



EARTH SYSTEMS SCIENCE

This lesson is taken from an education module developed for Challenger Center's *Journey through the Universe* program. *Journey through the Universe* takes entire communities to the space frontier.

Start the *Journey* at www.challenger.org/journey.

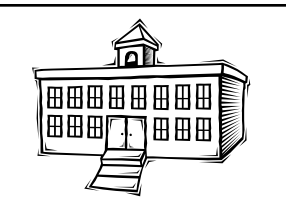
Funded by grants from NASA's Minority University Research and Education Division and Offices of Space Flight, Space Science, and Earth Science



Challenger Center, Challenger Center for Space Science Education, and the Challenger Center logotype are registered trademarks of Challenger Center for Space Science Education. No portion of this module may be reproduced without written permission, except for use within a *Journey* community. ©2002, Challenger Center for Space Science Education.

January 2002

Grade Level
9-12



Lesson 2: Rust Never Sleeps

Lesson Summary

In this activity, students will investigate the chemistry of rust — the formation of iron oxide (Fe_2O_3) — within a modern context, by experimenting with the conditions under which iron oxide forms. Students will apply what they have learned to deduce the atmospheric chemistry at the time that the sediments were deposited that eventually became common iron ore found in the United States and elsewhere. Students will interpret the necessary formation conditions of this iron-bearing rock in the context of Earth's geochemical history and the history of life on Earth.

Lesson Duration

Five 45 minute class periods



ESSENTIAL QUESTION

- ▶ What conditions are needed for rust to form?
- ▶ What does the presence of iron oxide in minerals show about the chemistry of the Earth's atmosphere?



OBJECTIVES

Students will be able to:

- ▶ Demonstrate chemical conditions under which rust forms, and conditions under which the formation of rust is inhibited.
- ▶ Interpret the composition and structure of banded iron ore to describe oxygen chemistry in the Earth system at the time the minerals were formed.



CORE STANDARDS

NRC Standards

CONTENT STANDARD B3:

- ▶ A large number of important reactions involve the transfer of either electrons (oxidation/reduction reactions) or hydrogen ions (acid/base reactions) between reacting ions, molecules, or atoms.

CONTENT STANDARD D2:

- ▶ The earth is a system containing essentially a fixed amount of each stable chemical atom or element. Each element can exist in several different chemical reservoirs. Each element on earth moves among reservoirs in the solid earth, oceans, atmosphere, and organisms as part of geochemical cycles.

Science Overview

Rust is a fact of life — life in general, not just modern technological life. Free oxygen in the Earth's atmosphere leads to the oxidation of materials in and on the Earth's surface, including iron. Plant life makes gaseous oxygen available, free to be breathed by animals and free to corrode metals. Some corrosion products, like iron (III) oxide (Fe_2O_3), may become buried by soil or sediments, preserving a record of free gaseous oxygen in the air. This has been the situation on Earth for a long time, a living world of plants and animals with an oxygen-rich atmosphere. However, there is clear geochemical evidence from the Earth itself that the atmosphere that the Earth was born with was very different from the atmosphere we have today. The early Earth's atmosphere was a brew of chemicals that are more or less poisonous to most modern Earth life. The rise of photosynthesizing bacteria — the cyanobacteria, also known as blue-green algae — set free large quantities of oxygen to transform the atmosphere. The record of those events is preserved in iron-bearing rock.

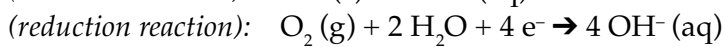
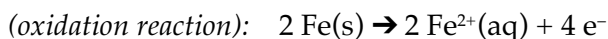
The following two sections describe the electrochemical process by which iron oxide forms, and discusses the different chemistry expected in oxygen-free (anoxic) conditions. The third section addresses the cyanobacteria that originated the Earth's oxygen-rich atmosphere. The fourth section addresses the structure and interpretations of banded iron formations (BIFs) with respect to the development of an oxygen-rich atmosphere for the Earth as the result of photosynthetic activity by cyanobacteria.

Rust Chemistry

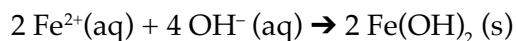
Metallic iron sitting in a lump on a table does not rust efficiently. The conversion of iron to iron oxide is an electrochemical process, requiring water into which the iron can dissolve. The lump of iron on the table rusts only because there is a film of water adhering to the surface from the Earth's relatively moist atmosphere. In regions with extremely low humidity, unprotected iron can last for a long time without significant corrosion.

The electrochemical nature of iron corrosion is apparent from the effect of salty water on iron objects: dissolved salts increase the conductivity of water, conducting electrons that reduce dissolved oxygen and water molecules into hydroxyl ions (OH^-), allowing doubly-charged iron ions to dissolve readily into the water. Anyone trying to buy or sell a used car in a state that salts its roads in the winter, or near an ocean shore, is aware of the effectiveness of salty water in promoting rust. Nevertheless, the salt itself does not react with iron and is not strictly necessary to form rust. Instead, the iron ions that dissolve into the water react with the hydroxyl ions to produce a solid precipitate, iron (II) hydroxide, which further reacts with dissolved oxygen and water to produce iron (III) hydroxide. Iron (III) hydroxide finally reacts with itself to form iron (III) oxide (familiar as rust) and water.

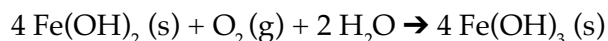
The first step in rust formation is the dissolution of solid iron into water (aqueous solution) in the form of a positively-charged iron (II) (ferrous, Fe^{2+}) ion and four electrons (oxidation reaction). At the same time, dissolved oxygen gas is reduced by the free electrons to react with water and to yield free hydroxyl ions in solution:



The dissolved iron (II) resulting from the oxidation reaction reacts in solution with the hydroxyl ions that result from the reduction reaction, to produce iron (II) hydroxide (ferrous hydroxide), which is insoluble in water and forms a solid precipitate:



The precipitated ferrous hydroxide reacts with dissolved oxygen and water to further oxidize the iron to obtain iron (III) hydroxide (ferric hydroxide), which also is insoluble in water:



CONTENT STANDARD D3:

- ▶ The Sun, the Earth, and the rest of the solar system formed from a nebular cloud of dust and gas 4.6 billion years ago. The early Earth was very different from the planet we live on today. Evidence for one-celled forms of life — the bacteria — extends back more than 3.5 billion years. The evolution of life caused dramatic changes in the composition of the Earth's atmosphere, which did not originally contain oxygen.

The ferric hydroxide, at last, reacts with itself to produce a hydrated molecule of iron (III) oxide (ferric oxide), two free water molecules that are recycled into the solution, and a water molecule of hydration attached to the ferric oxide:



The first step in iron oxidation occurs in solution, not in place, so that the resultant Fe_2O_3 molecule is not incorporated into the solid metallic iron's crystal structure. Iron rust forms deposits that do not adhere strongly to the metal and flake off, leaving unprotected raw metal at the surface of the metallic iron free to participate in further reactions (Petrucci, 1982). An important point, however, is that the Fe^{2+} (ferrous) ion stays in solution only so long as it does not encounter hydroxyl ions that result from the reduction of oxygen in water. In oxygenated water, the dissolved iron quickly precipitates out and does not travel far from the source of the iron.

