Electrostatic Nuisances and Hazards

1.Overview

- Although the phenomenon of static electrification has been known for hundreds of years, problems arising from it are of more recent vintage.
- These problems cover a wide variety of physical situations and touch on many human concerns, ranging from large-scale industries to domestic activities;
- They range in magnitude from major hazards, with potential loss of life and possible damage costing hundreds of millions of dollars, to minor annoyances in the home or office.

- The problems include:
  - Explosions during the handling filtering, refining, or transportation of volatile liquids or gases;
  - Dust explosions in sugar mills, granaries, sulfur mills, and coal mines;
  - Losses in the manufacture and handling of photographic film and integrated circuits;
  - Minor annoyances such as carpet electrification or the sticking of powders to the walls of containers.

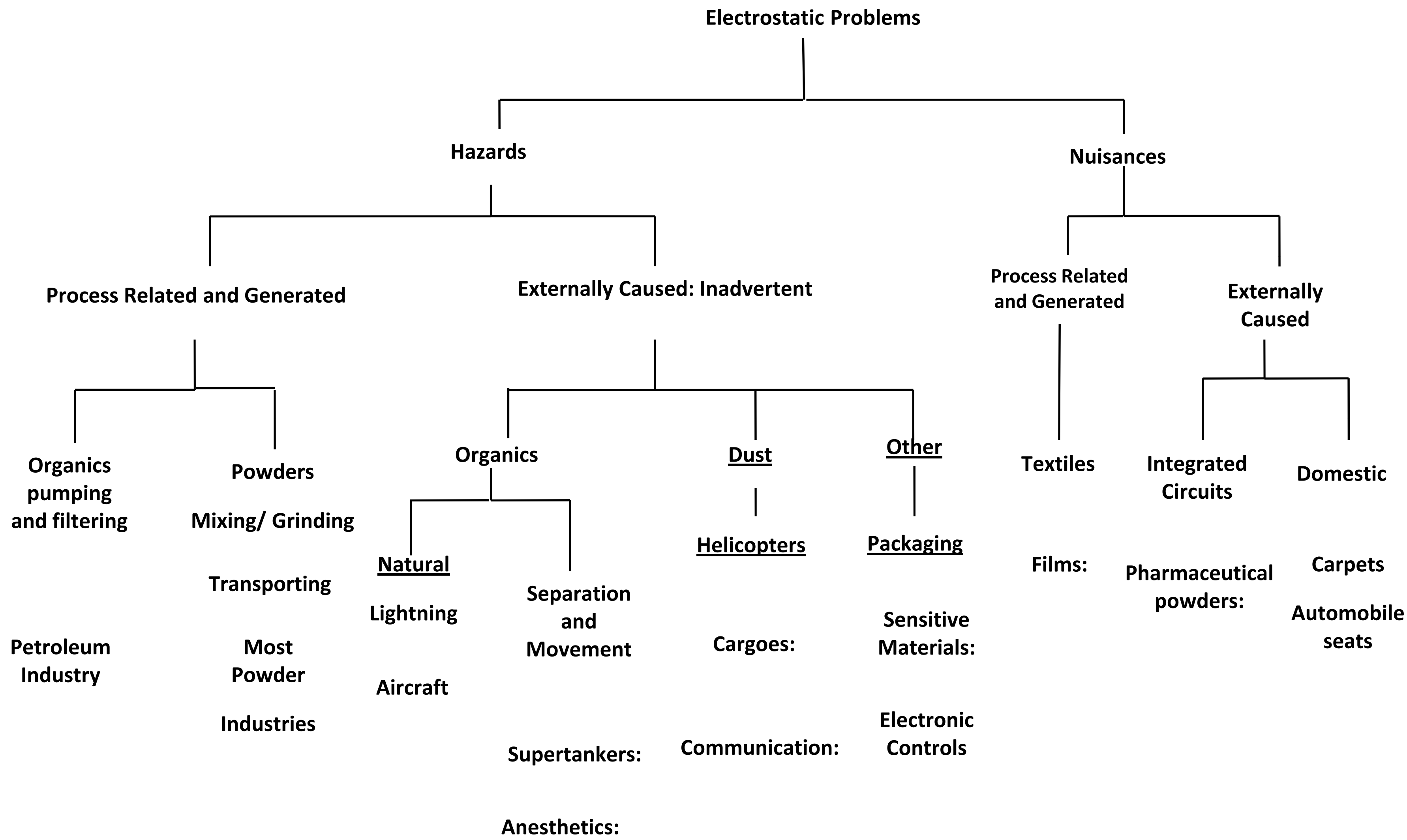

Fig. Some hazards and annoyances due to electrostatics.

- Some general comments regarding electrostatic hazards and nuisances. In all cases there are three criteria for the existence of an electrostatic hazard. These criteria are:

(1) Charging of the material, or nearby structures, occurs;

(2) The leakage of such charge is so slow and small that local spark breakdown potential can be reached and a minimal required amount of electrostatic energy stored; and

(3) The material ignites, explodes, or is damaged when subjected to the ensuing sparks. In the case of dust, triboelectric charging and physics of surfaces are involved; in organic liquids, charge layers form on surfaces and possibly disrupt such layers and the case of persons, dissimilar surfaces are separated by the action of walking, sliding, or the movement of clothing.

- Besides the mechanism of charging, we must consider the second important aspect, namely, the mechanism by which the materials concerned retain the charge.
- This involves the idea of a relaxation time τ, which depends on the resistivity ρ and the dielectric constant K of the material:

  $\tau = K_0 K_\rho$

  where K_0 is the permittivity of free space and equals 8.85×10^{-14} F/cm.

  Thus

  $\tau \approx 9 \times 10^{-14} K\rho$ sec where ρ is in Ω-cm.

- In general the value of the relaxation time is determined by what leakage paths are available to the charge generated.
