# Gas Laws Save Lives:
# The Chemistry Behind Airbags

## Stoichiometry and the Gas Constant Experiment

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### Key Concepts:

- Safety of Airbags
- Chemical Reactions to Generate the Gas to Fill an Airbag
  - Decomposition of Sodium Azide ($NaN_3$)
  - Reactions to Remove Harmful Products
- Ideal-Gas Law
  - $PV = nRT$
  - Estimating the Pressure to Fill an Airbag
    - Acceleration
    - Force
    - Pressure
- Protection in a Collision
  - Newton's Laws
  - Airbags Decrease the Force Acting on the Body
  - Airbags Spread the Force Over a Larger Area
- Undetonated-Airbag Disposal: Safety Considerations

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# Introduction: Airbags Improve Automobile Safety

### The Safety Advantage of Airbags

The development of airbags began with the idea for a system that would restrain automobile drivers and passengers in an accident, even if they were not wearing seat belts. Today, airbags are mandatory in new cars and are designed to act as a supplemental safety device in addition to a seat belt. Airbags have been commonly available since the late 1980's; however, they were first invented and-patented in 1953. In the late 1950's, the automobile industry started to research airbags and soon discovered that there were many difficulties in the development of a successful airbag. Crash tests showed that for an airbag to be useful as a protective device, the bag must deploy and inflate within 40 milliseconds. The system must also be able to detect the difference between a severe crash and a minor fender-bender. These technological difficulties account for the 30-year span between the first patent and the common availability of airbags.

Airbags have indeed saved lives and have lowered the number of severe injuries. The National Highway Traffic Safety Administration estimates that the combination of an airbag plus a lap/shoulder belt reduces the risk of serious head injury by 85 percent compared with a 60 percentage reduction for belts alone.  These statistics are continuing to improve as airbags become more widely used.  In recent years, increased reports in the media concerning deaths or serious injuries due to airbag deployment have led to a national discussion about the "safety" of airbags. Hence, there is still a need for development of better airbags that do not cause injuries. Also, better public understanding of how airbags work will help people to make informed and potentially life-saving decisions about using airbags.

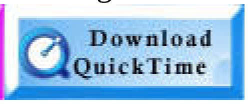
## Overview of How Airbags Work

Timing is crucial in the airbag's ability to save lives in a head-on collision. An airbag must be able to deploy in a matter of milliseconds from the initial collision impact. It must also be prevented from deploying when there is no collision. Hence, the first component of the airbag system is a sensor that can detect head-on collisions and immediately trigger the airbag's deployment. One of the simplest designs employed for the crash sensor is a steel ball that slides inside a smooth bore. The ball is held in place by a permanent magnet or by a stiff spring, which inhibits the ball's motion when the car drives over bumps or potholes. However, when the car decelerates very quickly, as in a head-on crash, the ball suddenly moves forward and turns on an electrical circuit, initiating the process of inflating the airbag.

Once the sensor has turned on the electrical circuit, a pellet of sodium azide ($NaN_3$) is ignited. A rapid reaction occurs, generating nitrogen gas ($N_2$). This gas fills a nylon or polyamide bag such that the front face of the bag travels at a velocity of 150 to 250 miles per hour. This process, from the initial impact of the crash to full inflation of the airbag, takes only about 40 milliseconds (Movie 1). Ideally, the body of the driver or passenger should not hit the airbag while it is still inflating. In order for the airbag to cushion the head and torso with air for maximum protection, the airbag must begin to deflate (*i.e.*, decrease its internal pressure) by the time the body hits it. Otherwise, the high internal pressure of the airbag would create a surface as hard as stone-- not the protective cushion you would want to crash into!

**Movie 1**

Click the blue button to download QuickTime and click on the pink button to view a QuickTime movie showing the inflation of dual airbags when a head-on collision occurs.



