MATH AND SCIENCE @ WORK

AP* PHYSICS Educator Edition

SPACE SHUTTLE SHORT CIRCUIT

Instructional Objectives

Students will

- apply Ohm's law to solve for unknowns in a DC circuit; and
- analyze data to derive a solution to a real life problem.

Degree of Difficulty

This problem is a fairly straightforward application of Ohm's Law.

- For the average student in AP Physics B the problem is moderately difficult.
- For the average student in AP Physics C: Electricity and Magnetism the problem is at a basic difficulty level.

Class Time Required

This problem requires 40-55 minutes.

- Introduction: 10-15 minutes
- Student Work Time: 20-25 minutes
- Post Discussion: 10-15 minutes

Background

This problem is part of a series of problems that apply Math and Science @ Work in NASA's Space Shuttle Mission Control Center.

Since its conception in 1981, NASA has used the space shuttle for human transport, the construction of the International Space Station (ISS), and to research the effects of space on the human body. One of the keys to the success of the Space Shuttle Program is the Space Shuttle Mission Control Center (MCC). The Space Shuttle MCC at NASA Johnson Space Center uses some of the most sophisticated technology and communication equipment in the world to monitor and control the space shuttle flights.

Within the Space Shuttle MCC, teams of highly qualified engineers, scientists, doctors, and technicians, known as flight controllers, monitor the systems and activities aboard the space shuttle. They work together as a powerful team, spending many hours performing critical simulations as they prepare to support preflight, ascent, flight, and reentry of the space shuttle

Grade Level
11-12

Key Topic
DC Circuit, Ohm's Law

Degree of Difficulty
Physics B: Moderate
Physics C: Electricity and Magnetism: Basic

Teacher Prep Time
5 minutes

Class Time Required
40-55 minutes

Technology
Calculator

AP Course Topics
Electricity and Magnetism:
- Electric Circuits

NSES
Science Standards
- Science and Technology
- History and Nature of Science

and the crew. The flight controllers provide the knowledge and expertise needed to support normal operations and any unexpected events.

One of the flight controllers in the Space Shuttle MCC is the Electrical Generation and Illumination Engineer (EGIL). The duties of this position include monitoring electrical systems, fuel cells and associated cryogenics (low temperature functions) of NASA's space shuttle. The complexity of this vehicle, built to operate in an extreme environment, have required flight controllers to break down the system into manageable tasks with simplified and solvable problems. The EGIL flight controllers are responsible for keeping the space shuttle operating safely during a mission while also accomplishing the mission objectives like building the International Space Station or servicing the Hubble Space Telescope. Flight controllers practice asking a lot of "what if" questions. In this way, they are prepared to ask the right questions at the right time and know how to answer them if a system failure occurs.

The space shuttle is a very complex machine with many control panels that require power to operate. Each control panel (PNL) has a reference that tells the flight controller where it is located on the space shuttle. For example, PNL MA73C is located on the middeck (M) on the aft wall (A), at column location 73 (inches from a reference point), and row location C.

