Safety Engineering

-Static Electricity and Charge Accumulation-
Conductive

- A material with a low electrical resistance, electrons flow easily across the surface or through the bulk of these materials and having a volume resistively equal or lower than $10^4 \Omega \cdot m$

Dissipative

- A material incapable or retaining a significant amount of electrostatic charge when in contact with earth and having a volume resistivity higher than $10^4 \Omega \cdot m$ but equal to or lower than $10^9 \Omega \cdot m$ measured at ambient temperature and 50% relative humidity.

Non-conductive

- A material prevent or limit the flow of electrons across its surface or through its volume. Non-conductive materials have a high electrical resistance and are difficult to ground and having a volume resistivity higher than $10^9 \Omega \cdot m$
Types of discharges

Spark Discharge

• Discharging of static electricity between two conductors.

• Generation of Spark Discharges.
  – Charge accumulation at a conductive object.
  – Field strength exceeds the electric strength of the ambient atmosphere.

• Ignitability--gases, vapors, dusts

• Energy transfer--up to 10,000 mJ
Types of discharges

Brush Discharge

- Generation of Brush Discharges
  - Conductive electrode moves towards a charged nonconductive object.
- Nonconductive lining or surface must have a breakdown voltage greater than 4 kV and a thickness greater than 2 mm.
- Nonconductive coating can be a layer of the powdered solid.
- Ignitability--gases, vapors
- Energy transfer--up to 4 mJ
Types of discharges

Propagating Brush Discharge

• Generation of Propagating Brush Discharge
  – Bipolar charging of the high resistivity material (non conducting) that is lining another conductor.
  – Field strength exceeds the electric strength of the high resistivity material. Non conducting lining must have breakdown voltage greater than 4 kV
• Ignitability--gases, vapors, dusts
• Energy transfer--up to 100,000 mJ
• Major contributor to static electricity ignitions.
Types of discharges

Cone Discharge

- Generation of Cone Discharge.
  - Vessels larger than 1 m$^3$.
  - Relatively fast filling rate, greater than 0.5 kg/s.
  - High resistivity (>10$^{10}$Ωm) bulk product, larger than 1 mm diameter.
  - Charge accumulation in the bulk product.
  - Field strength exceeds the electric strength of the ambient atmosphere.

- Ignitability--gases, vapors, dusts
- Energy transfer--up to 1000 mJ
## Ignitability of discharges

<table>
<thead>
<tr>
<th>Type of Discharge</th>
<th>Energy transfer</th>
<th>Ignitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark</td>
<td>&lt; 10 000 mJ</td>
<td>gases, vapor, dusts</td>
</tr>
<tr>
<td>Brush</td>
<td>&lt; 4 mJ</td>
<td>gases, vapor</td>
</tr>
<tr>
<td>Propagating Brush</td>
<td>&lt; 100 000 mJ</td>
<td>gas, vapor, dusts</td>
</tr>
<tr>
<td>Cone</td>
<td>&lt; 1 000 mJ</td>
<td>gas, vapor, dusts</td>
</tr>
<tr>
<td>Corona</td>
<td>&lt; 0.1 mJ</td>
<td>some gases with low MIE</td>
</tr>
</tbody>
</table>
Whenever two dissimilar materials come in contact, electrons move from one surface to the other. As these materials are separated and more electrons remain on one surface than the other, one material takes on a positive charge and the other a negative charge.

**Mechanisms for Charge Accumulation:**
- Contact and Frictional
- Double layer
- Induction
- Transport
Charge Accumulation

Contact and Frictional Charging

• Dust transport
  – e.g. pneumatic transport of powders/solids
• Pouring powders
  – e.g. pouring solids down chutes or troughs
• Gears and belts
  – e.g. transporting charges from one surface to another

Double layer charging

Caused by friction and movement at interfaces on a microscopic scale.
  – Liquid-liquid
  – Solid-liquid
  – Solid-solid
  – Gas-liquid
  – Gas-solid
Charge Accumulation

Induction charging

When an isolated conductor is subject to an electric field a charge polarity develops on the object. If the object is grounded then the charges closest to the grounding source flows away leaving the body with a net charge of opposite sign.

Charging by Transport

• Results from a charged dust, liquid or solid particles settling onto a surface and transporting their charges to this new surface.
• The rate of charge accumulation is a function of the rate of transportation.
Many fluid handling operations can generate static electricity. This becomes a problem when non conducting pipes (glass or Teflon lined) are used without adequate bonding.

