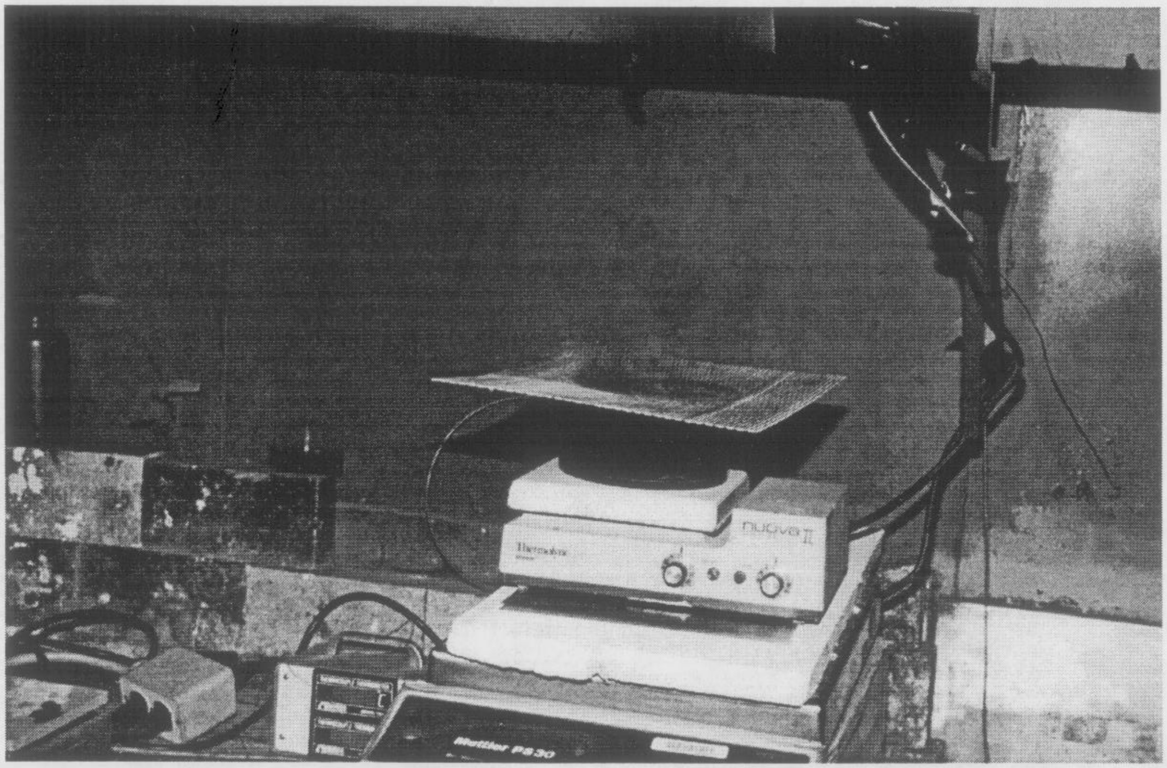


Figure 6. Dielectric fluid burn-rate test with perforated metal sheet over the dish to see if a flame plume would pass through it. None did.

Spray Tests

Spray ignition tests were done in the glove box apparatus shown in Figure 7. A spray nozzle with a 0.042-in. (0.1067-cm) orifice was positioned inside the box to direct the spray horizontally across the interior of the box as shown in Figure 8. The test fluid was contained and heated in a reservoir mount to the side of the glove box. A temperature probe extending down into the reservoir through the top was used to monitor the liquid temperature. Air pressure controlled through a remotely actuated solenoid valve was used to pressurize the reservoir, forcing the fluid out through the nozzle.

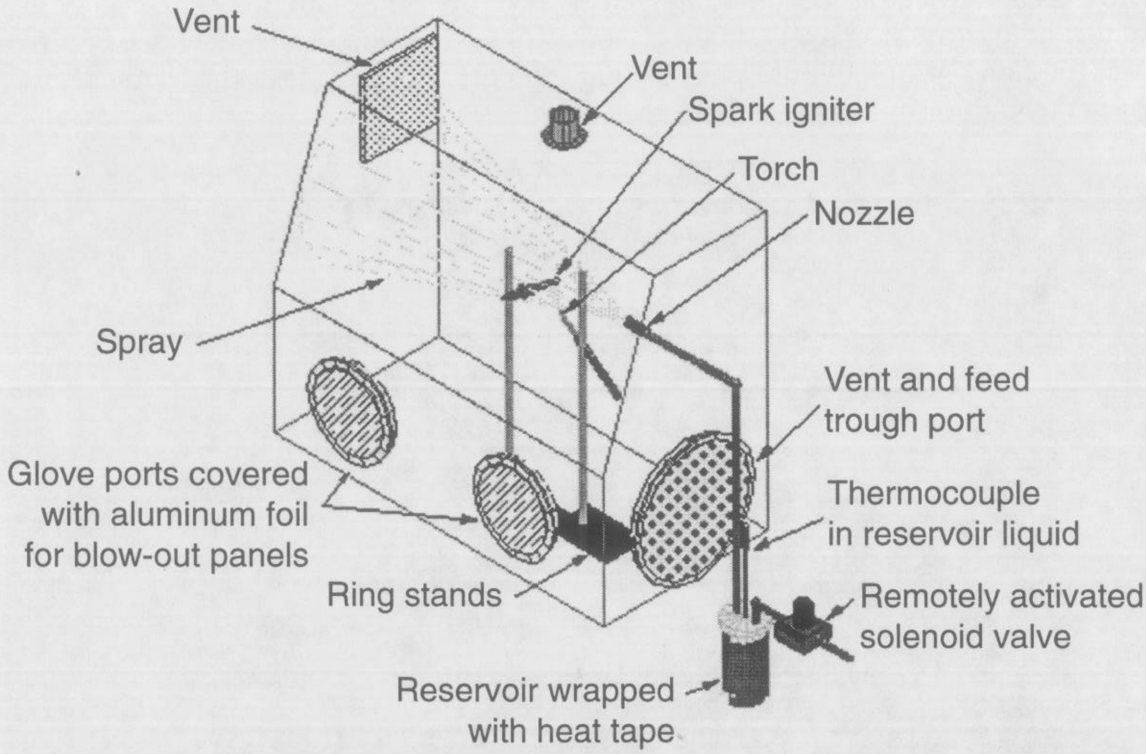


Figure 7. Schematic of glove box apparatus set up for dielectric fluid spray tests.