The critical feature in the formation of iron (III) oxide is the presence of oxygen in aqueous solution. Both oxygen and water are required to overcome two key hurdles: the reduction of oxygen and water together to yield hydroxyl ions, and the oxidation of iron (II) hydroxide to yield iron (III) hydroxide. Archaeological evidence shows that iron objects can last for a very long time in water that is low in dissolved oxygen (anoxic), even in salty water. Iron objects frequently are found well-preserved in ancient shipwrecks and in bogs if they are buried deep in undisturbed mud so that fresh oxygen cannot be mixed in to replenish oxygenated material used up during the initial burial of the iron. For example, the iron turret of the Civil War iron-clad warship USS MONITOR was raised essentially intact from anoxic bottom mud off the coast of North Carolina 140 years after it sank at sea.

Iron Chemistry in Water without Rusting

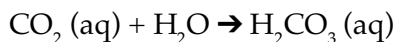
There are two ways to close off the reactions that produce rust from metallic iron once it has been dissolved in water: starve the reaction of oxygen, or starve the reaction of hydroxyl ions. We will not address special treatment of iron to prevent dissolution into water in the first place (by coating, by galvanization, by using a sacrificial anode, for example), which commands an inter-

esting area of chemistry in itself. Anoxic conditions can be safely arranged in the laboratory by exposing iron to water under an oxygen-free atmosphere (for example, CO₂ or SO₂ gas). Once the small amount of oxygen already dissolved into the water has been consumed by iron oxidation, there is no more O₂ available. The availability of hydroxyl ions can be decreased by immersing iron in an acidic solution, regardless of the atmospheric composition.

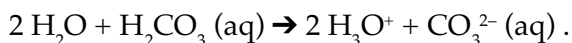
Carbon dioxide and sulfur dioxide are desirable as candidate gases to replace the normal oxygen-rich atmosphere in an experiment on iron oxidation because they are readily available as essentially pure gases, they can be handled safely with ordinary laboratory precautions, and they are common non-biogenic molecules in the gases emitted from volcanoes. Volcanic gases provide a good idea of the gases that formed the primordial atmosphere of the Earth, as these are the gases that would have been released during the accumulation of rock and debris that formed the Earth. A good comparison to the rusting of iron in oxygen-rich air is the chemistry of iron in the atmosphere of an Earth-like planet without photosynthetic plants to produce oxygen.

Carbon dioxide and sulfur dioxide do not merely dissolve in water, they react with it to produce carbonic acid and sulfurous (not sulfuric) acid, respectively. Carbon dioxide is not highly soluble, and only some of the dissolved CO₂ forms carbonic acid. The chemical reactions associated with CO₂ and carbonic acid are illustrated here; the behavior of SO₂ is entirely analogous, so it is not explicitly described here.

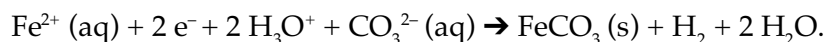
Carbon dioxide in aqueous solution may react with water to produce carbonic acid, H₂CO₃, in aqueous solution:



Being an acid (albeit a weak one), the carbonic acid molecule dissociates in water to release protons that attach to water molecules to form the hydronium ion, H₃O⁺, and the negatively charged carbonate ion, CO₃²⁻:



Dissolved carbon dioxide cannot actually displace oxygen from solution in water. However, if a CO₂ atmosphere is maintained over the water, then only carbon dioxide is available to dissolve into the water. Dissolved iron in water initially will react with the dissolved oxygen that is available from assembling the experiment. After the oxygen has been depleted, however, there is no more available, and the formation of iron (III) oxide (Fe₂O₃) stops. A new reaction now can take place, however: ferrous iron, Fe²⁺, can react with the double-negatively charged carbonate radical (CO₃²⁻) to produce iron carbonate. The electrons released during the initial oxidation reaction that dissolved the iron into water are available to reduce the hydronium ions, releasing hydrogen gas from the water:



Iron carbonate is insoluble (or weakly soluble) in water and precipitates out. Iron sulfite, FeSO₃, resulting from a similar set of reactions *is* soluble in water. Since the respective gases are only weakly soluble and do not strongly react with water, these species must form rather slowly.

Carbon dioxide and sulfur dioxide are by no means the only gases expected in the primordial atmosphere. Other species that would be chemically relevant are nitrogen (N₂), nitrous oxide (NO₂), carbon monoxide (CO), methane (CH₄), hydrogen (H₂), hydrogen sulfide (H₂S), hydrogen cyanide (HCN), and gaseous ammonia (NH₃). Nitrogen could be handled relatively safely if facilities permit access to liquid nitrogen or compressed nitrogen gas. The other species are not suggested for experimentation because they tend to be either explosive or powerfully toxic — or both! All of these species, however, have been identified in cometary ices or in the atmospheres of other worlds in the solar system. The nitrogen-bearing molecules, in particular, exist in the atmosphere of Saturn's largest moon, Titan. It is a rather important point that worlds possessing no signs of life of their own possess atmospheres that are enormously hostile to the majority of modern Earth life. It is also rather important that some of these other atmospheres would be chemically comfortable, at a different temperature, for many members of the most ancient group of living things on Earth, the cyanobacteria.

Cyanobacteria

The first fossilized life forms on Earth, microfossils of cyanobacteria, similar to modern forms, are found in some of the oldest rocks, dated by radioactive decay rates to be about 3.5 billion years old. The very oldest known Earth rocks are about 3.8 billion years old. The oldest dated rocks from anywhere are meteorites, the oldest of which formed about 4.6 billion years ago, setting the time of formation of the solar system. The Earth is thus known to have been a living world for almost the whole time that a rock record has existed, and for more than half the age of the Solar System.

Although cyanobacteria are not related to algae — algae are plants and cyanobacteria are more closely related to bacteria — cyanobacteria and algae share one very important trait: some modern strains of cyanobacteria are able to photosynthesize sugars (food) from the action of sunlight on carbon dioxide and chlorophyll, releasing gaseous oxygen as a waste product. Were ancient cyanobacteria capable of photosynthesis?

Not all the fossil evidence of cyanobacteria is microscopic. Stromatolites are large structures, sometimes forming entire Precambrian reefs, constructed of calcium carbonate (CaCO_3) by colonial communities of cyanobacteria and dependent on photosynthesis to support the community. Living stromatolites first were discovered in Shark Bay, Western Australia in 1956 and have subsequently been found in warm, shallow hypersaline waters all over the world. The stromatolite is a glob of filamentary mucilage encrusting a rock, formed by multitudes of photosynthetic bacteria. Successive generations of cyanobacteria grow where there is light available for photosynthesis, at the top of the stromatolite. As the stromatolite photosynthesizes sugars, it consumes carbon dioxide from local water and releases oxygen gas, raising the pH somewhat as carbonic acid leaves the solution. The hypersaline water becomes super-saturated in CaCO_3 , which is more soluble in acid solution (low pH), so that solid calcium carbonate precipitates into the stromatolite's sticky mucilage, which cements it together. New filaments continue to grow out past the layer of precipitate, which forms a growing shell of laminated layers of calcium carbonate. The structure of the stromatolite is a direct consequence of growing so that the moored population of actively photosynthesizing cyanobacteria remains in sunlight despite a constantly-growing sediment load.