**Splash Filling**

- When non conducting fluids (or solids) free fall through air they pick up a significant static charge.
- When there is spraying or splashing static electricity can build up.
- This can be a source of sparks
Fluid flow into vessels

- When fluid flows into a vessel it carries a charge with it which can build up in the tank if the tank is not properly grounded.
- Routine inspection of grounding minimizes the change for fire or explosion due to a spark discharge from the charged tank.
When a liquid or solid is flowing, there is a transfer of electrons from one surface to another as they flow past each other.

\[ I_s = \frac{f \rho v^2 \varepsilon_r \varepsilon_0 \zeta}{2 \eta} \]

- \( f \) - Fanning friction factor, -
- \( \rho \) - fluid density, kg m\(^{-3}\)
- \( \varepsilon_r \) - dielectric constant, -
- \( \varepsilon_0 \) - permitivity constant, \( 8.85 \times 10^{-12} \) (C\(^2\) N\(^{-1}\) m\(^{-2}\))
- \( \zeta \) - zeta potential \( 0.01 - 0.1 \) V
- \( \eta \) - dynamics viscosity, Pas
The time required for a charge to dissipate by leakage.

\[ \tau = \frac{\varepsilon_r \varepsilon_0}{\gamma_c} \]

**Example:**
toluene
- poor conductivity
- relaxation time: 21 s

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific conductivity[mho/cm]</th>
<th>Dielectric constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>$7.6 \times 10^{-8}$ to $1 \times 10^{-18}$</td>
<td>2.3</td>
</tr>
<tr>
<td>Toluene</td>
<td>$&lt;1 \times 10^{-14}$</td>
<td>2.4</td>
</tr>
<tr>
<td>Xylene</td>
<td>$&lt;1 \times 10^{-15}$</td>
<td>2.4</td>
</tr>
<tr>
<td>Heptane</td>
<td>$&lt;1 \times 10^{-18}$</td>
<td>2.0</td>
</tr>
<tr>
<td>Hexane</td>
<td>$&lt;1 \times 10^{-18}$</td>
<td>1.9</td>
</tr>
<tr>
<td>Methanol</td>
<td>$4.4 \times 10^{-7}$</td>
<td>33.7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$1.5 \times 10^{-7}$</td>
<td>25.7</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>$3.5 \times 10^{-6}$</td>
<td>25.0</td>
</tr>
<tr>
<td>Water</td>
<td>$5.5 \times 10^{-6}$</td>
<td>80.4</td>
</tr>
<tr>
<td>Other materials and air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>$1.0 \times 10^{-9}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Cellulose</td>
<td>$1.0 \times 10^{-14}$</td>
<td>3.9–7.5</td>
</tr>
<tr>
<td>Pyrex</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td>Paraffin</td>
<td>$10^{-16}$ to $0.2 \times 10^{-18}$</td>
<td>1.9–2.3</td>
</tr>
<tr>
<td>Rubber</td>
<td>$0.33 \times 10^{-13}$</td>
<td>3.0</td>
</tr>
<tr>
<td>Slate</td>
<td>$1.0 \times 10^{-8}$</td>
<td>6.0–7.5</td>
</tr>
<tr>
<td>Teflon</td>
<td>$0.5 \times 10^{-13}$</td>
<td>2.0</td>
</tr>
<tr>
<td>Wood</td>
<td>$10^{-10}$ to $10^{-13}$</td>
<td>3.0</td>
</tr>
</tbody>
</table>

\(\varepsilon_r\) - dielectric constant, 
\(\varepsilon_0\) - permitivity constant, \(8.85 \times 10^{-12} \text{ (C}^2 \text{ N}^{-1} \text{ m}^{-2})\)
\(\gamma_c\) - specific conductivity, \(\text{S m}^{-1}\)

1 mho/centimeter [mho/cm] = 100 siemens/meter [S/m]

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2. Resistance = 1/conductivity = 1/(mho/cm) = ohm cm.
Charging by Transport

Electrostatic Voltage Drops

For flow through a non conducting pipe (glass, Teflon lined) a voltage drop can develop from flowing liquid.

\[ V = I_s R \]

\[ R = \frac{L}{\gamma_c A} \]

- \( R \) - resistance, ohms
- \( L \) - length of the conductor, m
- \( \gamma_c \) - specific conductivity, S m\(^{-1}\)
- \( A \) - area of the conductor, m\(^2\)