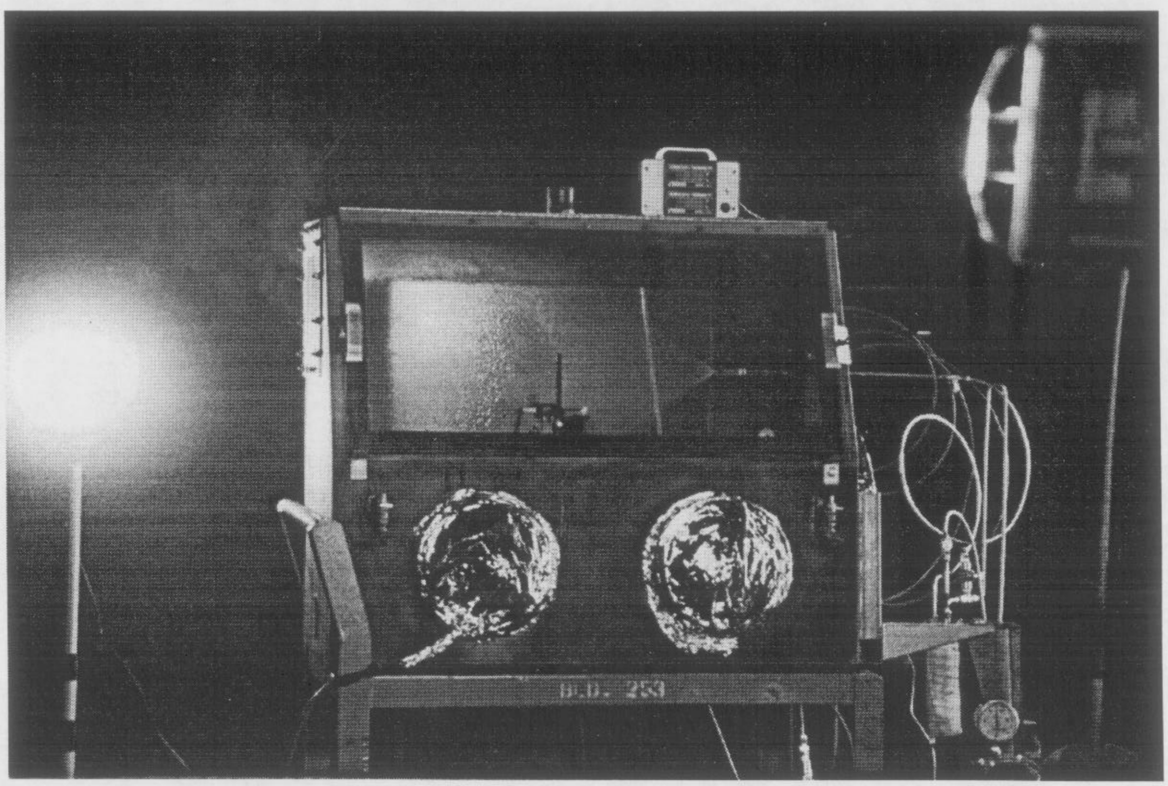


Figure 8. Spray nozzle positioned inside a glove box to direct spray horizontally across the interior of the box during dielectric fluid spray tests.

An electrode resembling an elongated spark plug and a welding torch with a flame guard were used as ignition sources for the spray. A 6000-V, 20-mA, 60-Hz ignition transformer was used to generate an electrical spark through the electrode. It was also used to ignite the torch. The torch was adjusted to produce a two-inch-long, premixed, propane and air flame. The flame was premixed with air to provide a smooth, stable yellow flame. Both the spark and the torch were remotely controlled for the operator's safety and to control burning within the glove box.

For each test, approximately 125 ml of the selected fluid was poured into the reservoir and heated. At room temperature, the fluid was too thick to freely flow through the spray nozzle, so it was necessary to heat the fluid. After the fluid was heated, the electrical arc was turned on, and the spray was actuated. If the fluid did not ignite from the arc, then the torch was lit from the continuing electrical arc. If ignition occurred, the spray was stopped, and the ignition source was extinguished. Continued burning of any residual material was recorded as duration and/or the means by which burning was sustained. The final event for each test was to try to ignite any aerosol produced from a spraying action, but without the spray present. To accomplish this, fluid was sprayed into the glove box, the spray was turned off, and spark and flame ignition sources were immediately ignited. The results of these tests are shown in Table 3, and the ignition events of the castor oil, rape-seed oil, and epoxy resin are shown in Figures 9–11 respectively. Figure 12 shows the light smoke typically produced during these tests.

Table 3. Results of dielectric fluid spray tests.

Dielectric material	Temperature C°	Spark & flame	Spark alone	Aerosol post spray spark/flame	Residual flame of surface
Castor oil	79	Yes	No	No	No
Castor oil	150	Yes	Yes	No	No
Rape-seed oil	64	Yes	Yes	No	No
Rape-seed oil	77	Yes	Yes	No	1–2 sec.
Rape-seed oil	94	Yes	Yes	No	Yes (wick)
Rape-seed oil	127	Yes	Yes	No	No
Epoxide resin	75	Yes	Yes	No	No
Epoxide resin	150	Delay	Yes	No	No

Note: Low temperature for each test is the minimum to achieve the heterogeneous spray.

Spray Tests Conditions:

Spray nozzle diameter = 0.042 in. (0.1067 cm).
Fluid reservoir pressure = 100 psi (7.03 kg).
Spark energy 6000 V ac at 20 mA.
Two-in.-long propane flame partially premixed with air to produce a smooth and stable flame.