- The leakage path through the air depends on the presence of ions and the possible presence of ionizing material.
- The leakage path through powders involves the resistivity of the powders, which is dependent on humidity and packing.
- If the resistivities of the leakage paths involved are of the order of, say, 10^{14} Ω-cm, long relaxation times, of the order of 1sec, will pertain.
- The first two criteria may suffice in a nuisance situation such as the sticking of powders to containers or the collection of dust by fabrics.

- The third criterion for a potential hazard is that sufficient electrostatic energy be developed at sufficiently high voltage that breakdown can occur and a spark can ensue with enough energy to ignite combustible materials.
- Typical values of these minimal energy requirements might be taken as 0.1mJ for organic vapors and 20mJ for combustible dust.
- These values are merely representative, since the possibility of ignition depends on the concentration of the material concerned, the oxygen content of the environment, and, in the case of dust, the particle size.

- Since the electrical capacitance of the human is approximately 300pF, the person could produce a spark of 15mJ upon discharge,
- The minimum spark energy required to ignite aviation gasoline vapor in air is estimated from data of Lewis and von Elbe[1] to be about 0.2 mJ; this means that an electrostatically charged person could be a fire hazard in the presence of aviation gasoline vapor.
- Many potentially hazardous situations involving large quantities of material can be analyzed by laboratory-scale experiments, and estimates can be made including predictions of the roles of additives, controlled humidity atmospheres, or the presence of fast ions to increase atmosphere conduction.

- All control systems involve reducing the relaxation time.
- Bonding and grounding is effective for good conductors.
- Bonding reduces any potential difference between good conductors, although both may still be at a potential(zero if they are grounded) that differs from other objects.
- The use of grounded screens through which powder or fluids may flow should not necessarily be undertaken, Electrification may be increased.
- Relative humidity in the 60 to 70% range can bring about water films on conducting materials which provide conducting paths.
- Ionization of the local atmosphere generally decreases the relaxation time for stored charge.