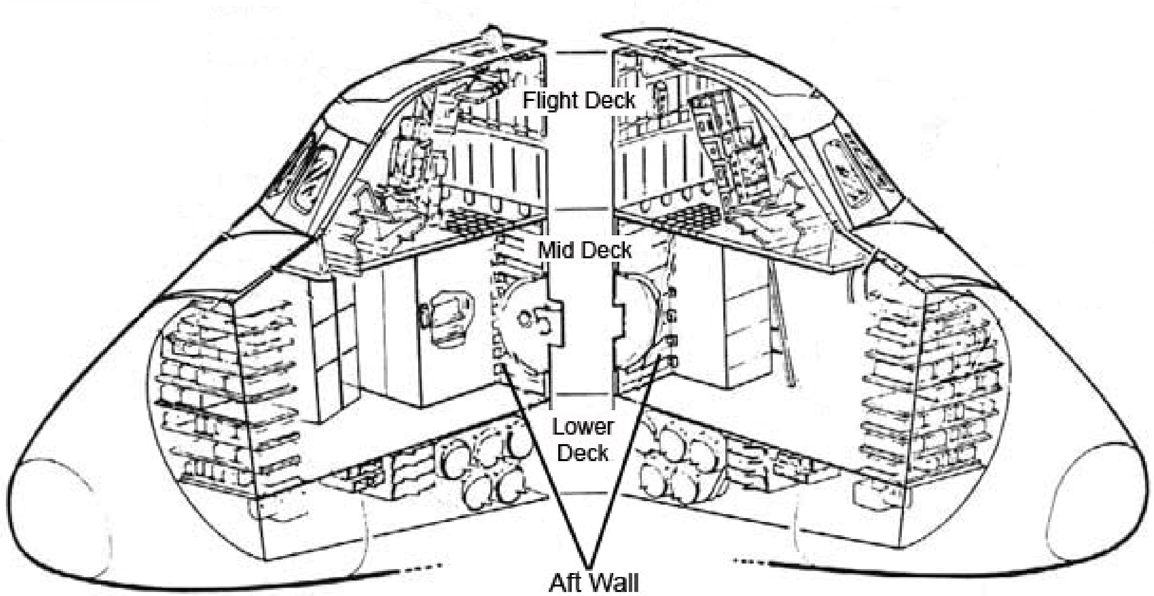

Figure 1: Crew Module Layout

The majority of the control panels on the space shuttle are connected and powered by long, low amperage wires strung together to form what is called a "control bus". A potential electrical problem is a short to ground (a low resistance current return path) somewhere on the wire. In the space shuttle, the negative poles of the fuel cells are tied to the airframe just like the negative battery pole in a car is tied to the frame. If a wire from a positive terminal touches the frame it will result in a large spark as a significant amount of current will take the path of least resistance.

Figure 2 shows wire damage that resulted from a powered wire touching a structure on the space shuttle. This happened immediately after liftoff during a space shuttle mission. The wiring to a main engine controller shorted, causing the circuit protection to trip for the engine controller. The backup engine controller took over automatically. The EGIL and Booster flight controllers recommended turning the bus sensors off to preclude an AC inverter problem from automatically tripping another bus which would potentially shut one of the main engines down. No further action was taken until after Main Engine Cut Off. Once on orbit, the EGIL operator directed the crew to provide status for the circuit breaker for the offending main engine controller to ensure that it had opened and there was not a wider electrical problem.

Figure 2: Damaged wire that resulted from a short to ground on the space shuttle.

The EGIL flight controller must be prepared to make decisions that will ensure the safety of the flight and crew if problems like this occur. Over the years of space shuttle operations, electrical problems highlighted the necessity for NASA engineers to have a deep understanding of short circuits, circuit protection, and insulation characteristics.

AP Course Topics

Electricity and Magnetism

- Electric Circuits
  - current, resistance and power
  - steady-state direct current circuits with batteries and resistors only

NSES Science Standards

Science and Technology

- Abilities of technological design
- Understanding about science and technology

History and Nature of Science

- Science as a human endeavor

Problem

Figure 3 is a simplified layout of a control bus for the space shuttle. At each end of the bus there is a 31 V power source and a 5 A circuit protection device called a remote power controller (RPC). The RPCs will break the circuit (trip) after exceeding the rated current for a specified duration and can be reset after a trip. There is also a 31.2 V power source connected at the center of the electrical bus through a 5 A fuse as shown in Figure 2. It is important to note that the circuit is a closed loop because the return path is through vehicle ground. Each switch function in each control panel takes the powered control bus input, feeds it through the switch out to electronic devices in the circuit, and then returns it to ground (not shown in diagram).

The control bus in Figure 2 uses 24-gauge wires. Wire gauge is a measurement of how large a wire is. As the diameter of the wire decreases, the gauge number increases as does the resistance in the wire. Because the wire gauge is small and the line length is long, the resistance in the wire is significant. The 24-gauge wire has a resistance of 0.0846 Ω/m. In the event of a short to ground somewhere on the wire, one source may draw enough current to trip the circuit protection. However, the resistance in the line may prevent a high enough current draw at the other sources to trip the circuit protection. This means that the short continues to be powered and could cause a fire.