# What about the Gas Used to Fill the Airbag?

## Chemical Reactions Used to Generate the Gas

Inside the airbag is a gas generator containing a mixture of $NaN_3$, $KNO_3$, and $SiO_2$. When the car undergoes a head-on collision, a series of three chemical reactions occur inside the gas generator. These reactions produce gas ($N_2$) to fill the airbag and convert $NaN_3$, a highly toxic substance, to harmless sodium and potassium silicate, a major ingredient of glass (Table 1). Sodium azide ($NaN_3$) can decompose at 300ºC to produce sodium metal (Na) and nitrogen gas ($N_2$). The signal from the deceleration sensor ignites the gas-generator mixture by an electrical impulse, creating the high-temperature condition necessary for $NaN_3$ to decompose. The nitrogen gas that is generated then fills the airbag. The purpose of the $KNO_3$ and $SiO_2$ is to remove the sodium metal (which is highly reactive and potentially explosive) by converting it to a harmless material. First, the sodium reacts with potassium nitrate ($KNO_3$) to produce potassium oxide ($K_2O$), sodium oxide ($Na_2O$), and additional $N_2$ gas. The $N_2$ generated in this second reaction also fills the airbag, and the metal oxides react with silicon dioxide ($SiO_2$) in a final reaction to produce silicate, which is harmless and stable. (First-period metal oxides, such as $Na_2O$ and $K_2O$, are highly reactive, so it would be unsafe to allow them to be the end product of the airbag detonation.)

**Table 1**

| Gas-Generator Reaction | Reactants | Products |
|---|---|---|
| **Initial Reaction Triggered by Sensor.** | $NaN_3$ | Na, $N_2$ (g) |
| **Second Reaction.** | Na, $KNO_3$ | $K_2O$, $Na_2O$, $N_2$ (g) |
| **Final Reaction.** | $K_2O$, $Na_2O$, $SiO_2$ | alkaline silicate (glass) |

## The Macroscopic Picture of Gas Behavior: Ideal-Gas Laws

### Calculation of the Amount of Gas Needed

Nitrogen is an inert gas whose behavior can be approximated as an ideal gas at the temperature and pressure of the inflating airbag. Thus, the ideal-gas law, $PV = nRT$, provides a good approximation of the relationship between the pressure (P) and volume of the airbag (V) and the number of moles (n) of $N_2$ it contains. A certain pressure is required to fill the airbag within milliseconds. Once this pressure has been determined, the ideal-gas law can be used to calculate the amount of $N_2$ that must be generated to fill the airbag to this pressure. The amount of $NaN_3$ in the gas generator is then carefully chosen to generate this exact amount of $N_2$ gas.

### Estimating the Pressure Required to Fill the Airbag

An estimate for the pressure required to fill the airbag in milliseconds can be obtained by a simple mechanical analysis shown in the calculation below. We assume that the airbag is supported in the back (i.e., all the expansion is forward) and that the mass of the airbag is all contained in the front face. When the airbag inflates during a collision, the front face of the airbag begins at rest ($v_i$ = 0.00 m/s) and travels a distance (d) equals to the thickness of the fully inflated airbag. If the front face travels at 89.4 m/s by the end of the inflation ($v_f$), and the thickness of a fully-inflated airbag is 30.0 cm, what is the acceleration of the front face?

- The airbag's **acceleration** (a) can be computed from one of the Equations of Linear Motion encountered in a basic physics text:

  $$v_f^2 - v_i^2 = 2ad. \qquad \textbf{(1)}$$

  Substituting in the values above, we have

  $$(89.4\ \text{m/s})^2 - (0.00\ \text{m/s})^2 = (2)(a)(0.300\ \text{m})$$
  $$a = 1.33\text{x}10^4\ \text{m/s}^2. \qquad \textbf{(2)}$$

- What is the **force** exerted on the front face of the airbag that can cause this acceleration? The force can be calculated using Newton's Second Law of Motion, F = ma. Let us assume the mass of the airbag is 2.50 kg. 2.5 kg is a fairly heavy bag, but if you consider how much force the bag has to withstand (see Figure 5), it becomes apparent that a lightweight-fabric bag would not be strong enough.

