MATH AND SCIENCE @ WORK

AP* PHYSICS Educator Edition

ARED – RESISTIVE EXERCISE IN SPACE

Instructional Objectives

Students will

- apply equations of pressure, force, torque, and harmonic motion to solve for unknowns;
- draw a free-body diagram; and
- analyze the design of exercise equipment used in space.

Degree of Difficulty

This problem requires that students have knowledge about pressure, torque, and simple machines. Question E, Part I, is a more challenging simple harmonic motion section. You may choose to spend more time reviewing the equations for this question before it is assigned or be prepared to spend more time on this question during post discussion.

- For the average student in AP Physics B, this problem is moderately difficult.

Class Time Required

This problem requires 25-40 minutes.

- Introduction: 5-10 minutes
- Student Work Time: 15-20 minutes
- Post Discussion: 5-10 minutes

Media Resources

Working Out Aboard the Station (4:41) is accessible to stream or download at the Math and Science @ Work website or at the link provided below. The video clip features Commander Scott Kelly demonstrating the Advanced Exercise Resistance Device (ARED) on the International Space Station (ISS). This video should be shown during the introduction of the problem, either before or after students have read the background section.

http://www.nasa.gov/multimedia/videogallery/index.html?media_id=39909781

Grade Level
11-12

Key Topic
Mechanics, Torque, Simple Harmonic Motion, Pressure

Degree of Difficulty
Physics B: Moderate

Teacher Prep Time
5 minutes

Class Time Required
25-40 minutes

Technology
Projector, movie player, calculator

A TNS file for TI-Nspire™ handhelds is available

AP Course Topics
Newtonian Mechanics:
- Work, energy, power
- Circular motion and rotation
- Oscillations and gravitation

Fluid Mechanics:
- Pressure

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

Background

This problem is part of a series of problems that apply Math and Science @ Work to human space exploration at NASA.

Exploration provides the foundation of our knowledge, technology, resources, and inspiration. It seeks answers to fundamental questions about our existence, responds to recent discoveries, and puts in place revolutionary techniques and capabilities to inspire our nation, the world, and the next generation. Through NASA, we touch the unknown, we learn and we understand. As we take our first steps toward sustaining a human presence in the solar system, we can look forward to far-off visions of the past becoming realities of the future.

The International Space Station (ISS) is a research laboratory that has helped us expand our knowledge of human space exploration since 1998 when its construction began. Astronauts aboard the ISS do not feel the effects of gravity as we do on Earth. As the ISS orbits the Earth, both the vehicle and crew members are in a constant state of free-fall causing astronauts to experience a feeling of weightlessness. In this reduced-gravity state, it is easier to accomplish routine physical activities because they require less use of muscles. Since minimal to no exercise would result in muscle deterioration and bone density loss, astronauts are prescribed exercise routines by exercise and rehabilitation specialists and medical doctors. Astronauts are scheduled to exercise approximately two hours per day to maintain their health while on the ISS.