Charges can accumulate as a result of streaming current

\[ \frac{dQ}{d\tau} = I_s \]

Assuming constant streaming current

\[ Q = I_s \tau \]
**Solid geometries** are almost always ill defined, so need to be based on empirical calculations. Solid processing operations have different empirically determined charge capacities.

\[ Q = \text{Charge Capacity} \times \text{Charge Rate} \times \text{time} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Charge Capacity (coulombs/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieving</td>
<td>$10^{-9}$ to $10^{-11}$</td>
</tr>
<tr>
<td>Pouring</td>
<td>$10^{-7}$ to $10^{-9}$</td>
</tr>
<tr>
<td>Grinding</td>
<td>$10^{-6}$ to $10^{-7}$</td>
</tr>
<tr>
<td>Sliding down incline</td>
<td>$10^{-5}$ to $10^{-7}$</td>
</tr>
<tr>
<td>Pneumatic transport</td>
<td>$10^{-5}$ to $10^{-7}$</td>
</tr>
</tbody>
</table>
**Capacitance**

Capacitance is the ability of a body to store an electrical charge.

**Capacitance for a sphere**

\[ C = \frac{Q}{V} \]

\[ C = 4\pi\varepsilon_r\varepsilon_0 r \]

- **R** - capacitance, farads or coulomb/volt
- **\(\varepsilon_r\)** - dielectric constant, -
- **\(\varepsilon_0\)** - permittivity constant, \(8.85 \times 10^{-12} \text{ (C}^2\text{ N}^{-1}\text{ m}^{-2})\)
- **\(r\)** - radius of the sphere, m
- **\(\ell\)** - thickness of the plate, m
- **\(A\)** - area of the plate, m\(^2\)
- **\(Q\)** - charge, coulomb
- **\(V\)** - voltage, volt

**Static Energy Stored**

\[ E = \frac{Q^2}{2C} \quad \text{units} \Rightarrow \frac{(\text{coulomb})^2}{\text{coulomb/volt}} = \text{coulomb} \cdot \text{volt} = \text{Joule} \]

\[ E = \frac{CV^2}{2} \quad \text{units} \Rightarrow \frac{\text{coulomb}}{\text{volt}}(\text{volt})^2 = \text{coulomb} \cdot \text{volt} = \text{Joule} \]

\[ E = \frac{QV}{2} \quad \text{units} \Rightarrow \text{coulomb} \cdot \text{volt} = \text{Joule} \]
Determine the capacitance, \( C \), of the object or container contents, expressed in *farads* or *coulombs* per *volt*.

Determine the accumulated charge, \( Q \), expressed in *coulombs*.

Compute accumulated energy, \( E \), expressed in *J* or *mJ*.

Compare to the MIE of the dust or vapor.

**Example – Solids handling**

Determine the potential hazard of pneumatically transporting a dry powder (dry powder with a particle size greater than 1 mm) at a rate of 30,000 kg/hr into a metal vessel which has a volume of 70 m\(^3\).

Given: The powder has a bulk density of 600 kg/m\(^3\); the vessel has a spherical geometry; 70 m\(^3\) of powder is charged into the vessel. The powder is flammable with a MIE of 20 mJ.
• Determine radius of sphere:

\[ r = \left( \frac{3V}{4\pi} \right)^{\frac{1}{3}} = \left( \frac{3 \cdot 70m^3}{4\pi} \right)^{\frac{1}{3}} = 2.5m \]

• Calculate capacitance:

\[ C = 4\pi\varepsilon_r\varepsilon_0 r \]

\( \varepsilon_r = 1 \) for air (Tab. slide15) Spark jumps across air gap

\[ C = 4\pi(1)\left( 8.85 \times 10^{-12} \text{ coul/volt} \cdot \text{m} \right)(2.5m) = 2.83 \times 10^{-10} \text{ coul/volt} \]
Example – solids handling – solution (cont.)

• Determine mass fed: 
  \[ \text{Feed} = 70m^3 \times 600 \frac{kg}{m^3} = 42,000kg \]

• Calculate charge accumulated (Tab. slide 17, pneumatic transport):
  \[ Q = \left( 10^{-5} \frac{coul}{kg} \right) (42,000kg) = 0.42coul \]

• Calculate energy:
  \[ E = \frac{Q^2}{2C} = \frac{(0.42coul)^2}{2 \left( 2.83 \times 10^{-10} \frac{coul}{volt} \right)} = 3.1 \times 10^8 J \]

• This is much greater than the MIE of the powder. If there is sufficient air this would be very hazardous.