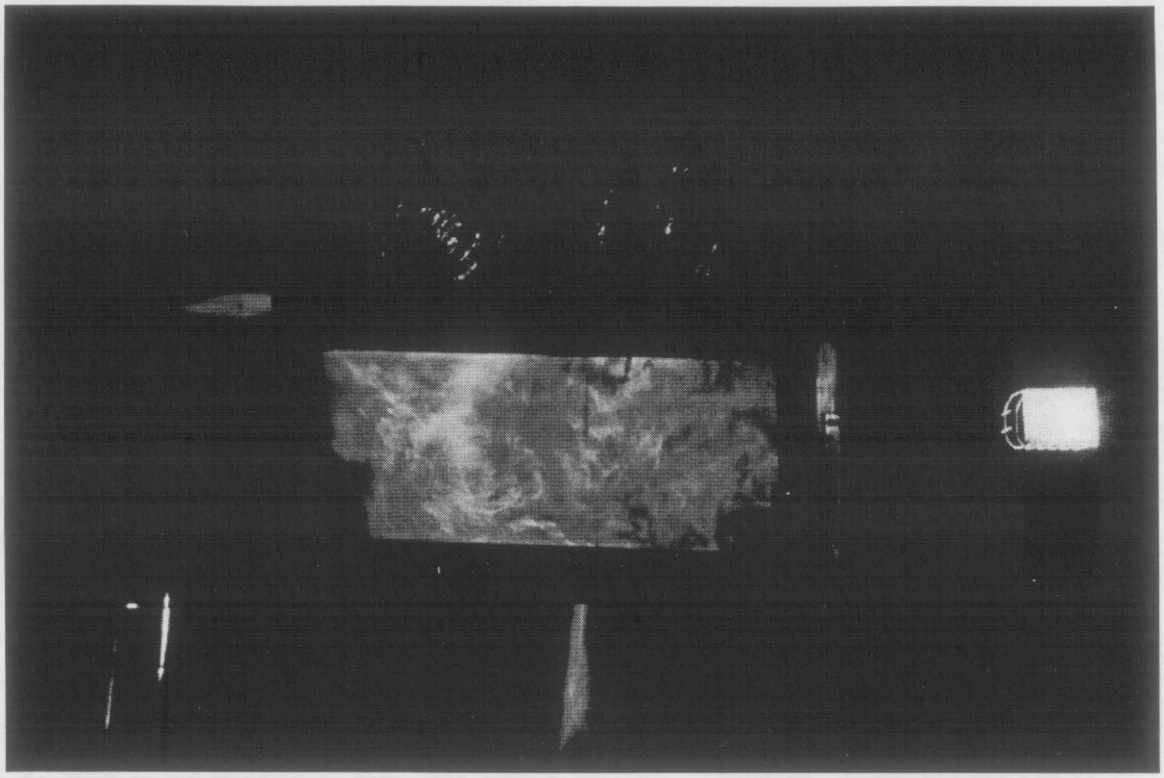


Figure 9. Caster oil spray test ignition event.

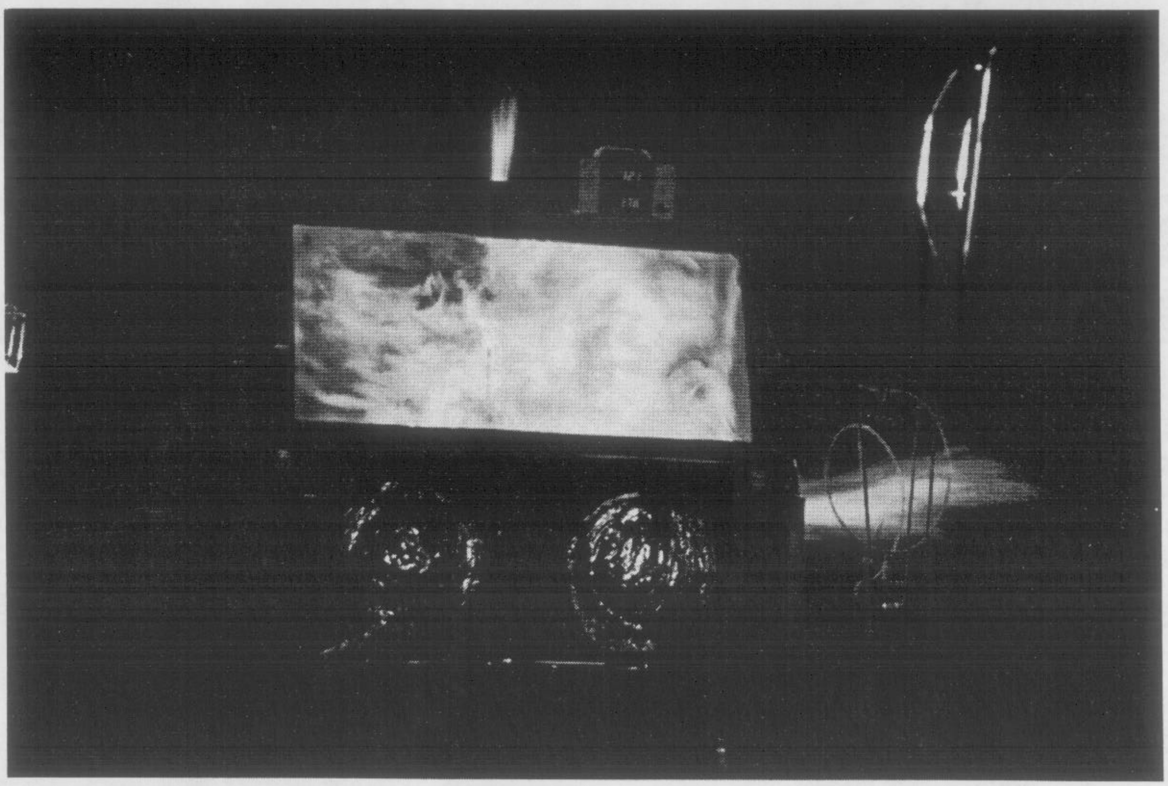


Figure 10. Rape-seed oil spray test ignition event.