Living stromatolites provide a definite biological model, repeated in many locations, that reproduces structures previously observed in widespread stromatolite fossils. Fossil stromatolites are recognized by the many fine curved laminations of sediments trapped by the growing blobs of cyanobacterial colonies. Stromatolites were not the only cyanobacteria that photosynthesized, but they provide clear evidence that photosynthesis already had evolved in the cyanobacteria. The first fossilized stromatolites appear in rocks formed 3–3.5 billion years ago. Oxygen had begun to enter our world even this early.

Banded Iron

The formation process for banded iron deposits is still a matter of debate and polite contention; papers arguing for or against particular mechanisms for the formation of characteristic mineral bands continue to appear in the current scientific literature. The general conclusions drawn from the existence of banded iron in the geologic record are straightforward, however: the Earth once had an atmosphere with no free oxygen, in which photosynthetic cyanobacteria evolved. Over the course of roughly a billion years, oxygen from cyanobacteria photosynthesis oxidized dissolved iron in the oceans to precipitate iron oxide deposits. By about 1.5–2 billion years ago, the atmosphere had become relatively oxygen-rich and banded iron formation tapered off. The contention is about how the detailed structure of the mineral bands came to be, and what does it imply for the history of life on Earth. At the center of the discussion is the chemistry of iron oxidation.

Banded iron formations (BIFs) consist of layers of iron-compound minerals, mainly Fe_2O_3 in the form of red or gray hematite and Fe_3O_4 (magnetite), alternating with layers of silicate minerals, as in the samples shown in the photographs below. Individual layers may be as thin as a fraction of a millimeter (as some are in sample a), or several meters thick. A thin layer may have taken only a few years, maybe even only months to accumulate. A thick layer may have accumulated over several millennia. Minerals in the silicate layers contain silicon and oxygen atoms compounded with a wide variety of other elements. The single most common silicate, however, is silicon dioxide (SiO_2), which forms quartz. The silicate layers in BIFs may include iron-bearing species cemented in with silicate grains.

Until about 2.5 billion years ago, banded iron formed in localized deposits, suggesting localized sources of oxygen to drive the oxidation of dissolved iron. From about 2.5 to 1.8 billion years

ago, BIFs were formed on the sea floor worldwide. About 90% of the world's iron ores were deposited in this period. Whatever processes were involved in creating the banded structures, they had to be in effect worldwide, for more than half a billion years. At about 1.8 billion years ago, the first "red beds" appeared in the rock record, and banded iron formation tapered off and stopped. A red bed is a continental deposit of iron oxide-rich soil.

The existence of worldwide oceanic deposits of iron oxide, ironically, is definite evidence for the lack of oxygen in the Earth's atmosphere. Recalling the reaction of the ferrous iron ion (Fe^{2+}) with hydroxyl (OH^-) in the process of forming ordinary rust, iron oxides and hydroxides form solid precipitates. The only way to distribute iron globally through the oceans is as a solute. Since Fe^{2+} cannot stay in solution with significant oxygen dissolved into the water, the Earth's global atmosphere must have remained chemically reducing (anoxic) throughout the period that banded

**a****b****c**

Samples of banded iron from the Lake Superior Banded Iron Formation. Iron (III) oxide (Fe_2O_3) minerals can appear reddish-brown or gray depending on grain size cemented within the mineral. In either case, it is called hematite. Samples (a,b) are each about 3.5 inches long. Sample (c) is about 4.5 inches long. (a) Red hematite layers alternated with silicate layers stained with iron-bearing fluids. (b) Iron is contained in the shiny bands of specular (reflective) hematite. The iron is banded with shale (organic-rich ancient clays), metamorphosed to slate. (c) Here, the iron oxide appears as specular hematite, banded with quartzite — SiO_2 , deposited as sand and metamorphosed. The quartzite was stained red by iron-bearing fluids at deposition. (*Samples and mineral descriptions provided by A. Joyal, Northern Michigan University*)

iron formed. Photosynthesizing cyanobacteria, distributed globally, produced oxygen at the location at which iron oxides were formed, since precipitation following formation of the iron (II) hydroxide is immediate.

After about 1.8 billion years ago, the formation of global BIFs tailed off and red beds first appeared. Red beds result from the chemical erosion by water of iron mineral deposits in the presence of oxygen. When the atmosphere was oxygen-poor, water erosion dissolved continental deposits of iron and washed it down to the sea. In an oxygenated atmosphere, corrosion occurred at the site of erosion, leaving continental deposits of iron oxide. Red beds, thus, are a definite sign of significant free oxygen. Note, however, that the global source of oceanic iron is not thought to have been continental erosion, but volcanic material introduced at the ancient mid-ocean ridges.

The end of global BIF deposition and the rise of free oxygen concentrations 1.8 billion years ago pose a chicken-and-egg problem. Did the appearance of oxygen-tolerant photosynthetic plants increase the oxygen concentration, thus preventing the diffusion of iron-rich water that would have supplied iron for new oxide sediments to form? Or, did the supply of dissolved iron run out, permitting oxygen levels to rise from photosynthesis without iron oxidation to limit it, so that only oxygen-tolerant species were able to survive?

The source of the characteristic banding in the deposition of BIFs is not certain. It seems clear that whatever controlled it must be a robust and fundamental process, as it persisted globally for 700 million years. Setting aside the (rather important) details, a general rule applies: when dissolved iron in anoxic water came together with oxygen derived from sea-surface photosynthesis of cyanobacteria, dissolved iron would be oxidized rapidly and precipitate to form reasonably pure iron minerals, while silicate precipitated much more slowly. During periods of low dissolved iron content or low levels of photosynthetic activity (or both), silicates would continue to precipitate slowly, filling in the silicate layers between the iron-rich mineral bands. Sample C below provides an exception to this model: silicates in the form of sand were deposited here on top of iron beds while the ocean water remained iron-rich, staining the sand which eventually metamorphosed to quartzite.

Depletion of dissolved iron and bacterial populations could have occurred together if the global source of dissolved iron were not steady, but pulsed (fluctuating). During a period of high iron concentration, bacteria could reproduce rapidly, as the oxygen waste from photosynthesis would be consumed in iron oxidation until finally the iron were depleted. The bacterial population then would crash due to oxygen poisoning until elimination of the remaining free oxygen, either by aerobic bacteria or by inorganic chemistry, returned widespread anoxic conditions. The next phase of high dissolved iron content would permit the next cycle of rampant photosynthesis/population crash to proceed. Whether this is the proper model for the formation of the bands in banded iron remains a matter for investigation.

Lesson Plan

Preparation & Management

- ▶ Familiarize yourself with the *Science Overview* sections on rust chemistry.
- ▶ Students should be familiar with stoichiometric equations and have some knowledge of acid-base chemistry. Especially, they should know that acids release H^+ and inhibit OH^- ; bases do the opposite.