• This is the total charge that could go into vessel while filling. Multiple discharges would occur, certainly there would be conical pile discharges (unless grounded).
Elimination of Charge Accumulation

Bonding and Grounding

• Charge buildup is always possible when you have moving fluids or solids. The potential for discharge is always present.
• We can eliminate sparks if we ensure that all parts of the system are connected with a conductor.
• Historically there was little problem when piping was all copper, stainless steel or iron. The problem comes when pipes or vessels are glass or Teflon lined or made from polymers or connected with non-conducting gaskets.
• There has always been a problem when you are pouring either liquid or a solid through an open space i.e., a filling operation.
Bonding and Grounding

• **Bonding**
  - Is the connection of a conducting wire between two or more objects.
  - The voltage difference between the two objects is reduced to zero, however they may have a voltage difference relative to ground or another non connected object.

• **Grounding**
  - Is the connection of a conducting wire between a charged object and the ground.
  - Any charge accumulated in the system is drained off to ground.
Elimination of Charge Accumulation

Bonding

- Solder Wire to Metal Pipe
- Conductive Hose
- Clamp or Strap on Metal Pipe
- #4 Wire
- Glass or Plastic Valve
- Solder Wire to Metal
- Tape
- One Brass Bolt, Nut and Washer per Flange
- Wire
- Glass Pipe
- Metal Pipe
- Non-Conducting Gasket
- Solder Wire to Brass Bolt
Elimination of Charge Accumulation

Grounding

- Grounded Water Line
- Nitrogen Vacuum
- Clamp or Strap
- Type "A" Clamp
- Nitrogen Fill Line
- Conductive Hose
- Wire Bonded to Metal Pipe
- Tank Car or Truck
- Ground
Elimination of Charge Accumulation

Grounding

Hose May Be Either Conducting or Non-Conducting

Nozzle in Contact with Container—No Other Bonding Necessary.

Insulating Support $10^6$ ohm or More

Conducting Support Less than $10^6$ ohms
Grounding

Bond Wire Necessary Except Where Containers Are Inherently Bonded Together—or Arrangement Is Such That Fill Stem Is Always in Metallic Contact with Receiving Container during Transfer.
Elimination of Charge Accumulation

Grounding

- Locations for Bonding Wire Fastened to Pipe
- Alternative Location for Bond
- Product Flow
- No Sparking Potential between Downspout and Truck
- Tank Truck with No Charge on Outside Surface
**Elimination of Charge Accumulation**

**Grounding Glass-lined Vessels**

- Glass and plastic lined vessels are grounded using tantalum inserts or a metal probe.
- This is less effective if fluid has low conductivity.
To eliminate the static charge that builds up from a fluid free falling through air, a dip leg is used. Note hole to prevent back siphoning.

An angle iron can also be used so fluid runs down the angle iron instead of free falling.
Case Studies from a production plant

Following are a series of case studies of accidents that actually happen at BASF and Dow and shared with the SACHE Chemical Process Safety Workshop participants.
Solids Filling Operation

• Situation
  – A non-conductive bulk product is fed out of 25 kg PE-bags in a vessel, in which a flammable liquid is being stirred. During shaking of the just empty bag an ignition occurred.

• Cause
  – All handling of non-conductive solids or bulk products may generate static electricity. Due to contact charging of the sliding bulk product, both the bulk product and non conducting package materials became charged. Brush discharges form the surface of the bad ignited the vapor/air mixture.

• Precaution
  – Either fill into a closed, inerted vessel or avoid charge generation.
Operator

- **Situation**
  - An operator filled a non-conductive bulk product out of 25 kg PE-bags in a solvent free mixer. Exhaust system operated. All equipment grounded, the floor was dissipative, the operator wore dissipative footwear. During pouring the product in the reaction vessel explode.

- **Cause**
  - The plastic wrap that held the sacks on the pallet was on the floor and the operator was standing on it. This allowed a static charge to build up in him.

- **Precaution**
  - Always guarantee ground connection.
Valve

- Situation
  - A ball-valve is installed in a waste gas collecting system. During usual production an explosion occurred; the pipe system was destroyed.

- Cause
  - A valve consists of conductive and non-conductive parts. Conveying of dust suspensions or droplets may generate charge accumulation on the ball and/or shaft if not bonded to the grounded housing. Spark discharge from charged ball to housing caused explosion.