- Either radioactivity or point discharge combs can be employed.
- If the leakage path is not primarily atmospheric, this is a limited mechanism(as e.g., with flowing liquids or powders).
- Various antistatic agents are available for surface or bulk treatments of fabrics/plastics which depend in principle on capturing surface films of moisture.
- The conductivity of organic liquids can be greatly increased by the addition of a few parts per million of commercial additives.
- Warning devices should be used in the process vicinity to indicate when the levels of electrostatic activity are becoming dangerously high.

- Static detectors may be conveniently divided into two types, namely, those which measure the electrostatic field and variations therein and those whose primary objective is the detection of spark discharges.
- The former range from very simple devices such as gold leaf electroscopes or neon lamps to sophisticated electrostatic volt meters, electrometers, and field mills.
- The second class of spark detectors is specifically aimed at detecting rapid changes in the electric field.
- These devices operate using a capacitive antenna such that when a discharge occurs, there is a change in the equilibrium charge on the antenna.
- This incremental charge becomes a signal which may be amplified and recorded.

2.DUST

- The electrostatic properties of dusts can lead both to annoyances and to major hazards.
- One of the outstanding aspects of electrostatic phenomena in moving powders is the widely differing distance scales on which these phenomena can occur.
- These range from the micro scale, as in the finer aspects of electrostatic copying or in the common annoyance of powders sticking to surfaces, through scales of kilometers or more, possibly to cosmic dimensions.
- Naturally occurring electrostatic phenomena associated with dust are sometimes seen in dust devils.

- Moving powders are often very active electrostatically, and high voltage and charge levels can be readily achieved by allowing the powders to impinge on targets or to be collected in containers which approximate Faraday cages.
- Qualitative data, useful from the point of view of industrial processes, can often be obtained by simple laboratory experiments.
- Thus the magnitude and polarity of the charge acquired by a powder or its container may depend on:

1) The moisture content of the atmosphere and the powder.

- As a rule, surfaces rapidly become coated with fine particles in the presence of moving powders.
- This generally reduces charging or causes polarity changes, since impacts are then between different sized particles of powder rather than between surface and powder.
- The thin layers of particles adhere very strongly, and a simple calculation shows that electrostatic binding forces can greatly exceed gravitational forces.
- Bernard Vonnegut has suggested an arrangement of equipment for tribo-electric measurements with blown powder.

- The accumulation of the charged particles on the filter causes a capacitor connected between the metal filter holder and ground to become charged and the potential is recorded with an electrometer.
- This system affords a convenient way of comparing the relative electrostatic activity of different powders.
- By varying the gas pressure, the rate of charging can be varied or even the particle size of powder blown up.
- Experiments such as these indicate that electrostatically active powders such as starch or cabosil can produce about 1μC of charge per gram of agitated powder.

- Assuming reasonable values for various parameters such as particle size and number density for typical powders, the following rough calculation shows that the particles must charge up approximately to breakdown potential.

Radius of particles	r ≈ 10μ
bulk density	D ≈ 1 g/cc
density	ρ ≈ 3 g/cc
Particle mass	m ≈ 10^{-8} g
Total Charge	Q ≈ 10^{-6} C/g
Charge per particle	q ≈ 10^{-14} C/particle
	= 3 x 10^{-5} esu/particle

- Thus the field f at the edge of the particle is given by

$$f = \frac{q^2}{r^2} \approx 3 \times 10^{-5} \times 10^{6} \text{ stat V/cm} \approx 9 \times 10^{3} \text{ V/cm}$$

- The gravitational force on particle mass 10^{-8} g ≈ 10^{-5} dyne.
- The electrostatic force P on a particle charge q in contact with a conducting plane is given by

$$P = \frac{q^2}{4r^2} \approx 2 \times 10^{-4} \text{ dyne,}$$

Where q is in electrostatic units and r is in centimeters.

- Thus the electrostatic force of attraction is approximately 20 times the gravitational force on the particle.