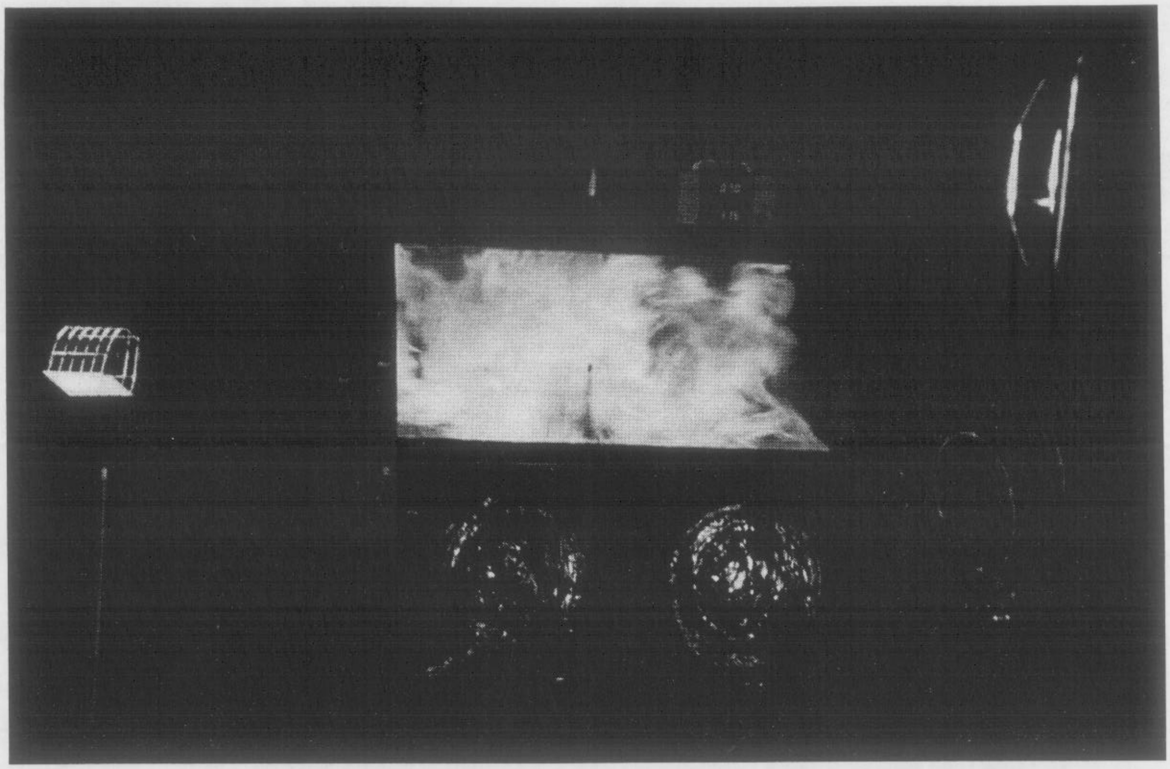


Figure 11. Epoxy resin spray test ignition event.

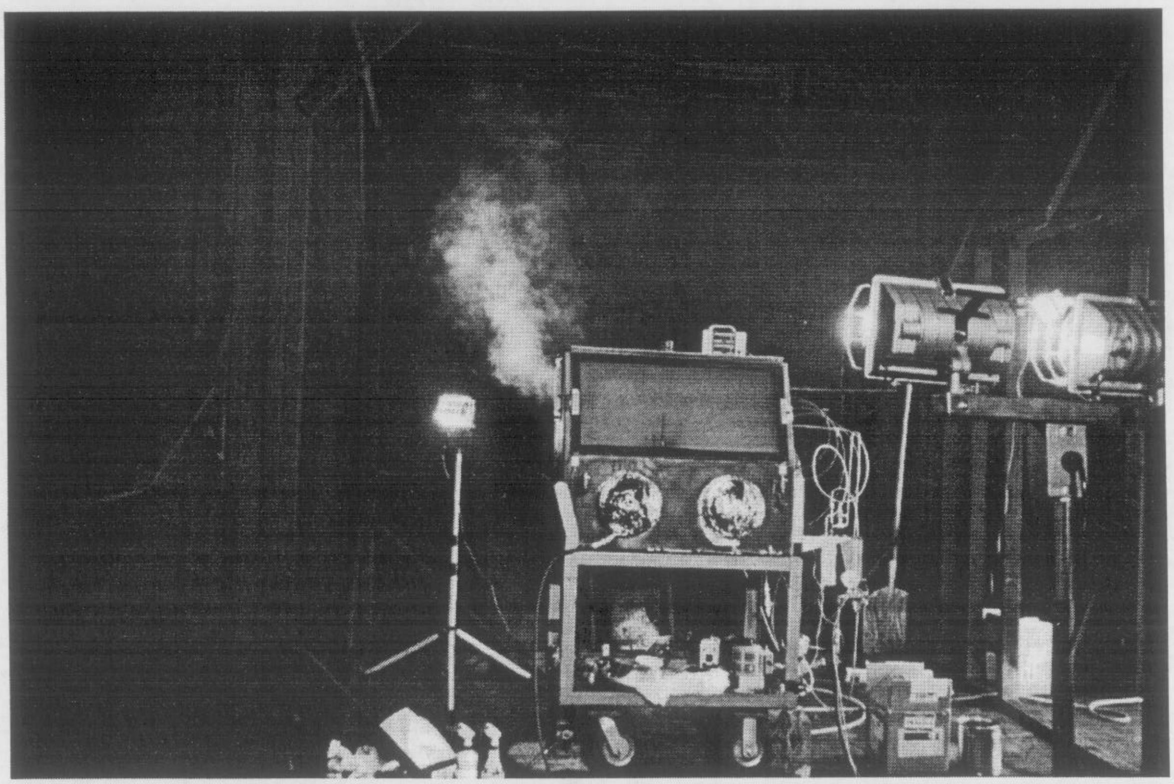


Figure 12. Light smoke produced during dielectric fluid spray test ignition events.