- Precaution
  - Guarantee ground connection of conductive equipment.
Lined metal drum filling

• Situation
  – A pure liquid was filled in a steel drum with an inner plastic liner. To avoid splash filling a short funnel was inserted in the spout. The nozzle, the drum and the weighing machine were all grounded. Despite having an exhaust system there was an explosion during drum filling.

• Cause
  – Electrostatic charge generation at the surface of the non-conductive coating cannot be transferred. The funnel had sufficient capacitance was insulated from the ground by the PE lined filler cap. Spark discharge from funnel caused explosion.

• Precautions
  – Guarantee ground connection of all conductive equipment.
Example – Fluid Handling

• Determine the voltage developed between a charging nozzle and a grounded tank and the charge accumulated during the filling process at 150 gpm.
Example – Fluid Handling (cont.)

• Additional information:
  – Non conducting hose length 20 ft
  – Hose diameter 2 in.
  – Liquid conductivity $10^{-8}$ mho/cm
  – Liquid diffusivity $2.2 \times 10^{-5}$ cm$^2$sec$^{-1}$
  – Dielectric constant 25.7
  – Density 0.88 g/cm$^3$
  – Viscosity 0.60 centipoise
  – MIE 0.10 mJ
Example – fluid handling - solution

• **Procedure**

• Calculate voltage drop using $V=I_sR$ (Eq. 7-17)

• Calculate $R$ using Eq. 7-18

• Calculate $I_s$ using Eq. 7-12 or 7-14

• Calculate $Q$ using $Q=I_st$

• Calculate $E=(QV/2)$

• Compare to MIE
Example – fluid handling – solution (cont.)

Calculate the Resistance

\[
L = (20 \text{ ft}) \left( \frac{12 \text{ in.}}{\text{ft}} \right) \left( \frac{2.54 \text{ cm}}{\text{in.}} \right) = 610 \text{ cm}
\]

\[
A = \pi r^2 = \pi (1 \text{ in.})^2 \left( \frac{3.54 \text{ cm}}{\text{in.}} \right)^2 = 20.3 \text{ cm}^2
\]

\[
R = \frac{L}{\gamma_c A} = \frac{610 \text{ cm}}{\left( 10^{-8} \frac{\text{cm}}{\text{cm} \Omega} \right) \left( 20.3 \text{ cm}^2 \right)} = 3.00 \times 10^9 \Omega
\]
Example – fluid handling – solution (cont.)

• Determine type of flow (laminar or turbulent)

\[
\bar{u} = \left( \frac{150 \text{ gallon/\min}}{\pi (1 \text{ in.})^2} \right) \left( \frac{\text{ft}^3}{7.48 \text{ gal}} \right) \left( \frac{144 \text{ in}^2}{\text{ft}^2} \right) \left( \frac{1 \text{ min}}{60 \text{ s}} \right) = 15.3 \frac{\text{ft}}{\text{s}}
\]

\[
\text{Re} = \frac{d\bar{u} \rho}{\mu} = \frac{(2 \text{ in}) \left( 15.3 \frac{\text{ft}}{\text{s}} \right) \left( 0.88 \frac{\text{g}}{\text{cm}^3} \right) \left( \frac{7750 \text{ cp}}{\text{in} \left( \frac{\text{ft}}{\text{s}} \right) \left( \frac{\text{g}}{\text{cm}^3} \right)} \right)}{(0.60 \text{ cp})} = 348,000
\]

Hence Turbulent
Example – fluid handling – solution (cont.)

• Calculate the streaming current:

\[
\tau = \frac{\varepsilon_r \varepsilon_0}{\gamma_c} = \frac{(25.7) \left(8.85 \times 10^{-14} \text{ s/cm} \cdot \Omega\right)}{10^{-8} \text{ mho/cm}} = 22.7 \times 10^{-5} \text{ s} \quad \text{(Eq. 7-16)}
\]

\[
\delta = \sqrt{D_m \tau} = \sqrt{\left(2.2 \times 10^{-5} \text{ cm}^2/\text{s}\right) \left(22.7 \times 10^{-5} \text{ s}\right)} = 7.07 \times 10^{-5} \text{ cm} = 2.78 \times 10^{-5} \text{ in} \quad \text{(Eq. 7-15)}
\]

\[
I_s = \left[\frac{5.89 \times 10^{-14} \text{ amp}}{\left(\frac{\text{ft}}{\text{s}}\right) \text{ volt}}\right] \cdot \frac{d \cdot \bar{u} \cdot \varepsilon_r \cdot \zeta}{\delta} \quad \text{(Eq.7-14)}
\]

\[
I_s = \left[\frac{5.89 \times 10^{-14} \text{ amp}}{\left(\frac{\text{ft}}{\text{s}}\right) \text{ volt}}\right] \cdot \frac{(2 \text{ in})(153 \text{ ft/s})(25.7)(0.1 \text{ volt})}{\left(2.78 \times 10^{-5} \text{ in}\right)} = 1.66 \times 10^{-7} \text{ amp}
\]
Example – fluid handling – solution (cont.)