- The relaxation time τ depends on the resistivity ρ and dielectric K constant of the powder; thus we have

$\tau = K_0 K_\rho$,

$K_0 \approx 9 \times 10^{-14}$ F/cm

- Measurements of these variables are also important in assessing a potentially hazardous situation with an electrostatically active powder.
- In general the value of τ is determined by the resistivity, which can vary over many orders of magnitude.
- Thus the leakage path through air depends on the presence of ions and the possible presence of ionizing material, and the resistivity of powders is very dependent on humidity and packing.
- The resistivity (Ω – cm) of the bulk material is computed from measurement of the resistance between the electrodes and the height of the powder.
- In order to use the method, a known force or pressure must be applied to the top of the sample.

- Fairly consistent measurements of resistivity as a function of applied pressure can be made using an Instron unit with the 100-kg load cell, which applies constant displacement to the upper powder surface and measures the force applied to the surface.
- Representative data (taken on various powders subjected to pressures from 0 to 5.6 kg/cm^2, in such a fashion that the pressure was first increased and then decreased) show two gross effects:

1. That the resistivity is very sensitive to increased packing
2. That a considerable hysteresis may occur.

- Resistivities of nonmetallic powders may range up to values greater than 10^{14} $\Omega - cm$, which is about the upper limit of conventional measurement techniques.

- Resistivities of this magnitude ensure long relaxation times of the order of seconds.
- In industrial practice where large quantities of powders are concerned, energies stored in the powder or on parts against which the powder has impacted may be considerable and can cause sparks sufficient to ignite the dust.
- Dust explosions caused by static discharges have occurred in a variety of industries concerned with powders.
- The U.S.Bureau of mines has determined the minimum ignition energy for a variety of dust clouds and layers. Generally, the energies required are of the order of 10 mJ.
- The apparatus consists of capacitors charged to a desired energy level, a spark gap, and a system to produce a small dust cloud which is synchronized with the spark.

- With such an apparatus it is easy to show that the energy required for ignition is strongly dependent on the duration of the spark.
- Thus, when on the of the points in the spark gap is directly grounded, the minimum energy stored in the capacitors required for ignition is at least an order of magnitude greater than the value quoted in Reference.
- When the point is grounded through a large choke (several henries), the spark is much more prolonged, and the values of the minimum energy required agree well with Reference, where a large choke was used in the circuit also.
- The energy required appears to increase with decreasing inductance in the circuit.

	Explosions Attributed to			
Kind of Dust	**Total Explosions**	**Unknown Cause**	**Electric Spark (Any Origin)**	**Static Discharge**
Plastic dust	35	7	3	3
Paper dust	35	-	2	1
Cork dust	40	8	--	5
Metal dust	81	19	5	3
Starch and corn dust	56	17	5	6
Sulfur dust	34	6	--	6

- This dependence of effects in dust clouds on the duration of the spark is not limited to ignition.
- If a system involving moving powders has undergrounded metal parts which are contacted by the powders, these will charge to very high potentials and sparks to other grounded conductors are virtually inevitable.
- However, even when all metal parts are grounded, the airborne powder is still charged and a space charge situation exists.
- If the system is large enough, the possibility of breakdown between this space charge of charged particles and the grounds exists in a manner analogous to ground- to – cloud streamers in thunder- storm situations.
- Little evidence is available regarding whether this occurs and, if it does, whether it has caused explosions.

- An interesting aspect of electrostatic charging due to moving dust is in the case of helicopters. The problem is as yet unsolved in a satisfactory fashion.
- Helicopters hovering within a few feet of the ground acquire very considerable amounts of electric charge due to triboelectric effects from blown dust, sand, and so on.
- For such helicopters 1mJ is considered an acceptable maximum level of stored electrostatic energy.
- This potential hazard has resulted in research sponsored by the armed services.
- In practice, without some means of reducing the charge on the helicopter, energies of many joules may be realized at potentials of hundreds of kilovolts and with charging currents of hundreds of microamperes.