Warm-up

1. Initiate class discussion with the question, “What makes iron rust?” Note that there are a lot of products available that claim to be able to reduce, eliminate, or reverse rust. That suggests that there is a lot of money to be made, or saved, by figuring out what makes rust happen so it can be prevented. Encourage students to contribute their own direct observations and ideas. For example, what happens to a bicycle left outside in the rain?
2. Encourage students to classify their contributions as:
 - direct observations
 - inferences (ideas they’ve come up with to explain evidence they’ve gathered or heard)
 - authority (facts or claims they’ve heard from trusted sources)
3. Develop new inferences from the students’ contributions to form a description of the condition (or conditions) under which they predict that rust will form. Highlight contradictory ideas, especially if students continue to disagree — this is an opportunity for direct experimentation. Bring attention to the fact that these are valid scientific hypotheses — predictions for the behavior of observable events that can be directly tested.
4. Ask students to suggest ways that their predictions could be tested, trying out different conditions that should promote or inhibit rust.



TEACHER MATERIALS

Activity 2: Rusting the Ocean Blue

- Sample of banded iron rock or overhead transparency of banded iron (e.g., from the *Science Overview*).

STUDENT MATERIALS

Activity 1: Experimenting with Rust

FOR ENTIRE CLASS

- 15 copies Student Worksheet 2 (Apparatus Assembly Report); may require more copies, one per apparatus
- 15 disposable aluminum loaf pans (may require more)
- 19 small aluminum foil cups (may require more)
- 15 plastic-wrap covers with elastic edging, or improvise plastic-wrap with rubber bands
- 4–6 pads steel wool or several tablespoons iron filings
- 8–10 liters distilled water
- 3–4 liters dilute vinegar or other dilute acid, pH about 5
- 3–4 liters dilute solution of ammonia (NH_3) or sodium hydroxide (NaOH), pH about 9
- 1–2 kg dry ice every other day during course of experiment — source of carbon dioxide (CO_2) gas
- 8 or more Camden tablets (sodium metabisulphite, $\text{Na}_2\text{S}_2\text{O}_5$)
- table salt (NaCl) or halite
- pH test strips or pH meter
- access to hot-melt glue gun and glue
- OPTIONAL: digital camera to record progress of experiment

FOR EACH STUDENT

- 1 copy Student Worksheet 1 (Experimental Procedure)
- 15 copies Student Worksheet 3 (Data Log), one per apparatus
- 1 copy Student Worksheet 4 (Results)

Activity 2: Rusting the Ocean Blue

FOR ENTIRE CLASS

- access to hot-melt glue gun and glue
- hacksaw, coping saw, or razor saw
- extra-fine emery cloth
- OPTIONAL: digital camera to record progress of experiment

FOR EACH GROUP

- 1 aluminum loaf pan
- 1 teaspoon iron filings or scrap of steel wool
- 0.5 liter distilled water (enough to half-fill loaf pan)
- 0.4 kg dry ice every other day during course of experiment — source of carbon dioxide (CO_2) gas
- 1 small aluminum foil cup
- 1 plastic-wrap cover with elastic edging or improvise plastic-wrap with rubber band
- 1 copy Student Worksheet 5 (Rusting the Ocean Blue)
- 1 copy Student Worksheet 6 (Apparatus Assembly Report)
- 1 copy Student Worksheet 7 (Data Log)

5. This is a good time to bring the discussion down to earth. We know that iron forms on Earth under ordinary benign conditions, so relevant experiments should not depend on dangerous chemicals or dangerous conditions. Express to students that this is standard scientific procedure — first test the variables that can be controlled easily, only try the extraordinary things after exhausting the ordinary.

TEACHING TIP

- *Encourage students to think of places in their life in which they have seen rust, or failed to see rust that they might have expected. What were the conditions of that area?*
6. Review with students the discussion of iron oxidation chemistry from the *Science Overview*. Highlight any contradictions between the oxidation reaction scheme and the students' theories.
7. Collaborate with class to revise the class experiment in light of the *Science Overview* and any identified contradictions in predictions. Ensure that students' thinking at this point includes atmospheric composition (presence of oxygen) and the availability of water.
8. Students by now should be considering the following for experiment:
 - Exposure of iron to dry air.
 - Exposure of iron to water under normal air or other gases.
 - Exposure of iron to salty water under normal air or other gases.
 - Exposure of iron to acid or to base under normal air or other gases.
9. As necessary, explain how limited resources may force a compromise on some of the suggested investigations. This happens in professional science all the time.

Pre-assessment

- ▶ Ask student to answer the following questions on a separate piece of paper to be used for later comparison.
 - What is the role of oxygen gas (O_2) in forming rust? Can O_2 be eliminated or replaced? Is it necessary to test concentrations of O_2 greater than Earth-normal? (*Answer: no, iron already rusts nicely with the O_2 that we have*).
 - What is the role of hydroxyl ion (OH^-) in forming rust? If necessary, remind students that pH measures H^+ concentration, and that low pH means large amounts of H^+ and small amounts of OH^- .
 - What is the effect of salt in aqueous solution (saltwater) on the formation of rust?

ACTIVITY 1: Experimenting with Rust

TEACHING TIP:

- ▶ If possible, photograph the development of the contents of each pan. Control camera settings as much as possible to ensure that each pan is photographed in the same way.

CAUTION

- ▶ CO_2 gas forms a weak acid in water solution and thus can be mildly corrosive on the wet surface of the lungs. CO_2 gas is an asphyxiating gas and can be harmful if breathed in quantity.
- ▶ SO_2 is a noxious gas with an unpleasant odor. Students with asthma should be particularly cautious to avoid breathing SO_2 . SO_2 gas forms a weak acid in water solution and, thus, can be mildly corrosive on the wet surface of the lungs. SO_2 gas is an asphyxiating gas and can be harmful if breathed in quantity.

Preparation & Management

- ▶ The entire class will assemble ONE complete set up, as there are many trials running simultaneously.
- ▶ The entire class will record data for all the pans.
- ▶ The suggested quantities of materials allow for 15 separate trials. The actual number of trials may be greater or fewer, depending on resources, time, class size, and student inventiveness. The list of 15 reaction conditions used in formulating the materials list are:
 - iron + air
 - iron + CO_2
 - iron + SO_2
 - iron + distilled water + air
 - iron + distilled water + CO_2
 - iron + distilled water + SO_2
 - iron + distilled water + salt + air
 - iron + distilled water + salt + CO_2
 - iron + distilled water + salt + SO_2
 - iron + dilute acid + air
 - iron + dilute acid + CO_2
 - iron + dilute acid + SO_2
 - iron + dilute base + air
 - iron + dilute base + CO_2
 - iron + dilute base + SO_2