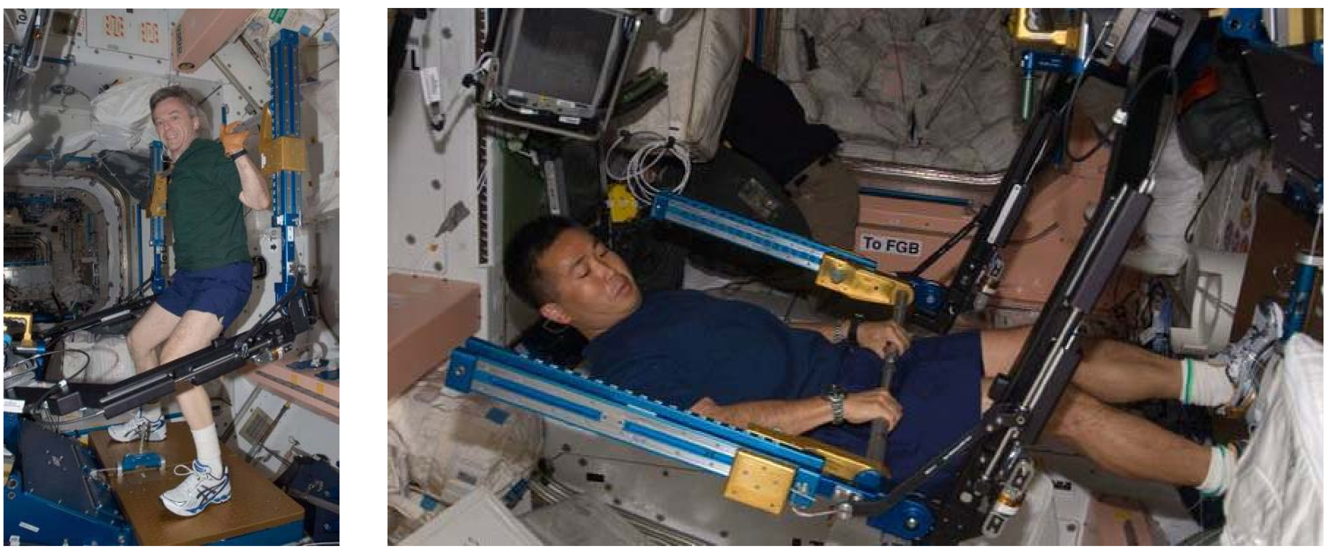


Figure 1: Canadian Astronaut Robert Thirsk (left) and Japanese Astronaut Koichi Wakata (right) use ARED onboard the ISS.

Numerous types of exercise equipment have been used in reduced gravity to evaluate and maintain astronaut fitness. The Advanced Resistive Exercise Device (ARED) allows the crew to engage in resistive exercise onboard the ISS by simulating the use of free weights. This device is used to maintain muscle strength, bone strength, and endurance. The resistive force is generated by two piston/cylinder assemblies with an adjustable load. For bar exercises, the load can be adjusted from 0 to approximately 2,670 N (0 to 600 lbs on Earth or in a 1 g environment). For cable exercises, it can be loaded up to approximately 670 N (150 lbs in a 1 g environment). Astronauts can perform 29 different free-weight style exercises including dead lifts, squats, heel raises, hip abduction and adduction, bench press, bicep curls, tricep extension, and upright rows.

The ARED is attached to the structure of the ISS with a Vibration Isolation System (VIS) installed between ARED and the ISS to limit forces transmitted to the ISS when astronauts are exercising. Springs, dampers, and shock absorbers in the VIS keep ARED centered in its operational volume and minimize the forces transmitted to the ISS to maintain an environment conducive to science.

AP Course Topics

Newtonian Mechanics

- Work, energy, power
    - Conservation of energy
- Circular motion and rotation
    - Torque and rotational static
- Oscillations and gravitation
    - Simple harmonic motion

Fluid Mechanics

- Pressure

NSES Science Standards

Physical Science

- Motions and Forces

Science and Technology

- Abilities of Technological Design

History and Nature of Science

- Science as a Human Endeavor

Problem and Solution Key (One Approach)

The Advanced Resistive Exercise Device (ARED) uses two piston/cylinder assemblies of 20.3 cm diameter to provide a constant load which simulates the use of free weights in the microgravity environment of the International Space Station (ISS). The pressure inside the cylinder is essentially zero Pa (or vacuum) and the atmospheric pressure inside the ISS is 101 kPa.