- In attempts to reduce the charge, active corona discharge systems are employed using corona points on the helicopter which are maintained at the proper polarity and potential by means of a power supply and sensor.

- Two major problems occur with this system as developed.

- First, it is difficult to obtain a sufficient discharging current from the points without employing an overly large, expensive, and potentially hazardous power supply;

- Second, the sensors currently used to determine the magnitude and polarity of the charge on the helicopter fail under field conditions.

- Helicopters operating at a few hundred feet above the ground and employing a long cable are less susceptible to triboelectric charging (except in rain, ice, or snow).

- They will, however, be at some potential relative to ground because of the atmospheric electric gradient.

- Thus in fair weather a helicopter at a 200 ft altitude will be at a potential of the order of 10^4V relative to the earth.

- Under thunderstorm conditions the helicopter may reach potentials of the order of 10^5 V relative to ground.

- The slurry mixing of sensitive materials poses another problem wherein simple determinations of resistance and capacitance may be of value.
- Eden et al.[14] have described a manufacturing situation in which a pyro-technic mixture was slurried with heptanes and the slurry dried on a moving belt 1m wide and approximately 7 m long.
- The belt was polypropylene approximately 0.1cm thick.
- The possible development of static charge on the pyrotechnic mix during the drying process and the characteristics of the dried and drying slurry material from the point of view of initiation by electrical discharge were investigated by means of model experiments.

- The purpose of the resistivity tests was to measure the electrical relaxation time τ of the mixes as functions of the relative humidity of the atmosphere in which they had been stored and of the amount of heptane present in the slurry.

- The method involved drying the slurry in a cell in a Buchner funnel with electrodes imbedded and monitoring the resistance of the cell.

- A relaxation time longer than about 1msec can permit appreciable electrostatic charge generation in a material and possibly spark breakdown.

- The results revealed that the electrical relaxation time at 50% relative humidity is 0.1 sec; at 90 to 100% relative humidity it is 10^{-8} sec.

- Thus at low relative humidity, the relaxation time of a specimen is long enough to permit appreciable electrostatic charge separation.

- When a cake of the mixture was allowed to break contact with a sheet of polypropylene by sliding off it, the cake and the sheet charged with opposite polarities to potentials of the order of 100 V.

- The potential of the polypropylene sheet may have been an order of magnitude higher. Rough estimates show the energies involved were in the range 10^{-5} to 10^{-7} J.

- Ignition level tests showed that all the specimens conditioned for several days at a room humidity (i.e., at relative humidity values from 25 to 75%) charred when subjected to sparks of some 20mJ.There is a difference between the energies required for slight charring and the energies required for complete ignition of the specimen. The experiments present two clear conclusions:

(1) That the relaxation time for these materials when dry was relatively long, and

(2) That they could be ignited by electrostatic discharge.

- The third aspect, the degree of electrical charging which occurs when the material is dried or moved, was indefinite.

- An experiment that would correctly model possible charging in the actual drying process is difficult to envisage, but it seems likely that some charging would occur and that safety could only be ensured by reducing the resistivity.

3.Organic Vapors

- Another serious area of electrostatic hazard occurs in operations involving hydrocarbon vapors.
- This may include such diverse situations as the use of anesthetics in hospitals, the filling and pumping of gasoline, the filtering of hydrocarbons, the cleaning of storage tanks, and, indeed, any dynamic situation wherein hydrocarbon liquid exists in contact with its vapor.
- Primarily this is because of the very low energy requirements for ignition of organic vapors and the generally high resistivity which ensures long relaxation times.
- The lower and upper "explosive limits" for the concentration of flammable vapors in air are roughly 50 to 400% of the stoichiometric proportion for combustion.

- At the high and low limits, 5 to 10 mJ is needed for ignition, and as we near stoichiometric proportions the spark energy required is about 0.2mJ.
- Ignition of combustible gases may require not only a minimum spark energy but also a critical voltage.
- Below the critical voltage, ignition requires greatly increased spark energy.
- The critical voltage for diethyl – ether – air mixtures has been found by Boyle and Llewellyn to be about 1500V.
- The corresponding value for gasoline – air mixtures is probably similar or strictly higher.
- Such energies may be readily attained even by the charging of a human operator.