ACTIVITY 1: Experimenting with Rust

- ▶ Carbon dioxide will be needed to replace air in several of the experiment apparatus, every other day that the experiment runs. CO₂ can be obtained most easily from sublimation of dry ice, for which the procedures are written. Dry ice can be stored in a super-insulated container for several days. A total of 3–4 inches of Styrofoam insulation, at least, is required as insulation for extended storage. Compressed CO₂ cartridges (seltzer cartridges) can be used as a source of CO₂, but do not fill containers as gently as dry ice sublimation.
- ▶ Sulfur dioxide will be needed to replace air in several of the experiment pans, every other day that the experiment runs. SO₂ can be obtained most easily from Camden tablets (sodium metabisulphite, Na₂S₂O₅) dissolved in water. SO₂ gas evolves, leaving a residue of insoluble sodium oxide (NaO).
- ▶ Assign student groups as needed to maintain each experiment pan each day. Some groups will have very little to do. For very small classes, individual students may have to take responsibility for more than one pan.
- ▶ Provide time for students to review procedures before assembling apparatus.
- ▶ Student groups will assemble their own apparatus and complete an Apparatus Assembly Report (Student Worksheet 2) to record what they have done.
- ▶ Ensure that everyone uses standard laboratory safety practices in handling *all* liquids. Some of the proposed test liquids are caustic, but indistinguishable from water in appearance.
- ▶ Assembly of apparatus and initiation of experiment should take one class period.
- ▶ Experiment will require maintenance for a few minutes each day and taking notes. Student groups will share data, not interpretations.

ACTIVITY 1: Experimenting with Rust**Procedures**

1. Inform students that the gases with which they will work (other than air) will have to be limited to CO_2 and SO_2 . The following reasons may be cited:
 - They are easy to work with — not aggressively poisonous, not explosive.
 - Readily available as pure gases.
 - They are highly oxidized already, so they make good replacement gases to eliminate oxygen.
 - They are representative of volcanic gases that would form the atmosphere of the Earth in the absence of oxygen-producing plants.
2. Ask student groups to assemble the experiment pans for which they are responsible, according to the instructions of Student Worksheets 1 and 2, and to complete the Apparatus Assembly Report (Student Worksheet 2) to certify that the apparatus has been assembled properly.
3. Be sure to cover all pans, even those exposed to normal air, to eliminate evaporation of the test liquid.
4. Agree upon a procedure for the acquisition of pH data for each pan containing liquid, to ensure uniformity.
5. Each student will be responsible for maintaining a Data Log (Student Worksheet 3) of observations of each test apparatus each day.
6. Ask students to acquire their initial data and to record initial observations of progress in each experiment pan. Be alert to relatively rapid changes in each pan at the beginning of the experiment.
7. Apparatuses will require daily maintenance. If students are absent, they must faithfully record failure to observe the experiment on those days (if no one else can provide a second-hand observation) or record secondhand observations marked as such.

ACTIVITY 1: Experimenting with Rust

8. At the completion of the tests (several days required), students will complete Student Worksheet 4 (Results).
9. Dispose of acid and base solutions properly (neutralize), according to standard lab procedure for your school district. All other solutions are consistent with ordinary water chemistry and can be disposed of in the drain.
10. Use a magnet wrapped in plastic wrap to test rust samples for magnetic behavior.
11. Use a magnet wrapped in plastic wrap to test remaining iron samples for magnetic behavior.
12. Scrape iron sample out of sample cup and observe residue in bottom.
13. Dispose of solid waste (pans, covers, iron oxides, remaining iron) as ordinary refuse.

TEACHING TIP

- ▶ *Examination of magnetic properties and residue in cup is ungraded, but may contribute to students' ideas about the experimental results. Let it be an invitation to curiosity.*

ACTIVITY 1: Experimenting with Rust**Routine Maintenance**

- ▶ Before interfering with pans in any way, students should make notes on the appearance of each pan.
- ▶ Remove covers from pans and photograph (if class is doing so).
- ▶ Group responsible for each test apparatus measure pH. Record value and report to class.
- ▶ Blow out the old atmosphere from the apparatus each day. Blowing by mouth is sufficient.
- ▶ Daily maintenance procedure varies according to initial atmospheric composition in test apparatus:
 - For pans exposed to normal air, replace cover after freshening the air in the pan.
 - For pans initially exposed to CO₂, alternate days of exposure to CO₂ with days of exposure to normal air. Replace cover after exchanging atmosphere.
 - Day 1: Test with CO₂.
 - Day 2: Test with normal air.
 - Day 3: Test with CO₂. (New lump of dry ice required).
 - Day 4: Test with normal air.
 - ... and so on
 - For pans initially exposed to SO₂, alternate days of exposure to SO₂ with days of exposure to normal air, similar to the procedure for CO₂. A new Campden tablet will be required each time that SO₂ must be produced. The water in the foil cup does not need to be replaced each time.

ACTIVITY 1: Experimenting with Rust**Reflection & Discussion**

- ▶ After collecting Student Worksheet 4 (Results), discuss observations and interpretations with students.
- ▶ Encourage class to collaborate to develop a more complete picture of iron chemistry. Especially, what conditions encourage iron transport from an iron deposit to a location at which iron oxide is formed?

Transfer of Knowledge

- ▶ Mars is covered with red dust that often is cited as being oxidized iron. Can you speculate as to why there is rust essentially all over Mars? Additional research may be encouraged to pursue this question.
(Short answers: (1) Mars has had 4.6 billion years for rust to form, it doesn't need to happen efficiently. (2) Mars is not entirely dry — it has small amounts of water vapor to stick to surfaces and facilitate oxidation. (3) Ultraviolet light reaching the surface breaks down the CO₂ atmosphere into CO and O₂. It also produces hydrogen peroxide (H₂O₂) from water, which is highly oxidizing.)
- ▶ Mars Global Surveyor has identified three regions on Mars that appear to show outcroppings of the mineral hematite, a mineral formed by the precipitation of Fe₂O₃ crystals from aqueous solution. What would you infer about Mars at the time that the mineral formed?
(Answer: On Earth, crystalline hematite only forms from water solution. MGS geologists consider this evidence for ancient lakes or oceans in these regions. One of the Mars Exploration Rovers (MER) is targeted to one of these regions for further investigation.)



ACTIVITY 1: Experimenting with Rust

ASSESSMENT

Student Worksheets 2 and 3 (graded together):

4 Points

- All observations are complete
- Notes accurately describe the results.
- Good use of adjectives to describe results.
- Writing is clear, understandable, and precise.

3 Points

- All observations are complete.
- Notes accurately describe the results.
- Writing is understandable.

2 Points

- Observations are not complete, but sufficient.
- Notes describe results, incompletely or not completely accurately.
- Writing is difficult to understand.

1 Point

- Observations are incomplete, do not sufficiently describe events.
- Notes do not accurately describe the observed results.

0 Points

- No observations are complete.
- Writing off-topic or unrelated.
- Writing is not readable.

Placing the Activity Within the Lesson

Students will acquire direct experience to interpret the abstract chemistry outlined in the Warm-up. Students should now have a grasp of the conditions under which iron can become widespread and the conditions under which iron oxide forms. In the remaining activity, students will use this understanding to predict the conditions under which the formation of iron oxide bands will occur in sedimentation, and prepare and execute a physical model for their proposed mechanism.