  $$F = ma \qquad \textbf{(3)}$$
  $$F = (2.50\ \text{kg})(1.33\text{x}10^4\ \text{m/s}^2)$$
  $$F = 3.33\text{x}10^4\ \text{kgm/s}^2 = 3.33\text{x}10^4\ \text{N}. \qquad \textbf{(4)}$$

- **Pressure** is defined as the force exerted by a gas per unit area (A) on the walls of the container, so the pressure (in Pascals) in the airbag immediately after inflation can be determined using the force calculated above and the area of the front face of the airbag (the part of the airbag that is pushed forward by this force).

  $$P = F/A \qquad \textbf{(5)}$$

- The **amount of gas** needed to fill the airbag at this pressure is then computed by the ideal-gas law. ***Note that the pressure used in the ideal gas equation is absolute pressure***. The pressure calculated in Eq. 5 is not the absolute pressure inside the airbag; it is the net pressure (**gauge pressure**) required to push the front face forward. When the gas inside the airbag pushes the front face forward, it has to act against the atmospheric pressure. Therefore, the absolute pressure inside the bag is greater than the gauge pressure.

  ***Absolute pressure = Gauge pressure + atmospheric pressure***

**Deflation of the Airbag**

When $N_2$ generation stops, gas molecules escape the bag through vents. The pressure inside the bag decreases, and the bag deflates slightly to create a soft cushion. By two seconds after the initial impact, the pressure inside the bag has reached atmospheric pressure (i.e., gauge pressure decreases to zero).

# How Does the Presence of an Airbag Actually Protect You?

Newton's familiar first law of motion says that objects moving at a constant velocity continue at the same velocity unless an external force acts upon them. This law, known as the law of inertia, is demonstrated in a car collision. When a car stops suddenly, as in a head-on collision, a body inside the car continues moving forward at the same velocity as the car was moving prior to the collision, because its inertial tendency is to continue moving at constant velocity. However, the body does not continue moving at the same velocity for long, but rather, it comes to a stop when it hits some object in the car, such as the steering wheel or dashboard. Thus, there is a force exerted on the body (by the steering wheel or the dash board) to change its velocity. Injuries from car accidents result when this force is very large. Airbags protect you by applying a restraining force to the body that is smaller than the force the body would experience if it hit the dashboard or steering wheel suddenly, and by spreading this force over a larger area. For simplicity, in the discussion below, we will consider only the case of a driver hitting the steering wheel. The same arguments could be applied to a passenger hitting the dashboard, as well.

Recall F = ma, where

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} \qquad \textbf{(6)}$$

F is the force exerted on the body causing the body to accelerate (or decelerate). If F>0, the body is accelerating; if F<0, the body is decelerating. During a collision, when the driver traveling at the speed of a moving car ($v_i$ ) hits the steering wheel and coming to a stop, the steering wheel is applying a force to the body causing it to change its velocity from $v_i$ to $v_f$, in which $v_f = 0$, since the body is stopped by the steering wheel; ?t is the time interval over which the force is applied to the body, and m is the mass of the body. In this case,

$$a = \frac{-v_i}{\Delta t}$$

Thus, the body is decelerating and the force exerted by the steering wheel (an immovable object) on the body to bring it to rest is

$$F = m\left(\frac{-v_i}{\Delta t}\right). \qquad \textbf{(7)}$$

This force from the steering wheel causes the injuries to the body in an accident.

?t in Equation 7 is the time duration of the deceleration. When the body hits the steering wheel and comes to a stop suddenly, ?t is the time interval from the moment the body touches the steering wheel to when it finally comes to a stop, which is a very short time interval. Hence the force is large and injuries are severe. However, if the car is equipped with an airbag, when a body hits an airbag, it pushes the gas through the vents and deflates the bag. Because the gas in the bag can only leave at a certain rate, the bag deflates slowly, and the time duration of the deceleration (?t) increases (*i.e.*, the airbag reduces the magnitude of deceleration). Therefore, the force on the body is smaller and fewer injuries result.