TEST SUMMARY

Tests conducted on the candidate dielectric fluids show that these fluids are difficult to ignite and that they self-extinguish on impervious surfaces. Flammability of the three fluids are similar once ignited, e.g., flame from 6-in.-diameter fuel reservoirs were not vigorous, smoke production was minimal, and the heat release rate was substantially less than high-vapor-pressure fluids like gasoline or kerosene.

Ignitability of both spray and bulk fluids were similar and followed the order of published flash-point data listed in Table 1, where the data listed is probably from Penski-Martin closed-cup flash-point tests. In the screening tests, the temperature of the bulk fluid required for ignition decreased in the order of castor oil < rape-seed oil < dielectric fluid epoxide resin. These data should be similar to Cleveland open-cup flash-point results. In the spray ignition tests, the rape-seed oil and the dielectric fluid epoxide had similar spray ignition behavior. Rape-seed oil alone produced transient episodes of residual burning on surfaces, lasting only 1–2 seconds. In all cases, the ignited spray flames would not continue burning without an ignition source. Consequently, a transient ignition source such as a discharge arc could only produce a limited quantity of ignited fluid. Moreover, if this burning fluid should contact a metal surface, heat loss to the surface would quench the flame. It is possible that flames could be sustained on porous and low-density materials (which are not abundant in the capacitor module).

OVERPRESSURE ANALYSIS

Both experimental test results and published dielectric fluid properties are such that it is highly unlikely for any of these low-vapor-pressure fluids to produce sufficient volumes of ignited aerosols or vapors to cause significant overpressurization of the NIF capacitor modules. However, failing capacitors have caused fires in existing facilities, and dielectric fluid deposits have been found splattered around the areas where catastrophic capacitor failures occurred. If the dynamics of dielectric fluid release from exploding capacitors are ever defined, and if this information indicates that ignited aerosols can be formed in the capacitor modules, there is then need to anticipate countermeasures required for safely releasing overpressures that may be produced by this process.

Limited descriptions of dielectric release from catastrophic failures of capacitors indicate that the initial event is a flash followed by leaking of fluid from the ruptured capacitor case. There is no information available to define the quantity of fluid causing the observed flash event, but since there is no indication that extensive physical or thermal damage is caused by these flashes, it is likely that amount of fluid produced is relatively small. By assuming different realistic pressure levels in a module, it is possible to calculate the quantity of fluid atomized, mixed with air, and ignited to produce the different assumed pressures. With this information, the area of vents necessary to dissipate the assumed overpressure are determined using the ratio between the surface area of the fireball and the surface area of the enclosure. Data required to calculate the capacitor module vent areas for assumed overpressures include (1) free volume and interior surface area of the module, (2) physical properties of the dielectric fluids, (3) flame temperature of stoichiometric mixtures of the dielectric fluids (we have used 2000°K for all three candidate dielectric fluids), (4) estimated chemical formula of the dielectric fluids, and (5) thermodynamic properties of the mixtures.

Table 1 contains both published and calculated properties of castor oil, rape-seed oil and dielectric fluid epoxide, with source references. MSDS disclosures generally did not contain data on the chemical composition, the ignition limits, or the vapor density of the fluids. Organic chemistry references[2, 3] provided information about the composition of castor oil and rape-seed oil from which other properties such as fuel stoichiometry, specific vapor volume, and vapor density could be calculated. Chemical composition and formula for dielectric fluid epoxide were included in the Union Carbide MSDS. Dimensions of the NIF capacitor modules are estimate from Figure 13, which is an isometric view of the current design of an NIF capacitor module. To estimate the internal free volume of the module, these dimensions were used along with approximate capacitor dimensions. The volume of damping elements was also scaled using the module dimensions. Attachment 1 and Tables 1–3 summarize these calculations. The estimated free volume of the module is calculated to be 8.7 m^3, and the internal surface area is scaled to be 375.5 ft^2 (110.6 cu meters). (The vent area equation used for this analysis is in English units.)

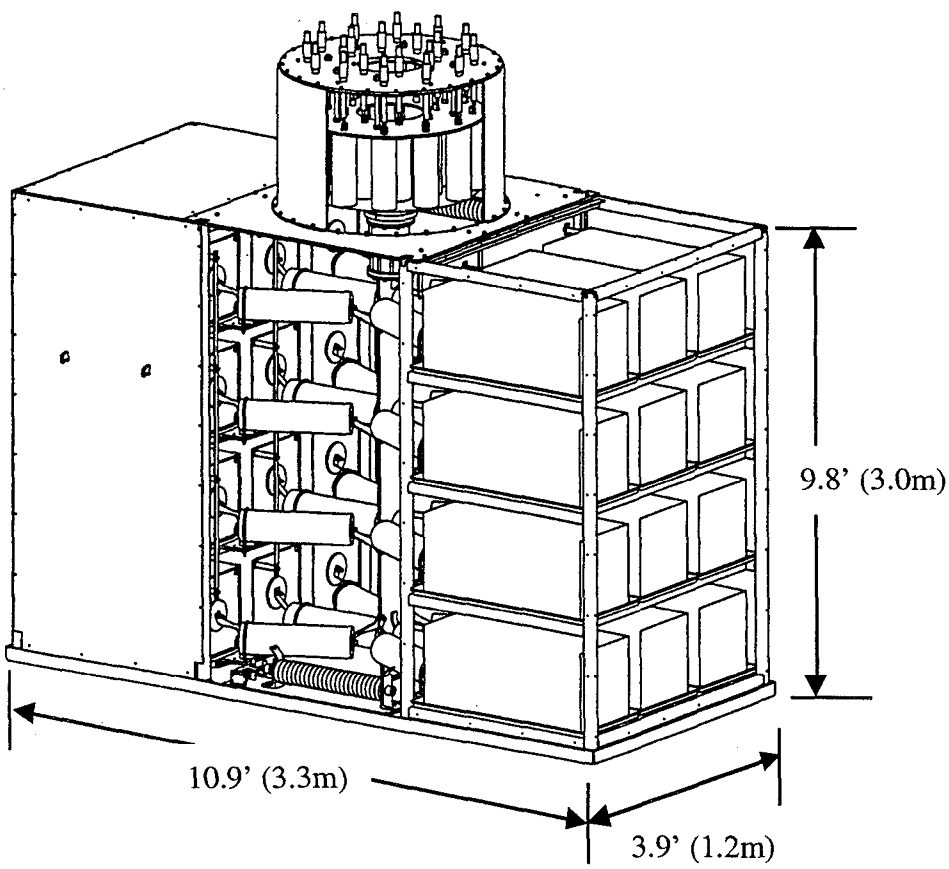


Figure 12. Isometric view of the current NIF capacitor module design.