ACTIVITY 2: Rusting the Ocean Blue

TEACHING TIPS

- ▶ Calcium sulfate (CaSO_4), also known as Plaster or Paris, is used as an inert sediment between iron layers in the models students make.
 - Plaster solidifies by forming a hydrate from dry powdered gypsum. It does not react in water to form a new compound.
 - Fully hydrated CaSO_4 is $\text{CaSO}_4 \cdot 10 \text{H}_2\text{O}$. The solid is formed from the hydrogen bonds between water molecules of hydration.
 - CaSO_4 will solidify under water.
 - CaSO_4 cannot be used in acidic solution because the acid attacks it. The issues of consistency and robustness in the formation of banded iron discussed in the *Science Overview* suggest that variable acidity of ocean water can be overlooked as a mechanism for banded iron formation.

Preparation & Management

- ▶ Obtain a mineral sample or photograph of banded iron (for example, from the *Science Overview*).

TEACHING TIP

- ▶ A real sample of banded iron can be scanned on a flatbed scanner at high resolution in order to make a transparency at high magnification to show grain structure. The banded iron sample can be viewed under a low-power microscope, if available.
- ▶ Students will work independently or in groups, depending on availability of materials.
- ▶ Students will construct a fresh apparatus similar to Activity 1; one apparatus per student or student group.

ACTIVITY 2: Rusting the Ocean Blue**Procedures**

1. Show students the banded iron sample.
2. Inform students that similar deposits, found all over the world, formed on the ocean floor a long time ago — current climate and atmospheric conditions may not have been in effect. They will try to learn more about the chemical conditions under which the sample formed.
3. Identify the sediment layers that are rich in iron oxide compared to the layers that are poor in iron oxide (verify with documentation or with the seller for a banded iron sample that you obtain yourself, if you are not certain).
4. Ask students to speculate, based on their recent experiments, what chemical conditions could cause water to deposit iron oxide sometimes, but not at other times? (Their experience should tell them that iron can be dissolved and diffused in water under anoxic conditions; iron (III) oxide is precipitated from water that carries dissolved oxygen when it is exposed to oxygen.)
5. Note that the real material has inert sediments filling the layers in-between the iron-rich layers. Real sediments are typically silicate (e.g., sand, SiO_2), but may also include materials like calcium carbonate (CaCO_3 , metamorphoses to the mineral limestone) and calcium sulfate (CaSO_4 , mineral gypsum). CaSO_4 can be purchased as Plaster of Paris and used as a convenient sediment in a classroom model.
6. Ask students to conceive a model for simulating the formation of banded iron using what they know and materials that they have used, along with Plaster of Paris for iron-poor sediments.
7. Encourage classroom discussion of ideas for a few minutes. Write consensus ideas on the board.
8. Ask students now to fill out Student Worksheet 5 in order to get their ideas into written form.
9. Accept Student Worksheet 5 now for critique and grading. Students will need to refer to the worksheets because they will be putting their own ideas into action to model banded iron formation.

ACTIVITY 2: Rusting the Ocean Blue

10. After grading Student Worksheet 5, students will put their critiqued models into effect. The critiqued model description now should include the following elements:
 - Exposure of iron immersed in test liquid to anoxic atmosphere (CO_2 or SO_2 gas) to encourage iron to dissolve in liquid.
 - Exposure to oxygen-rich atmosphere (normal air) to precipitate iron oxide from solution.
 - Alternating these atmospheric compositions to produce layers of deposited sediment.
 - Schedule for deposition of iron-poor sediments (for example, deposit Plaster of Paris every time that the atmospheric composition is exchanged).
11. Ask students to assemble the necessary apparatus for their model from materials similar to Activity 2. Each student must complete a copy of Student Worksheet 6 (Apparatus Assembly Report) in order to document the assembly of their apparatus.
12. Define how long the experiment will be permitted to progress. Possibilities include:
 - Until the sediment mound breaks the surface of the water.
 - Until the water level rises to the point of near overflowing.
 - Finite number of days (e.g., two weeks).
13. Students must maintain their own apparatuses and keep records of their observations and of their actions in manipulating the models on the Data Log pages (Student Worksheet 7).
14. At the completion of the experiment, drain liquid from the model apparatuses and allow the Plaster of Paris sediment deposit to finish curing for several days.
15. Saw the sediment deposits in half using a fine-toothed hacksaw, coping saw, or razor saw. Polish the exposed face with extra-fine grit emery cloth.
16. Assemble a display of the model banded iron sediments collected by the class. Do any of them resemble the sample that they are supposed to model?

ACTIVITY 2: Rusting the Ocean Blue**Reflection & Discussion**

- ▶ Ask students to look at their original answers from the warm-up. After conducting these two experiments, ask them if they would change their responses. What misconceptions did they have at the beginning of this lesson? What did they learn in addition to these original questions?
- ▶ Are students surprised that an exploration of something ordinary like rust ended with a model for part of the history of life on Earth?
- ▶ Inform students that banded iron formations (BIFs) were deposited between 1.8 and more than 2.5 billion years ago.
- ▶ Review with students the line of reasoning connecting banded iron to the rise of worldwide oxygen levels through photosynthesis. Compare the *Science Overview* with students' ideas in forming their models. What do they have in common? Any differences?
- ▶ Bring students' attention to the cyanobacteria as the probable culprits in filling the planet's air with oxygen.

Transfer of Knowledge

- ▶ Ask students to research and to write a short essay to:
 - Support one of the two viewpoints on the end of banded iron formation, the rise of global oxygen levels, and the appearance of oxygen-tolerant plant species — that is, either oxygen-tolerant plants stopped banded iron from forming, or the end of banded iron formation forced the appearance of oxygen-tolerant plants.
 - Debate the evidence for and against both viewpoints described above.
 - Argue (based on empirical evidence) against both viewpoints described above.

**ACTIVITY 2: Experimenting with Rust****ASSESSMENT**

Student Worksheets 5 & 6 (combined)

4 Points

- Description of class consensus and of mineral sample is complete and accurate.
- Description of model components is complete and addresses how the model is expected to produce banding.
- Good use of adjectives to describe results.
- Writing is clear, understandable, and precise.

3 Points

- Description of class consensus and of mineral sample is accurate.
- Description of model components is clear and at least partly addresses how the model is expected to produce banding.
- Writing is understandable.

2 Points

- Description of class consensus and of mineral sample is understandable, but not completely accurate.
- Description of model is incomplete.
- Writing is difficult to understand.

1 Point

- Description of class consensus and of mineral sample is incomplete.
- Model description and notes on model assembly are not consistent.

0 Points

- Description of class results is incomplete and inaccurate.
- Proposed model not sufficiently described to understand.
- Writing is off-topic or unrelated.
- Writing is not readable.



ASSESSMENT

Student Worksheet 7

4 Points

- All observations are complete.
- Notes accurately describe the results.
- Good use of adjectives to describe results.
- Writing is clear, understandable, and precise.

3 Points

- All observations are complete.
- Notes accurately describe the results.
- Writing is understandable.

2 Points

- Observations are not complete, but sufficiently describe events.
- Notes describe results, incompletely or not completely accurately.
- Writing content is difficult to understand.