Additionally, airbags help reduce injuries by spreading the force over a larger area. If the body crashes directly into the steering wheel, all the force from the steering wheel will be applied to a localized area on the body (Figure 5a), and serious injuries can occur. However, when the body hits an airbag, all the force from the airbag on the body will be distributed over a larger area of the body (Figure 5b). Therefore, the force on any particular point on the body is smaller. Hence, less serious injuries will occur. In summary, an airbag lowers the number of injuries by (1) increasing the time over which the decelerating force is applied and thus lowers the force exerted (by the steering wheel or dash board) on the body, and (2) by spreading the force over a larger area of the body.

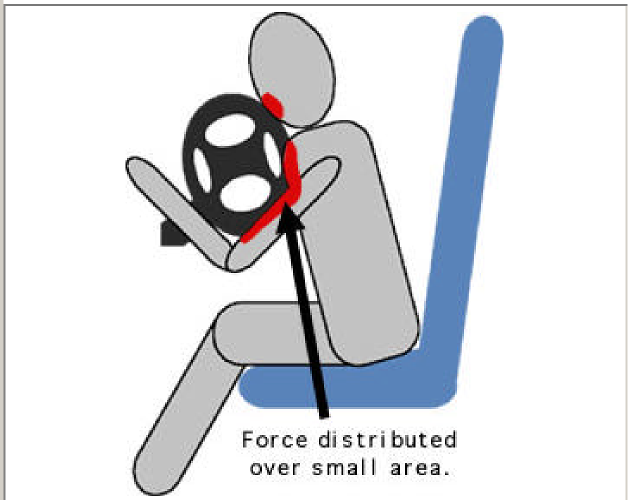



**Figure 5a**

When a body hits the steering wheel directly, the force of this impact is distributed over a small area of the body, resulting in injuries to this area. The area that hits the steering wheel is shown in red.

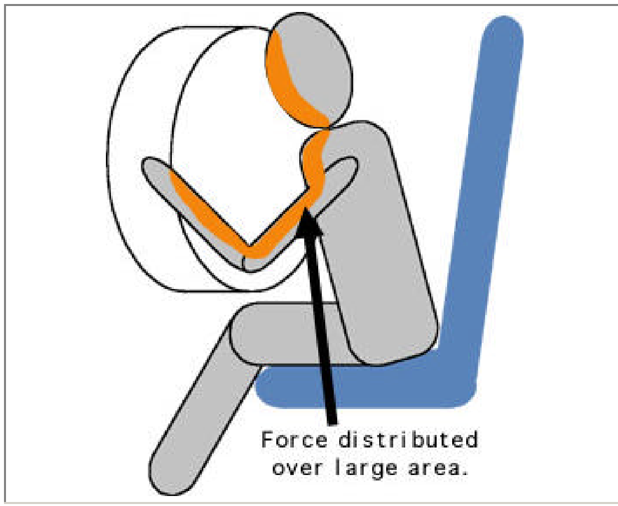



**Figure 5b**

When a body is restrained by an airbag, the force of the impact is distributed over a much larger area of the body, resulting in less severe injuries. The area that hits the airbag is shown in orange.

# Additional Considerations: Undetonated-Airbag Disposal

Thus far we have discussed how airbags function to protect us when there is a head-on collision. But fortunately, the vast majority of airbags in cars are never deployed within the lifetime of the automobile. What happens to these airbags? Typically, cars are flattened and recycled at the end of their lifetime, and the airbags are never removed from the cars. This can be hazardous because these airbags still contain the highly toxic sodium azide. The maximum concentration of $NaN_3$ allowed in the workplace is 0.2 $mg/m^3$ air. The presence of sodium azide in the airbag during the automobile-recycling process endangers workers and can damage recycling equipment and the environment.