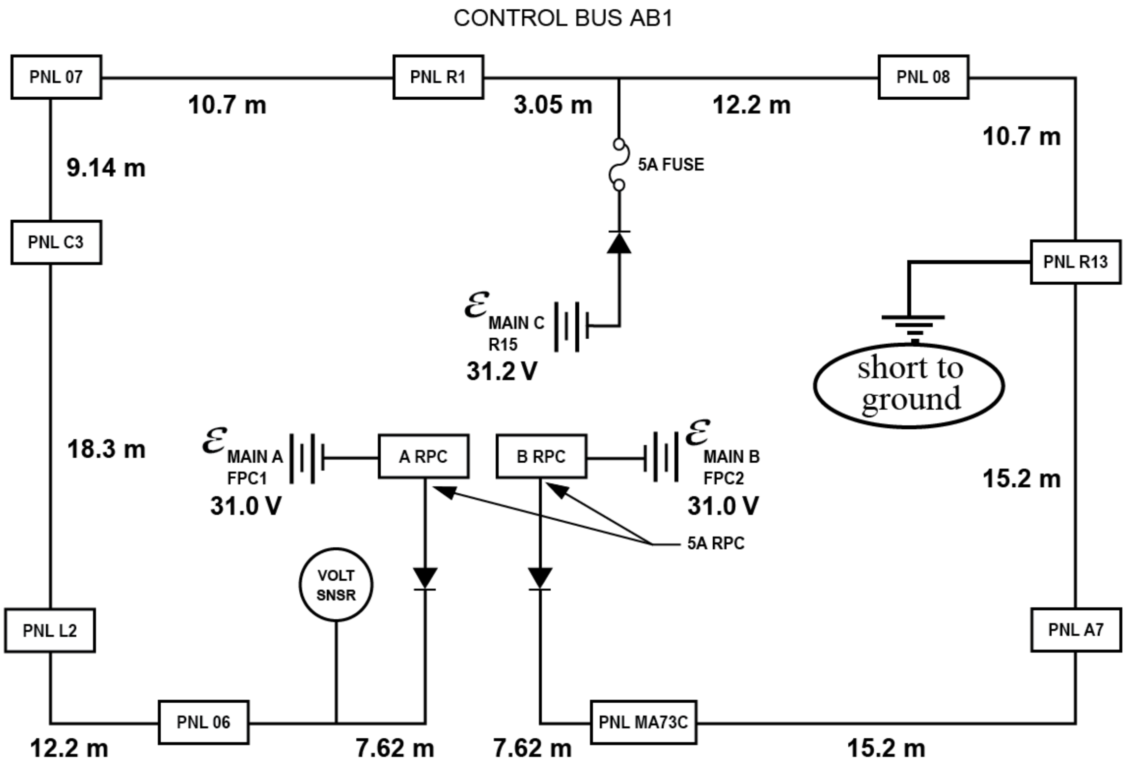

Figure 3: Simplified control bus layout. This is a closed loop because the return path is through vehicle ground (not shown in diagram). PNL=Panel, RPC =Remote Power Controller, SNSR = Sensor. The Volt SNSR provides a reading that can be used in conjunction with panel switch functionality to determine the approximate location of a short. A low voltage reading indicates a problem close to the A RPC end of the control bus.

A. Suppose a short to ground occurs at panel R13 as shown in Figure 3. Determine which circuit protection devices will trip. (The 5 A fuse will trip at 3 times the rated current. The 5 A RPCs will trip at 1.5 times the rated current.)

   Note: *Fuses and circuit breakers have characteristic trip curves that level off at somewhere above the rated trip current. This allows the user to safely operate a load at the rated current without fear of tripping the circuit. These thermal devices rely on heat buildup, so it takes some finite period of time to trip.*

B. The control panels are guaranteed to function down to 24 V, but may function as low as 22 V. Referring to Figure 3, determine which control panels will receive enough voltage to still function.

C. If NASA were going to design a new spacecraft and use the same wiring as shown in Figure 3, what should be the maximum length of a wire run to ensure that a 5 A fuse would trip with a short anywhere on the wire? Repeat for a 5 A RPC. Assume the power system supplies 28 V.

D. If NASA used a 3 A fuse instead of a 5 A fuse, would they need to use a longer wire or would a shorter wire run be sufficient to guarantee the fuse would trip? Justify your answer.

Solution Key (One Approach)

A. Suppose a short to ground occurs at panel R13 as shown in Figure 2. Determine which circuit protection devices will trip. (The 5 A fuse will trip at 3 times the rated current. The 5 A RPCs will trip at 1.5 times the rated current.)

Note: *Fuses and circuit breakers have characteristic trip curves that level off at somewhere above the rated trip current. This allows the user to safely operate a load at the rated current without fear of tripping the circuit. These thermal devices rely on heat buildup, so it takes some finite period of time to trip.*

Step 1: Find the resistance for each length of wire from the circuit protection device to the short.

$$R_{\text{A to short}} = (.0846\,\tfrac{\Omega}{\text{m}})(7.62 + 12.2 + 18.3 + 9.14 + 10.7 + 3.05 + 12.2 + 10.7)\,\text{m} = 7.10\,\Omega$$
$$R_{\text{B to short}} = (.0846\,\tfrac{\Omega}{\text{m}})(15.2 + 15.2 + 7.62)\,\text{m} = 3.22\,\Omega$$
$$R_{\text{fuse to short}} = (.0846\,\tfrac{\Omega}{\text{m}})(12.2 + 10.7)\,\text{m} = 1.94\,\Omega$$

Step 2: Determine the amount of current to trip the device.