1 Point

- Observations are incomplete and do not sufficiently describe events.
- Notes do not accurately describe the observed results.

0 Points

- No observations completed.
- Writing is off-topic or unrelated.
- Writing is not readable.

Placing the Activity Within the Lesson

- ▶ Students have used a model, in which they control all the inputs, to test specific ideas about geological processes that occurred outside the range of human observation. The inability to repeat the “experiments” of nature with geology does not stop geology from being a science, because we are able to make laboratory tests based on hypotheses drawn from observations of nature.
- ▶ Students have directly confronted evidence for the alteration of the Earth through time, interpreting the evidence using the tools of chemical description that they have developed in this investigation of iron oxidation.

Lesson Closure

- ▶ Breaking the world down into simple problems, like experimenting with the chemistry of iron, can provide powerful tools to interpret seemingly unrelated problems.
- ▶ Theoretical and practical knowledge of the abstract subject of iron oxidation is applicable to discoveries in the real world. Knowing that iron ore is in the form of oxides requires specific chemistry to extract iron from ore.
- ▶ Complex ideas for the development of the Earth through time are not arbitrary notions. Laboratory knowledge of processes like iron oxidation provides a way to read the signs in the world around us. Even though we don't know the details of events billions of years ago, what we know about iron forces us to draw some conclusions about things that must have happened.
- ▶ Things that are common and ordinary can remain fascinating and mysterious. Ninety percent of the world's iron ore is in banded iron formations, yet we don't have a good model that is widely accepted for why iron minerals formed in characteristic bands over a period of 700 million years, nor do we have a specific model for why it ended when it did.

References

Petrucci, R. H. (1982). General Chemistry: Principles and Modern Applications (3rd ed.). New York: MacMillan.

Supplemental Resources

CYANOSITE: A Webserver for Cyanobacterial Research. A web site for professional research on cyanobacteria, hosted by the Department of Biological Sciences at Purdue University. Includes links, images, bibliographies.

<http://www-cyanosite.bio.purdue.edu/>

GeoMania. A geology web site maintained by an instructor at Rogue Community College in Oregon. Links to geological web sites, and the Ask GeoMan! FAQ page. The author is opinionated and occasionally states as fact, matters that may be controversial.

<http://jersey.uoregon.edu/~mstrick/>

Illustrated Glossary of Geologic Terms. A helpful reference maintained at Iowa State University.

http://www.ge-at.iastate.edu/courses/Geol_100/old_files/glossary.v2.html

Introduction to the Cyanobacteria: Architects of Earth's atmosphere. University of California, Berkeley, Museum of Paleontology web site on the subject of cyanobacteria in general, both ancient and modern.

<http://www.ucmp.berkeley.edu/bacteria/cyanointro.html>

Let's Talk Science. Canadian science literacy organization, web site hosted by the University of Western Ontario Department of Physiology and Pharmacology. Hands-on home or classroom activities and experiments, including "Trust in Rust."

<http://www.letstalkscience.uwo.ca/activities/index.ihtml>

Virtual Tour of the National Museum of Natural History: Early Life. One of the Smithsonian Institution museums in Washington, DC. There are other tours of this great museum accessible from the Virtual Tour home page. Information on the web pages is very limited, however.

<http://www.mnh.si.edu/museum/VirtualTour/Tour/First/Early/index.html>



STUDENT WORKSHEET 1 - EXPERIMENTING WITH RUST



EXPERIMENTAL PROCEDURE

1. The class will assemble a set of apparatuses, each of which will contain an iron sample exposed to a test gas or exposed to a test liquid and a test gas. Each student will maintain a record of the identity of the test conditions and the student groups responsible for maintaining each. Each student will maintain a record of observations for all of the apparatuses.
2. The specific test gases are decided by the class. The test gases may include some of the following or others:
 - a. Normal air; carbon dioxide (CO_2); sulfur dioxide (SO_2).
 - i. Neither CO_2 nor SO_2 should be breathed, particularly by students with asthma. Other non-oxygen gases should be treated with similar or greater caution.
 - ii. CO_2 and SO_2 can be irritating to the lungs.
 - iii. CO_2 and SO_2 can be asphyxiating in large quantities.
 - b. The test gas atmosphere will be exchanged regularly, to replace depleted oxygen in normal air and to test response to variable oxygen in non-oxygen atmospheres.
 - i. For normal air, remove the cover and blow out the trapped gas daily before replacing cover.
 - ii. For non-oxygen gas, exchange the gas with normal air every other day. For example: Day 1 – Fill with CO_2 ; Day 2 – Fill with air; Day 3 – Fill with CO_2 ; Day 4 – Fill with air; ... etc...
3. The specific test liquids are decided by the class. The test liquids may include some of the following or others:
 - a. Distilled (pure) water; salt water; acid solution; base solution.
 - i. These liquids appear similar (clear).
 - ii. Some of these liquids can be caustic.
 - iii. Use lab safety practices at all times to avoid accidents with misidentified or mislabeled liquids.
4. Individual students or groups will be responsible for the assembly and maintenance of an assigned sample apparatus. Complete the Apparatus Assembly Report (Student Worksheet 2) to certify the correct components and assembly of the apparatus.
5. Each group will be responsible for the acquisition of pH measurements from their sample (if relevant) to share with the entire class, to minimize disturbance of the apparatus. If maintaining the apparatus requires exchanging some component, measure pH immediately before and after making the change.
6. The test samples will be observed on a daily basis (or more often if desired and possible). Record observations on the Data Log (Student Worksheet 3), one page per sample apparatus.

**STUDENT WORKSHEET 2 - EXPERIMENTING
WITH RUST****Apparatus Assembly Report**

Assembly Team(print names) 1: _____
2: _____
3: _____
4: _____

Assigned Apparatus Designation _____

Standard Components Check List(check as used)

- Aluminum foil loaf pan
- Aluminum foil cup (sample cup)
- Iron (Fe) sample (0.5–1 tsp filings or steel wool scrap)
- Plastic wrap cover
- Paper or adhesive label for apparatus

Special Components Check List(cross-off unused)

Table salt (NaCl, 1 Tbs)
Aluminum foil cup for evolved gas
Campden tablet, 1
Dry ice (solid CO₂)

Test Liquid(cross-off unused)

None
Distilled water(salt will be added later for salt water)
Acid Solution (composition: _____)
Base Solution (composition: _____)

Assembly Start Date/Time _____

Initial pH of Test Liquid _____

Assembly Completion Date/Time _____



STUDENT WORKSHEET 2 - EXPERIMENTING WITH RUST



Assembly Instructions:

1. Glue foil sample cup flat to loaf pan bottom at one end.
2. For pan with SO_2 test gas: glue foil cup into a corner opposite sample cup. Glue in two places on edge, for strength. For a pan to contain a test liquid, glue cup near the top of the pan. For a pan with no liquid, glue cup into the bottom of the pan.
3. Place pan in final test location, so it will not have to be moved after filling.
4. Place iron sample in sample cup.
5. Add test liquid to pan.
 - a. Avoid disturbing iron sample.
 - b. Do not spill into second cup.
 - c. Fill to within 1 inch of top of pan, or halfway up second cup.
6. Special ingredients:
 - a. For pans to contain salt water: Sprinkle NaCl over water. Record pH. Apply cover.
 - b. For pans to contain SO_2 gas: Record pH of test liquid. Fill corner cup with distilled water to height of test liquid. Add Campden tablet, immediately apply cover.
 - c. For pans to contain CO_2 gas: Record pH of test liquid. Add lump of dry ice to test liquid, immediately apply cover.
7. Prepare descriptive label and attach.