• Calculate the voltage drop, accumulated charge and energy:

\[ V = I_s R = (1.66 \times 10^{-7} \text{ amp})(3.00 \times 10^9 \Omega) = 498 \text{ volts} \quad \text{(Eq. 7-17)} \]

Determine fill time

\[ t = \frac{(300 \text{ gal})(60 \frac{s}{\text{min}})}{150 \frac{\text{gal}}{\text{min}}} = 120s \]

Determine accumulated charge

\[ Q = I_s t = (1.66 \times 10^{-5} \text{ amp})(120s) = 1.99 \times 10^{-5} \text{ coulomb} \]

Determine Energy

\[ E = \frac{QV}{2} = \frac{(1.99 \times 10^{-5} \text{ coulomb})(498 \text{ volt})}{2} = 4.9mJ \]

This is greater than the MIE, so there is a fire or explosion hazard.
Static electricity & charge accumulation

• Definitions
• Types of discharges
• Mechanisms of charge accumulation
  – fluid systems - Streaming current
  – Solids handling
• **Balance of charges**
• Bonding and grounding
• Case studies
Balance of Charges

- When you have a vessel that has multiple inputs and outputs, you can determine the charge accumulation by a charge balance.

- Consider streaming currents in, charges carried away by flows going out, and charge loss due to relaxation.
Charge Balance

\[ \frac{dQ}{dt} = \sum_{i=1}^{n} (I_s)_{i, \text{in}} - \sum_{j=1}^{m} (I_s)_{j, \text{out}} - \frac{Q}{\tau} \]

where

\[ \sum_{i=1}^{n} (I_s)_{i, \text{in}} \] is the current coming into the vessel

\[ \sum_{j=1}^{m} (I_s)_{j, \text{out}} \] is the current flowing out of the vessel

\[ \frac{Q}{\tau} \] is the charge loss due to relaxation

\[ \tau \] is the relaxation time
**Charge Balance**

The charge flowing out of the vessel depends on the charge already in the tank

\[ (I_s)_{j,\text{out}} = \frac{F_j}{V_C} Q \]

where

- \( F_j \) is the rate of discharge through outlet \( j \)
- \( V_C \) is the container or tank volume
- \( Q \) is the total charge in the tank
**Charge Balance**

Hence the charge balance becomes

\[
\frac{dQ}{dt} = \sum_{i=1}^{n} (I_s)_{i,\text{in}} - \sum_{j=1}^{m} \frac{F_j}{V_C} Q - \frac{Q}{\tau}
\]

If flows, \(F_j\), streaming currents, \((I_s)_{i,\text{in}}\), and relaxation times, \(\tau\), are constant, then this is a linear differential equation that has the solution:

\[
Q = A + Be^{-ct}
\]

where

\[
A = \frac{\sum_{i=1}^{n} (I_s)_{i,\text{in}}}{\left(\frac{1}{\tau} + \sum_{j=1}^{m} \frac{F_j}{V_C}\right)} \quad B = Q_0 - \frac{\sum_{i=1}^{n} (I_s)_{i,\text{in}}}{\left(\frac{1}{\tau} + \sum_{j=1}^{m} \frac{F_j}{V_C}\right)} \quad C = \left(\frac{1}{\tau} + \sum_{j=1}^{m} \frac{F_j}{V_C}\right)
\]
Charge Balance

• This relationship is used to determine the charge developing in the tank as a function of time relative to an initial charge of $Q_0$.
• The capacitance of the vessel is calculated as before (typically assume equivalent spherical vessel).
• The static energy stored in the vessel is then calculated from $E=Q^2/2C$.
• Examples 7-9 and 7-10 demonstrate using this relationship.
Static electricity & charge accumulation

• Definitions
• Types of discharges
• Mechanisms of charge accumulation
  – fluid systems - Streaming current
  – Solids handling
• Balance of charges
• Bonding and grounding
• Case studies