Attachment 1 contains the equations used to calculate the volume of dielectrics required to produce the assumed overpressurization in the capacitor module. The procedure is to use Equation 1 to estimate the theoretical maximum pressure rise that could occur in the module, assuming that the free volume of the module was filled with a stoichiometric mixture of dielectric vapor and air. In this case, using the assumed adiabatic maximum flame temperature of 2000°K, the theoretical enclosure pressure rise is 6.7 atmospheres (~100 psi [7.03 kg/sq cm]). The next step is to guess a range of overpressures in the module that would be consistent with the reported flash observed emanating from exploding capacitors. In the example in Attachment 1, 1.0 psi [0.0703 kg/sq cm] (0.07 atmospheres) is the estimated overpressure. Manipulating Equation 2 to solve for the mass of fuel burned, M_B, the calculated mass–volume of castor oil, rape-seed oil, and dielectric fluid epoxide required to produce a 0.07 atmosphere pressure pulse in the capacitor module is 0.12 kg/125 cc, 0.11 kg/120 cc, and 0.21 kg/180 cc, respectively. Table 4 lists the mass and volume of castor oil, rape-seed oil, and dielectric fluid epoxide required to produce overpressures in the capacitor module of 0.5 (.035), 1.0 (.07), 2.0 (.14), and 4.0 (.281) psi (kg/sq cm). The volumes of castor oil and rape-seed oil required to produce the assumed overpressures are nearly identical, while almost twice as much dielectric fluid epoxide is required to produce the same effect.

The equation in Table 5 is used to estimate the size of vent necessary to limit pressure rise in enclosures containing explosive atmospheres. This relationship is applicable to enclosures where vent closures are set to open at relatively low-pressure levels. The basic premise is that maximum pressure is simultaneous to the maximum rate of combustion, which occurs when the enclosure volume is filled with flame. Thus, the internal surface area of the enclosure is the confining surface of the explosion and, as such, is a defining parameter for determining the vent size. The flame surface area, based on the adiabatically expanded fireball for the assumed overpressure events from exploding capacitors, is a small fraction of the interior surface area of the capacitor module. Consequently, the fireball surface area is used to calculate the vent area. Flame volume and surface area are calculated by assuming that adiabatic expansion of stoichiometric mixtures of the dielectric fluids with air occurs from combustion of fluids during ejection from the exploding capacitors.

Vent areas necessary to relieve the assumed overpressures from deflagration of atomized dielectric fluids are listed in Table 5. Differences in the calculated areas are relatively small for the candidate fluids. The difference in vent area at the lowest assumed overpressure of 0.5 psi (0.35 kg/sq cm) is ~3%, and at 4 psi, the difference is ~4%. The difference in vent area for any of the fluids over the range of assumed overpressure is ~40%, which appears not too extreme for a factor of 8 pressure differential.

Table 4. Mass and volume of caster oil, rape-seed oil, and dielectric fluid epoxide.

Assumed pressure	Castor oil	Rape-seed oil	Dielectric fluid epoxide
PSI (Kg/sq cm)	$M_B(V_B)$ *	$M_B(V_B)$ *	$M_B(V_B)$ *
0.5 (0.035)	0.056kg (58cc)	0.053kg (58cc)	0.102kg (87cc)
1.0 (0.070)	0.12kg (125cc)	0.11kg (119cc)	0.21kg (180cc)
2.0 (0.140)	0.23kg (243cc)	0.22kg (241cc)	0.43kg (362cc)
4.0 (0.281)	0.44kg (460cc)	0.41kg (453cc)	0.80kg (681cc)
PSI (Kg/sq cm)	Vapor Volume †	Vapor Volume †	Vapor volume †
0.5 (0.035)	0.0045m^3	0.0041m^3	0.0097m^3
1.0 (0.070)	0.0098m^3	0.0085m^3	0.022m^3
2.0 (0.140)	0.019m^3	0.017m^3	0.041m^3
4.0 (0.281)	0.036m^3	0.032m^3	0.076m^3
PSI (Kg/sq cm)	Stoichiometric vapor/air volume **	Stoichiometric vapor/air volume **	Stoichiometric vapor/air volume **
0.5 (0.035)	0.052m^3	0.052m^3	0.054m^3
1.0 (0.070)	0.113m^3	0.106m^3	0.120m^3
2.0 (0.140)	0.218m^3	0.216m^3	0.230m^3
4.0 (0.281)	0.413m^3	0.408m^3	0.429m^3
PSI (Kg/sq cm)	Adiabatic flame volume ft^3 (m^3)††	Adiabatic flame volume ft^3 (m^3)††	Adiabatic flame volume ft^3 (m^3)††
0.5 (0.035)	10.6 (0.30)	10.6 (0.30)	10.9 (0.31)
1.0 (0.070)	22.6 (0.64)	21.2 (0.60)	24.0 (0.68)
2.0 (0.140)	43.8 (1.24)	43.4 (1.23)	46.3 (1.31)
4.0 (0.281)	82.9 (2.35)	82.3 (2.33)	86.5 (2.45)

1. $M_B(V_B)$ in liquid phase

† V_B in vapor phase 1.0 (Liter) = $0.83 * \frac{\text{SpGr}}{\text{Vapor density}}$ (m^3)

** $\frac{\text{Vapor Volume } (V_V)}{\text{Stoichiometric Ratio}}$

†† Stoichiometric $\left(\frac{\text{Vapor}}{\text{Air}}\right) * \Delta P$, $\Delta P = 5.7$

Table 5. Vent areas necessary to relieve the assumed overpressures from deflagration of atomized dielectric fluids.