- The source of charging may be the motion of the liquid itself either because of free charges on the surface of the liquid or because the liquid is in contact with other materials.
- In particular, the flow through pipes, the settling of mixed fluids, and filtering provide opportunities for the generation of static charge.
- Reference 3 supplies examples of computations that can be made to estimate the amount of charge and potentials generated in such cases.
- In general liquid hydrocarbons have high values of resistivity in the range of 10^{14} Ω – cm, and thus the relaxation times in such situations are relatively long.
- A variety of antistatic additives have been developed in the petroleum industry for addition to these insulating liquids to help reduce relaxation times.

- Considerable attention has been paid to the control of electrostatic hazards in the handling of organic liquids and vapors. There are two interesting examples wherein the charging and mechanism is not necessarily the motion of the liquid itself but, rather, is due to other operations carried out in the presence of the vapor. These are the classical problems of the use of anesthetics in operating theaters and the relatively new issue of the explosion of tankers at sea during wash down procedures.

- Less active anesthetic agents have recently been developed, but initially, when ether was first introduced, candles, gaslights, and coal stoves caused fires and mild explosions of the vapor – air mixtures.

- Such problems were soon minimized; however, the ignition of the vapors by electrostatic sparks proved a more difficult problem.
- In 1964 Eichel stated that the estimated number of deaths occurring annually from operating –room explosions may be of the order of 1000 in the United States.
- In these situations the clothing and shoes of the personnel involved are of consequence.
- Cotton is now generally considered to be nonhazardous in hospital operating rooms above 65% relative humidity.
- Outer garments of synthetic materials can build up considerable static charges when moved away from the body.

- In low humidity environments and inflammable atmospheres enriched with oxygen, the static levels reached from such sources may be dangerous.
- Similarly, conductive footwear or conductive floors have been suggested to minimize the accumulation of static on personnel.
- The provision of leak paths of suitable resistance to prevent the development of potentials of 1000-V eliminates the electrostatic hazard and provides a reasonable factor of safety.
- An idea of the leak path resistance that may be required to avoid excessive charge accumulation was given by Bulgin.
- In hospital operating rooms, where highly combustible mixtures of ether or cyclopropane and oxygen are possible, he recommended resistance of 10^5 to 10^7 Ω.

- The hazard due to personal clothing in such situations can be handled in three basic ways.
- Increased humidity causes the relaxation time associated with cotton materials to become acceptable, but it is less effective with synthetic materials.
- Various organic antistatic agents have been developed which can be sprayed on textiles or applied during finishing operations for the cloth.
- They tend not to be durable and to lose effectiveness at low humidities.
- In some instances they cause materials to become stiff and uncomfortable.
- The third alternative is the use of conducting fibres, either metallic or carbon based, in the manufacture of the textiles.

- For example, Ref.19 states that primarily synthetic materials containing 0.5% Brunsmet fibers produced only 10 to 20% of the voltage produced by cotton or polyester fabrics in a simple test in which the subject removed a laboratory coat.
- Recently there have been reports of tankers having blown up at sea.
- These ships might be regarded as being of the super tanker class.
- In the course of 3 weeks in 1969, the 200,000 ton tanker Merpessa exploded and sank off the Senegal Coast.
- Two weeks later the Macta exploded in the Mozambique Channel, and the next day the King Haakon VII exploded off Liberia.

- Later two more tankers exploded. From the facts generally available, the following picture emerged.
- The tankers were travelling empty and were being cleaned when the explosions took place in the tanks.
- During this process, a high-power water jet was used to wash down the walls with a high-velocity jet of water and sometimes with air venting.
- These were major explosions involving a loss of life and economic losses of hundreds of millions of dollars.
- It has been suggested that the electrical charging developed by Lenard splashing during the washing operations may be a cause.