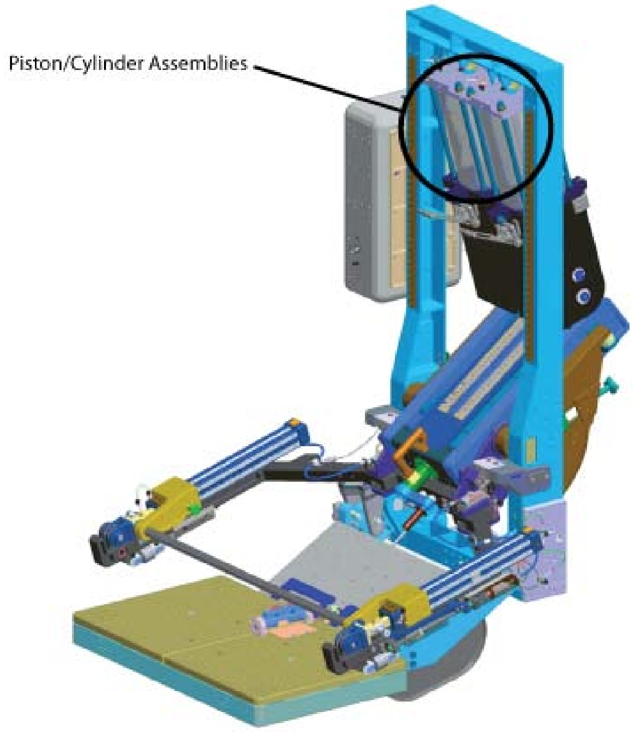


Figure 2: A model of ARED showing the piston/cylinder assemblies

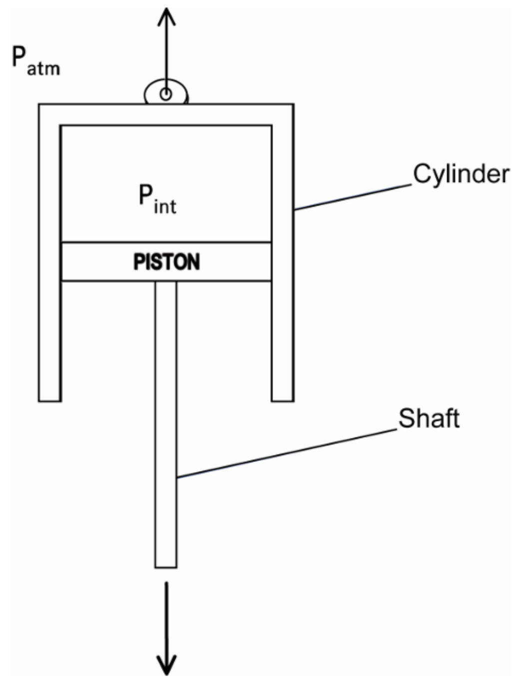


Figure 3: Cross-sectional force diagram of one ARED piston/cylinder assembly

Instructor Note: If the class is using the TI-Nspire handhelds, distribute the TI-Nspire document, ARED.tns, to their handhelds. The problem situation and questions are found in the documents. Students will still need a hard copy of the student handout to refer to background information and figures.

A. Calculate the total force on the pistons.

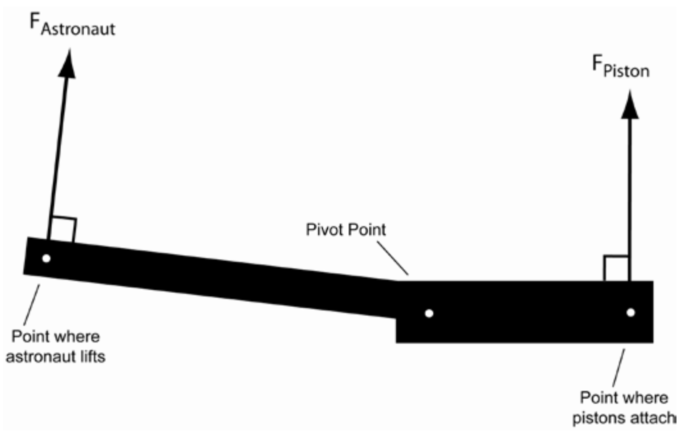
$$P = \frac{force}{area}$$

$$101\ kPa = \frac{F}{\pi\left(\frac{0.203\ m}{2}\right)^2}$$

$3270\ N = F$

There are two pistons, thus the force is 2(3270 N) = 6540 N.

B. Draw and label the forces acting on the bent lever arm below based on Figure 4. Assume that the angle formed by the bent lever arm and the pistons is 90°.