Pressure PSI (Kg/sq cm)	Castor oil	Rape-seed oil	Dielectric fluid epoxide
P_{Red}	Flame volume ft^3 (cu meter)*	Flame volume ft^3 (cu meter)*	Flame volume ft^3 (cu meter)*
0.5 (0.035)	10.60 (0.30)	10.6 (0.30)	10.9 (0.31)
1.0 (0.070)	22.60 (0.64)	21.2 (0.60)	24.0 (0.68)
2.0 (0.140)	43.80 (1.24)	43.4 (1.23)	46.3 (1.31)
4.0 (0.281)	82.90 (2.35)	82.3 (2.33)	86.5 (2.45)
P_{Red}	Flame diameter ft (cu meter)†	Flame diameter ft (cu meter)†	Flame diameter ft (cu meter)†
0.5 (0.035)	2.70 (0.08)	2.70 (0.08)	2.75 (0.08)
1.0 (0.070)	3.50 (0.10)	3.40 (0.10)	3.60 (0.10)
2.0 (0.140)	4.30 (0.12)	4.36 (0.12)	4.50 (0.13)
4.0 (0.281)	5.40 (0.15)	5.40 (0.15)	5.50 (0.16)
P_{Red}	A_F flame surface area ft^2 (cu m)**	A_F flame surface area ft^2 (cu m)**	A_F flame surface area ft^2 (cu m)**
0.5 (0.035)	23.00 (0.65)	23.00 (0.65)	23.70 (0.67)
1.0 (0.070)	38.50 (1.09)	36.30 (1.03)	41.00 (1.16)
2.0 (0.140)	60.00 (1.70)	60.00 (1.70)	63.60 (1.80)
4.0 (0.281)	91.60 (2.59)	91.60 (2.59)	95.00 (2.69)
P_{Red}	A_V, vent area ft^2 (cu m)††	A_V, vent area ft^2 (cu m)††	A_V, vent area ft^2 (cu m)††
0.5 (0.035)	5.50 (0.16)	5.50 (0.16)	5.70 (0.16)
1.0 (0.070)	6.50 (0.18)	6.20 (0.18)	7.00 (0.20)
2.0 (0.140)	7.20 (0.20)	7.20 (0.20)	7.70 (0.22)
4.0 (0.281)	7.80 (0.22)	7.80 (0.22)	8.10 (0.23)

* Flame volume from Table 4 † $V_B = 0.524\, d_f^{2}$ ** $A_F = \pi d \frac{2}{f}$ $A_V = \frac{C\, A_F}{\sqrt{P_{Red}}}$

The size of venting area (A_V) required to relieve calculated overpressure development.

Fire Protection Engineering Handbook, 2nd Edition, Section 3, Chapter 16, p. 3-322, Equation 9.

$$A_V = \frac{C\, A_S}{\sqrt{P_{Red}}}$$

A_V = Required free vent area
A_S = Proportion of internal surface of enclosure exposed to flame contact
C = Fuel characteristic constant
P_{Red} = Internal over pressure limit (psi)

$C \Rightarrow 0.17$ (for HC gases, e.g. Propane)

As proportional to ratio of flame volume surface (assume sphere): $V_S = 0.524 d^3$
A_F and internal surface of module: $A_M \cong 375 ft^2$ $A_F = \pi d^2$
These calculations do not include capacitor surfaces. $\therefore A_S = A$

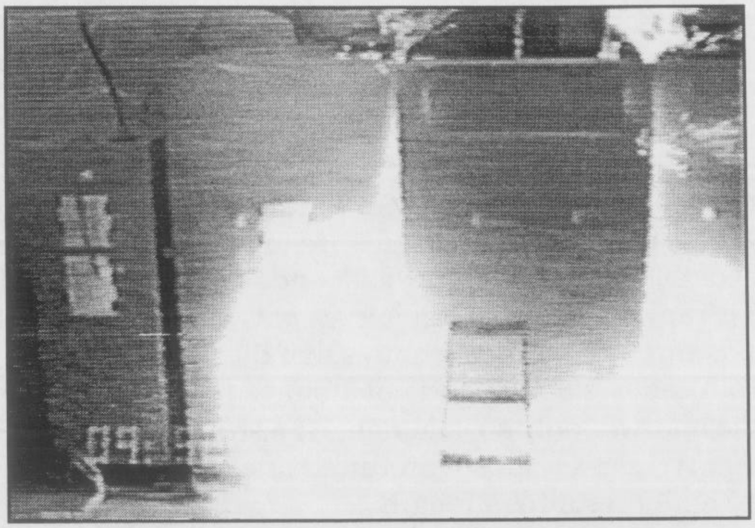
CONCLUSIONS

This analysis is based on limited information. No hard data on capacitor failure modes or description of dielectric release dynamics have been provided as background for the study. Information on flammability of candidate dielectric fluids is limited, and data about ignition ease and heat release rates are unavailable. The screening tests reveal that ignition of the bulk fluids is difficult and that ignited fluid above its flash-point temperature is rapidly quenched on impervious surfaces of lower temperature. To atomize the fluids through nozzles requires that they be preheated. If this is not done, the spray produced is globular and not atomized. Even the hot atomized fluids are difficult to ignite and will only sustain flame if a strong ignition source is maintained in the spray. Dense aerosol produced after the spraying tests never did ignite, regardless of ignition source strength.