- Both theory and experiment indicate that the situation is governed by the equation

$$\frac{dN}{dt} = \frac{Q}{e} - 10^{-13} N$$

- Where N = number density of large charge carriers

  T = time

  e = Electronic charge

  Q = ca.10^{-11}C/g(for seawater)

- These values correspond to N≈ 10^5/cm^3 and space-charge densities of 10^{-8} C/m^3.
- The study concluded that the electrification within a supertanker cargo tank may be sufficiently intense for a large-scale spark streamer to develop with a potential for an explosion hazard.

- The field within a closed container is approximately proportional to the product of the linear dimension of the container and the space-charge density; this charge becomes larger as the size of the cargo tank increases.
- Electrostatics and organic fields also present problems in aviation. Lightning and static electricity pose a hazard to high-speed aerospace vehicles.
- The potential threat of lightning to aircraft and, in particular, the possibility of a catastrophic fuel explosion have long been under investigation.
- The greatest danger of explosion is probably associated with ignition at the fuel vent, although the composite plastic materials for the primary structure are vulnerable.

- On the average, a given commercial air plane is struck by lightning once every 5000 to 10000 hr of flying time.
- Fuel ignition was the probable cause of the two lightning-related disasters to commercial aircraft- in 1959 near Milan, Italy, involving a Lockheed Constellation, and in 1963 at Elkton, Maryland, involving Boeing 707.
- In addition, a number of military aircraft have been destroyed by lightning.
- There is some danger of accidental fire and explosion in fueling because of improved quality aviation fuel and of the higher flow rates being used to speed refueling.
- The J.P -4 fuel, a blend of kerosene and gasoline, is more volatile than gasoline and may be more electrostatically active.

- Desulfurization of fuel has resulted in lower conductivities.
- Klass reported on a conference at which several explosions were attributed to electrostatic sparks in using such fuel.

4. Nuisances

- Electrostatics can play a role in industry which can cause loss of product and difficulty in the production process without the existence of danger to personnel or major facilities.
- Two well-known examples occur in the production and handling of photographic film and in the textile industry.
- The photographic industry was at one time at the mercy of static problems.
- Charge was produced on the back of the film as it passed over rollers or guides and sparks occurred as the surfaces separated.

- Familiar dendritic discharge patterns on the film were produced. References 27 and 28 discuss the problems in some detail.
- In the textile industry, the problems similarly involve the transport of materials in belt fashion and the production of charge by the separation of contacting surfaces.
- Fibrous dust is attracted to the material and handling is made difficult.
- Nowadays these textile problems are generally reduced by maintaining moist atmospheres.
- Problems caused by electrostatic discharges occur in the most modern of industries (e.g., the integrated circuit manufacturing industry).
- In particular this is a problem in the manufacture and handling of metal – oxide- silicon(MOS) devices.

- In these devices an electric field, applied through an oxide – insulated gate electrode, is used to control the conductants of a channel layer in the semiconductor material under the gate.
- The channel is a lightly doped region between two highly doped areas called the source and the drain.
- The extremely thin oxide separating the silicon and the metallization can easily be destroyed by electrostatic discharges.
- In monolithic structures as well as in some discrete devices, the external leads are protected by means of resistor networks and zener diodes.
- These protective devices may be habituated on the common substrate with the MOS circuit and interconnected in a way that protects the circuit

- However, the failure rates between shipment of the products from the vendors and final testing in end-use circuits is rumored to be as great as 2%.
- Failure occurs during shipment, inspection, testing, or assembly into circuits, and it appears that the protective diode devices on the chips are not fully successful.
- With the market for MOS devices projected to be of the order of $100 million in the year 1972-1973, such losses are considerable.
- The probable main cause of gate breakdown is handling by electrostatically charged operators.
- Another source of static voltages is the Styrofoam containers in which the semiconductor products are often shipped.