$$I_{\textit{to}\text{ trip 5A fuse}} = (5\text{A})(3) = 15\text{ A}$$
$$I_{\textit{to}\text{ trip 5A RPC}} = (5\text{A})(1.5) = 7.5\text{ A}$$

Step 3: Use Ohm's law to determine the amount of current at the circuit protection device and compare to the amount of current to trip the device.

$$I = \frac{V}{R}$$
$$I_{\text{A to short}} = \frac{31\,\text{V}}{7.10\,\Omega} = 4.4\text{ A} \rightarrow \text{under } 7.5\text{ A}$$
$$I_{\text{B to short}} = \frac{31\,\text{V}}{3.22\,\Omega} = 9.6\text{ A} \rightarrow \text{over } 7.5\text{ A}$$
$$I_{\text{fuse to short}} = \frac{31.2\text{ V}}{1.94\,\Omega} = 16.1\,\text{A} \rightarrow \text{over } 15\text{ A}$$

The 5 A fuse and the 5 A RPC B will trip.

B. The control panels are guaranteed to function down to 24 V, but may function as low as 22 V. Referring to Figure 2, determine which control panels will receive enough voltage to still function.

Use Ohm's law to calculate the voltage used by each length of wire to each panel and subtract from the voltage source to see if panel will receive the 22 V necessary to work.

$$V = IR$$
$$\text{At Panel 06} \rightarrow V = 31\,\text{V} - (4.4\text{ A})(7.62\,\text{m})(0.0846\,\tfrac{\Omega}{\text{m}}) = 28.2\text{ V};\ \text{panel will still work}.$$
$$\text{At Panel L2} \rightarrow V = 31\,\text{V} - (4.4\text{ A})(19.8\,\text{m})(0.0846\,\tfrac{\Omega}{\text{m}}) = 23.6\text{ V};\ \text{panel will still work}.$$

At Panel C3 $\rightarrow V = 31\text{ V} - (4.4\text{ A})(38.1\text{m})(0.0846\,\frac{\Omega}{\text{m}}) = 16.8\text{ V};$ panel will not work .

No other panels will work.

Voltages will continue to decrease along the wire from RPC A as you get farther from the voltage source and closer to the short.

The panels between the fuse and the short and between RPC B and the short will not receive any voltage because circuit protection devices tripped.

C. If NASA were going to design a new spacecraft and use the same wiring as shown in Figure 2, what should be the maximum length of a wire run to ensure that a 5 A fuse would trip with a short anywhere on the wire? Repeat for a 5 A RPC. Assume the power system supplies 28 V.

Use Ohm's law to determine the resistance limit and then use the resistance/m value to determine the maximum length of wire.

Step 1: Find the resistance for the 5 A fuse and for the 5 A RPC.

$$R = \frac{V}{I}$$

$$R_{5\text{A fuse}} = \frac{28\text{ V}}{15\text{ A}} = 1.87\,\Omega$$

$$R_{5\text{A RPC}} = \frac{28\text{ V}}{7.5\text{ A}} = 3.73\,\Omega$$

Step 2: Find the length of the 5 A fuse and of the 5 A RPC.

$$length_{5\text{A fuse}} = \frac{1.87\,\Omega}{0.0846\,\frac{\Omega}{\text{m}}} = 22.1\text{m}$$

$$length_{5\text{A RPC}} = \frac{3.73\,\Omega}{0.0846\,\frac{\Omega}{\text{m}}} = 44.1\text{m}$$

D. If NASA used a 3 A fuse instead of a 5 A fuse, would they need to use a longer wire or would a shorter wire run be sufficient to guarantee the fuse would trip? Justify your answer.

A longer wire would need to be used. A 3 A fuse would trip with less current than a 5 A fuse. Assuming the same voltage applied, it would take a higher resistance to achieve the required current to trip (due to the inverse relationship between current and resistance).

Scoring Guide

Suggested 15 points total to be given.

Question		Distribution of points
A	*5 points*	1 point for correct process in finding resistance
		1 point for correct process in finding current
		1 point for using Ohm's Law
		1 point for determining currents at circuit protection devices
		1 point for correctly identifying which devices will trip
B	*5 points*	1 point for determining Panel 06 will still work
		1 point for determining Panel L2 will still work
		1 point for determining Panel C3 will not work
		1 point for explanation of why the panels on the wire between C3 and the short will not work
		1 point for recognition that the devices that tripped determine all other panels will not work
C	*3 points*	1 point for correct resistance limit
		1 point for correct length
		1 point for units used throughout calculation
D	*2 points*	1 point for identifying the longer wire
		1 point for correct justification

Contributors

This problem was developed by the Human Research Program Education and Outreach (HRPEO) team with the help of NASA subject matter experts and high school AP Instructors.

NASA Experts

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