How does the damage occur? Sodium azide can react in several ways when it undergoes the conditions of the recycling process itself. The first step of this process is to flatten the automobile hulk. Once the car is flattened, it is impossible to see whether or not it contains an airbag. If the container holding the $NaN_3$ is damaged during flattening, then $NaN_3$, which is potentially mutagenic and carcinogenic, can be released into the environment. The next step in recycling cars is to shred them into fist-sized pieces so that the different types of metal can be separated and recovered. Sodium azide released during this process may contaminate the steel, iron, and nonferrous metals recovered at this stage. Of greater concern, however, are the large amounts of heat and friction generated by the shredder. Recall that $NaN_3$ reacts explosively at high temperatures; hence, there is a risk of ignition when airbags pass through the automobile shredder. This danger is amplified if sodium azide comes in contact with heavy metals in the car, such as lead and copper, because these may react to form a volatile explosive. The pieces of the car may also pass through a wet shredder. Here, another danger arises because if the $NaN_3$ dissolves in water, it can form hydrazoic acid ($HN_3$):

$$NaN_3 + H_2O \rightarrow HN_3 + NaOH.$$

$HN_3$ is highly toxic, volatile (*i.e.*, it becomes airborne easily), and explosive.

What can be done to prevent these reactions of sodium azide in undetonated airbags? Somehow, the airbags must be prevented from going through the automobile-recycling process. Warning devices that would alert recyclers to the presence of an undetonated airbag in flattened car hulks have been tested, but these are generally expensive to implement, and they would need to be in every automobile airbag. Also, it is extremely difficult or impossible to remove an airbag from a car that has already been flattened, and so the question of what to do with these flattened cars containing airbags remains unanswered. This will become an increasingly large problem, as airbags have recently become mandatory equipment in new automobiles. Hence, the proportion of cars with airbags in recycling plants will increase. A better solution is to remove the airbag canister before the car is sent for flattening or recycling. This is cheaper, simpler, and more efficient, and it allows the car to be recycled safely. This strategy is already used for other hazardous components of cars, such as lead-battery cases. However, there is an added incentive for removing batteries that is not yet applicable for removing airbags from cars before recycling. The lead from batteries can be re-sold, but currently there is no market value for airbag canisters. Thus, strictly-enforced laws or a market-based incentive system may be required to ensure that airbags continue to protect our safety, even after the lifetime of the automobiles that contain them.

# Summary

Airbags have been shown to significantly reduce the number and severity of injuries, as well as the number of deaths, in head-on automobile collisions. Airbags protect us in collisions by providing a cushion to decrease the force on the body from hitting the steering wheel, and by distributing the force over a larger area. The cushion is generated by rapidly inflating the airbag with $N_2$ gas (from the explosive decomposition of $NaN_3$ triggered by a collision sensor), and then allowing the airbag to deflate.

Fundamental chemical and physical concepts underlie the design of airbags, as well as our understanding of how airbags work. The pressure in the airbag, and hence the amount of $NaN_3$

needed in order for the airbag to be filled quickly enough to protect us in a collision, can be determined using the ideal-gas laws. Newton's laws enable us to compute the force (and hence the pressure) required to move the front of the airbag forward during inflation, as well as how the airbag protects us by decreasing the force on the body.

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## Additional Links:

- This site from Technical Services Forensic Engineering shows a photograph of the collision sensor that triggers airbag deployment.

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## References:

Bell, W.L. "Chemistry of Air Bags," (1990) *J. Chem. Ed.* **67** (1), p. 61.

Crane, H.R. "The Air Bag: An Exercise in Newton's Laws," (1985) *The Physics Teacher*, **23**, p. 576-578.

Cutler, H. and E. Spector. "Air bags and automobile recycling," (1993) *Chemtech,* **23**, p. 54-55.

Madlung, A. "The Chemistry Behind the Air Bag: High Tech in First-Year Chemistry," (1996) *J. Chem. Ed.*, **73** (4), p. 347-348.

Newton's Apple: Teacher's Guides. "Airbags and Collisions." 22 June 1998. <http://www.ktca.org/newtons/9/airbags.html>.

Statistics on Air Bag Injury…<http://www.productliabilitylawyer.com/statistics.cfm>

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