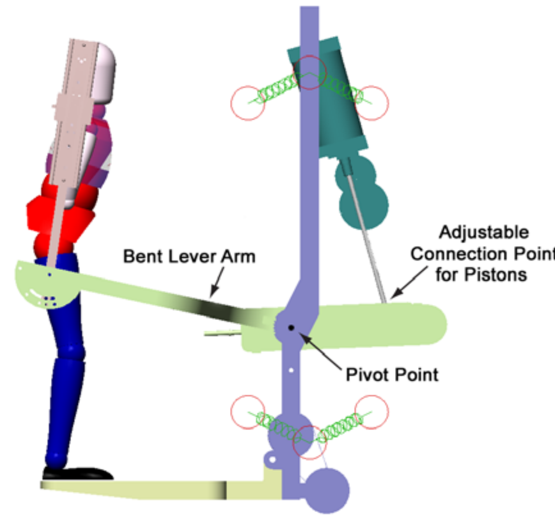


Figure 4: A side-view illustration of ARED showing the bent lever arm

Refer to Figure 4. The distance of the astronaut to the pivot point is 1.22 m. The distance from the pivot point to the piston shaft connection point can be varied to adjust the exercise load for the astronaut. The maximum load available for the astronaut is 2,670 N.

C. As the distance increases between the pivot point and the piston shaft connection point, what is the effect on the force the astronaut experiences?

As the distance between the pivot and the connection point of the pistons increases, the force the astronaut experiences will increase.

D. Determine the distance from the pivot point to the piston shaft connection point when the maximum load available for the astronaut is used.

Sum of the torques: $-\tau_{astronaut} + \tau_{pistons} = 0$

$$\tau_{pistons} = \tau_{astronaut}$$

$(6540\ N)d = (2670\ N)(1.22\ m)$ *assuming the angle is approximately* $90°$

$d = 0.498\ m$ *or* $49.8\ cm$

E. The ARED is attached to the International Space Station (ISS) at a point on each side of the device with a Vibration Isolation System (VIS). While ARED is in use, the VIS isolates the energy created by the astronaut exercising from the space station structure. When the astronaut completes a workout, the VIS is manually locked to prevent inadvertent motion of ARED.

I. Suppose an astronaut forgets to lock out the VIS on ARED after completing a workout. While moving from one module to another on the ISS, one of the astronauts accidentally kicks ARED, displacing it 3.70 cm from equilibrium. The resulting force exerted by the 650. kg ARED through the VIS into the ISS structure is 4.50 N. Calculate ARED's resulting period of oscillation.

Hooke's Law

$$F = kx$$

$$k = \frac{4.50\ N}{0.0370\ m} = 122\ \tfrac{N}{m}$$

$$T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{650.\ kg}{122\ \frac{N}{m}}}$$

$$T = 14.5\ s$$

Alternate solution

$$F = ma$$

$$4.50\ N = 650.\ kg \cdot a$$

$$6.92 \times 10^{-3}\ \frac{m}{s^2} = a$$

$$a = \omega^2 A \text{ and } \omega = \frac{2\pi}{T}$$

$$6.92 \times 10^{-3}\ \frac{m}{s^2} = (0.0370\ m)\left(\frac{2\pi}{T}\right)^2$$

$$14.5\ s = T$$

II. Explain why the ARED cannot be bolted to the structure of the ISS without the VIS. Hint: It is similar to the reason that a large group of people cannot walk across a bridge in step.

The rhythmic motion of a 50 kg astronaut can set up resonance in the entire structure of the ISS. If this vibration matches the natural frequency of the structure, large damage can occur. Even small vibrations can ruin science experiments on the ISS.

Scoring Guide

Suggested 15 points total to be given.

Question		Distribution of points
A	*3 points*	1 point for substitution of values into $P = \frac{F}{A}$
		1 point for correctly using area equation $A = \pi r^2$
		1 point for correct answer (2× force of one piston)
B	*4 points*	2 points for 2 forces acting on the bar
		1 point for correct labels
		1 point for no additional forces (like a force of gravity which should not be considered in this weightless environment)
C	*1 point*	1 point for correct answer of increase
D	*3 points*	1 point for sum of the torques
		1 point substitution of force from part A
		1 point for correct answer 49.8 cm or 0.498 m
E	*4 points*	1 point for finding the spring constant with Hooke's Law or for finding the acceleration with Newton's 2nd Law
		1 point for $T = 2\pi\sqrt{\frac{m}{k}}$ and correct substitution or for combination of $a = A\omega^2$ and $\omega = \frac{2\pi}{T}$
		1 point for correct answer to part I
		1 point for part II - resonance or natural frequency

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 Physics instructors.

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