STUDENT WORKSHEET 3 - EXPERIMENTING WITH RUST



Name: _____

Apparatus Designation: _____

Assembly/Maintenance Group: _____

	pH	Description/Actions Taken
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		

**STUDENT WORKSHEET 4 - EXPERIMENTING
WITH RUST**

Name: _____

1. In which pan(s) did the iron sample form rust in the sample cup?
2. In which pan(s) did rust form elsewhere than in the sample cup?
3. Under what atmospheric condition(s) did rust appear to form away from the sample cup?
4. In which pan(s), if any, did rust never form?
5. If rust did not form, did any other deposits form?
6. Did pH vary in any of the sample liquids?
7. Did pH vary with the changing of test gases?
8. Interpret your observations: Why did rust sometimes form away from the iron sample cup and sometimes not?
9. Interpret your observations: Following your answer to question 8, what procedure would you follow to intentionally cause widespread formation of rust deposits?

**STUDENT WORKSHEET 6 - RUSTING THE OCEAN
BLUE****Apparatus Assembly Report**

Experimenter(s) 1: _____
2: _____
3: _____
4: _____

Assigned Apparatus Designation _____

Components Check List(check as used)

- Aluminum foil loaf pan
- Aluminum foil cup (sample cup)
- Iron (Fe) sample (0.5–1 tsp filings or steel wool scrap)
- Plastic wrap cover
- Paper or adhesive label for apparatus

Test Gas(es): _____

Test Liquid(s): _____

Assembly Start Date/Time _____

Initial pH of Test Liquid _____

Assembly Completion Date/Time _____

Describe and justify the design and contents (identity of test gas, test liquids, additional ingredients) of the apparatus, with special attention to non-standard construction details (may continue on additional sheet).



**STUDENT WORKSHEET 7 - RUSTING THE OCEAN
BLUE**



Name: _____

Apparatus Designation: _____

	pH	Description/Actions Taken
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		
Date: Time:		

At completion, drain the water and allow the plaster to complete hardening (e.g., over a weekend). Saw the plaster sediment in two and examine the structure. Does it look like banded iron? If not, can you suggest why not?

Answer Key

Student Worksheet 4

1. The iron sample should form surface rust when exposed to water, salt water, and base solution, regardless of the test gas, due to residual oxygen dissolved in the water or oxygen dissolving into the water when exposed to normal air. Some surface rust may appear in the sample exposed to SO_2 gas only, no liquid, due to the humidity from the wet cup after the periodic removal of the SO_2 atmosphere. Iron exposed to dry air and to CO_2 should not rust significantly. Salt water should promote the rusting rate. Base solution should rust heavily in place.
2. In the pans periodically exposed to CO_2 and SO_2 , widespread rust deposits should form during periods of exposure to normal air. The SO_2 pan rusts more slowly. Iron exposed to acid should eventually form widespread rust deposits as the iron solubility saturates and the dissolved iron is exposed to normal air.
3. After replacement of the CO_2 and SO_2 atmospheres by normal air, rust will form everywhere in the test pan. Resumption of the CO_2 or SO_2 atmosphere should return clear water as iron dissolves and iron oxide precipitates.
4. Rust might never form during the period of observation in the pan of acid test solution and in the dry pans.
5. It is possible that deposits of iron carbonate, iron sulfide, or iron sulfite may form, looking different from the deposits of iron (III) oxide.
6. pH should go down under CO_2 and SO_2 test atmospheres as they form carbonic and sulfurous acid. pH should rise in the acid solution as iron reacts with the free hydrogens to form ferrous ion and hydrogen gas. pH should decrease in the base solution as iron reacts with the hydroxide radicals to form hydroxides and oxides directly on the sample. pH should be indifferent to salt content in the water.

7. pH should decrease as CO_2 or SO_2 dissolve into water, increase as they dissolve out of water and are replaced by dissolved oxygen.
8. Under acidic and anoxic conditions, iron dissolves into the water and diffuses throughout the volume of water. When the water with a high load of dissolved iron is exposed to normal air (oxidizing atmosphere), iron hydroxides and iron oxide form, precipitating immediately. Under basic or oxic conditions, iron hydroxides and oxides formed from dissolved ferrous ion right at the sample, before the ion could diffuse far.
9. Applying acid to iron or imposing a non-oxygen atmosphere allows the iron to dissolve into water as ferrous ion and to diffuse far and wide from the source location. Once iron is widespread, allow the solution to evaporate, increasing the dissolved iron concentration in the remaining solution volume past the point of saturation; or, exchange the atmosphere for an oxygen-rich atmosphere and allow the oxides to form in place.

Challenger Center Programs



The internationally acclaimed **Challenger Learning Center** Network currently consists of state-of-the-art, innovative educational simulators located at 49 sites across 29 states, Canada, and the United Kingdom. Staffed by master teachers, the core of each Center is a two-room simulator consisting of a space station, complete with communications, medical, life, and computer science equipment, and a mission control room patterned after NASA's Johnson Space Center. See www.challenger.org for information.

A joint initiative of Challenger Center for Space Science Education, the Smithsonian Institution, and NASA, *Voyage — A Journey through our Solar System* is a space science exhibition project that includes permanent placement of a scale model solar system on the National Mall in Washington, DC, and at locations all over the world. See www.voyageonline.org for information.



Space DaySM launches new *Design Challenges* created by Challenger Center each school year. The inquiry-based challenges are designed to inspire students in grades 4-8 to create innovative solutions that could aid future exploration of our solar system. See www.spaceday.org for information.

Challenger Center's *Journey through the Universe* program provides under-served communities with diverse national resources, including K-12 curriculum materials, teacher workshops, classroom visits by scientists from all over the country, and Family Science Nights. See www.challenger.org/journey for information.



The **MESSENGER** spacecraft (MErcury Surface, Space ENvironment, GEOchemistry and Ranging) is to be launched in 2004 and go into Mercurian orbit in 2009. Challenger Center is one of the partner organizations charged with MESSENGER education and public outreach activities. See www.messenger.jhuapl.edu for information.

Through the Challenger Center **Speakers Bureau, Voyages Across the Universe**, staff members speak to student audiences of 30-1,000, conduct workshops for 100-300 educators, give keynote and featured presentations at conferences, as well as conduct Family Science Nights at the National Air and Space Museum, and other facilities across the nation, for audiences of 300-1,000 parents, students, and teachers. See www.challenger.org/speakers for information.

For information about other Challenger Center programs, or to purchase our classroom resources, visit www.challenger.org/store.