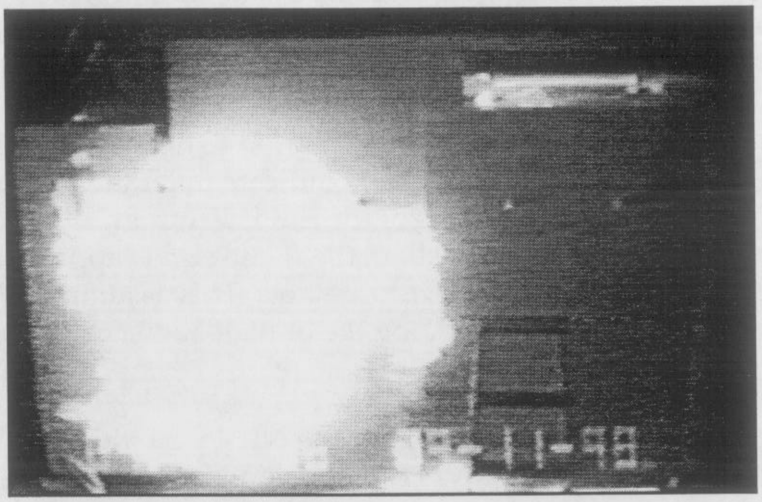
Observations of capacitor explosions describe a sequence in which indication of failure is a "flash" followed by limited burning of collected dielectric. The character of the flash is not known, i.e., is it a manifestation of electrical arc or is it ignition of dielectric aerosol or vapor? Calculations of flame size produced from moderate quantities of atomized dielectric fluid when compared to descriptions of the flash described by observers of exploding capacitors indicate that the flash event is transient, resulting from ignition of small quantities of the fluid. Thus, even if the flash was a manifestation of a homogeneous combustion, the flame size is apparently too small to have the potential of producing strong overpressures. This assumption is bolstered by operators' description of these events and by the only documentation of a catastrophic failure of a capacitor.

During testing of new capacitor designs for the NIF by Sandia National Laboratory (SNL), a capacitor failed. This failure was captured on video. Three frames from this video were digitized in sequence and are shown in Figure 14(a–c). The object in the foreground of the pictures appears to be a small stepladder. The resulting fireball apparently produced minimal overpressure.

To insure that overpressures produced by exploding capacitors do not cause damage to capacitor module enclosures, provisions for pressure relief should be included in the final module design. Vents designed to accommodate the vent areas contained in Table 5 need not be elaborate. Gaps between panels should suffice, and a hinged panel could also provide the needed area. The pressure-producing capacity of the candidate dielectric fluids does not differ greatly. In general, the flammability of the castor oil and rape-seed oil is similar, while the flammability of the dielectric fluid epoxide is greater, i.e., it is easier to ignite, and its burning rate is faster. However, if only the potential for producing overpressure is the measure for selecting the dielectric, all three of the candidates perform similarly.



(a)



(b)

(c)

Figure 14 (a–c). Digital video frames of a capacitor failure at SNL and resulting explosion and fireball.

References

1. Frederick MacDougall, Martin Hudis, Ronald Rice, Xiao Hui Yang, "The Development and Performance of High Reliability, High Energy Density Pulsed Discharge Capacitors," *16th Capacitor and Resistor Technology Symposium*, March, 1996, pp. 218–220.

2. *Handbook of Chemistry & Physics*, 67th Ed., 1985–1987, CRC Press.

3. W. B. Sandere, *Chemistry of Organic Compounds*, NOLLER, 1951.

Attachment 1

Equation 1.

Theoretical pressure rise in unvented enclosure

$$\frac{P_m}{P_o} = \frac{M_o T_b}{M_b T_o}$$

P_m = Maximum pressure from complete combustion

P_o = Initial pressure prior to ignition (1 Atmosphere)

M_b = Molecular Wt. of combustion products mix

M_o = Molecular Wt. of fuel–air mix

T_b = Max Temperature rise (~ 2000K° for all dielectrics)

T_o = Initial temperature of fuel–air mixture (~300°K [ambient])

$$\frac{M_o}{M_b} \sim 1$$

$$\frac{P_m}{P_o} = 1\left(\frac{2000}{300}\right) = 6.7 \text{ Atm.}$$

Equation 2.

To determine mass of fuel (M_V) required to produce specified pressure rise in unvented NIF capacitor module—(module volume estimate ~8.7m^3)

$$\frac{P - P_o}{P_m - P_o} = \frac{M_B}{M_V}$$

P_o = Ambient pressure = 1.0 Atm

P_m = $\frac{P_m}{P_o}$ = 6.7 Atm

P = Pressure rise from ignition of fuel/air mixture in fraction of total volume

M_B = Mass of fuel actually burned in fraction of total module volume

M_V = Mass of fuel at stoichiometric concentration for total module volume

Equation 2a.

Calculate for internal module pressure rise at 1 psi (0.07 Atm) to find M_B

$$P_M\text{-}P_O = 6.7 - 1.0 = 5.7 \text{ Atm}$$

$$P - P_O = 1.07 - 1.0 = 0.07 \text{ Atm}$$

$$M_V = V_E \; \rho_A \; \% \text{ fuel} \left(\frac{\text{Mol fuel}}{\text{Mol air}}\right)$$

$$V_E = 8.7 \text{ m}^3$$

$$\rho_A = 1.2 \frac{\text{kg}}{\text{m}^3}$$

% Fuel
= 0.087 (Castor oil)
= 0.079 (Rape-seed oil)
= 0.18 (Epoxide)

$\frac{\text{Mol fuel}}{\text{Mol air}}$
= 10.29 (Castor oil
= 10.7 (Rape-seed oil)
= 9.06 (Epoxide)

$$M_B = M_V \frac{P - P_O}{P_M - P_O} = M_V(0.0123)$$

M_B
= 0.12kg (Caster oil)
= 0.11kg (Rape-seed oil)
= 0.21kg (Epoxide)

$$V_B \cong \text{sp.gr. } \rho_{H_2O}$$

$\therefore V_B$
= 125cc (Castor oil)
= 120cc (Rape-seed oil)
= 180cc (Epoxide)

Reference

Fire Protection Engineering Handbook, 2nd ED, Section 3, Chapter 16, pp. 3-316 to 3-319.