MATH AND SCIENCE @ WORK

AP* PHYSICS Educator Edition

SPACE SHUTTLE LANDING

Instructional Objectives

Students will
- apply equations of rotational kinematics and dynamics to solve for unknowns;
- apply equations of motion, force, work and energy to solve for unknowns;
- represent a situation graphically; and
- analyze data to derive a solution to a real life problem.

Degree of Difficulty

This problem requires students to know several concepts and how they are related from an entry level physics course.

- For the average student in AP Physics B this problem is at an advanced difficulty level.
- For the average student in AP Physics C: Mechanics, this problem is at a basic difficulty level.

Class Time Required:

This problem would require 30-45 minutes.
- Introduction: 5 minutes
- Student Work Time: 15-20 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.

Grade Level
11-12

Key Topic
Equations of Motion, Force, Work, and Energy

Degree of Difficulty
Physics B: Advanced
Physics C: Mechanics: Basic

Teacher Prep Time
5 minutes

Class Time Required
30 - 45 minutes

Technology
Calculator

AP Course Topics
Newtonian Mechanics:
- Kinematics
- Newton's Laws of Motion
- Work, Energy, Power
-Circular Motion and Rotation

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

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

Figure 1: Space Shuttle Endeavour landing

One of the flight controllers in the Space Shuttle MCC is the Mechanical, Maintenance, Arm, and Crew Systems engineer, whose call sign is MMACS (pronounced “Max”). One of the responsibilities of this position is to monitor the data associated with the landing and deceleration systems on the space shuttle. This includes monitoring the landing gear deployment functionality and timing, as well as the braking system pressures to ensure proper braking profiles. The MMACS flight controllers also verify the main and nose landing gear deployment with position sensors that detect whether the gear has moved to the down position, and finally verify drag chute deployment and jettison. It is the flight control team’s responsibility to ensure the systems on the space shuttle are operating within expected limits, or nominally. If the systems do not operate nominally, the MMACS team in mission control can call the crew to perform troubleshooting actions to put the vehicle in a safe configuration for landing.

AP Course Topics

Newtonian Mechanics

- Kinematics
  - motion in one dimension
- Newton’s laws of motion
  - dynamics of a single particle
- Work, energy, power
  - work and work-energy theorem
  - conservation of energy
- Circular motion and rotation
  - Torque and rotational statics
  - Rotational kinematics and dynamics

NSES Science Standards

Physical Science

- Motions and forces
- Conservation of energy and increase in disorder

Science and Technology

- Understanding about science and technology

History and Nature of Science

- Science as a human endeavor

Problem

At main gear touchdown, the space shuttle is traveling at approximately 110 meters per second. When the drag chute is deployed, the vehicle is traveling at approximately 95 meters per second. While the chute is fully deploying, the vehicle rotates downward for nose gear touchdown and continues to decrease speed. See Figure 2. Express all answers to questions in 2 significant figures.

A. The main landing gear tires each have a mass of 105 kg and are 1.2 m in diameter. At main gear touchdown, how much force does the runway exert on one tire to get it to rotate at speed? The tires have an initial rotation speed of zero at touchdown and are rotating at speed 0.50 seconds after touchdown. Assume that one tire can be approximated as a disk.

   I. Find the rotational inertia.

   II. Find the angular acceleration.

   III. Find the torque.

   IV. Find the force.

B. When the space shuttle reaches about 72 m/s ground speed, braking begins. The crew should maintain a deceleration rate of 2.5 m/s^2 by using a combination of the drag chute and the braking system until a speed of about 21 m/s is reached. How far does the space shuttle travel during this portion of the landing?

C. Assume that the chute is jettisoned at the instant the shuttle has slowed to a speed of 21 m/s. After it has reached this speed, assume that additional deceleration is only caused by braking on the main gear. After the chute is jettisoned, flight rules call for a deceleration rate of less than 1.8 m/s^2. If the crew uses the maximum braking deceleration of 1.8 m/s^2, what is the time required for the space shuttle to come to a stop from a speed of 21 m/s?

D. Using the information from questions B and C, sketch a graph of space shuttle velocity versus time, starting from when braking is initiated to the point at which the shuttle comes to a stop (assuming the drag chute is jettisoned at 21 m/s).

E. The mass of the space shuttle is approximately 90,800 kg at landing. Find the braking force after the chute is jettisoned. Use the maximum deceleration rate as defined by the flight rules.

F. How much work is done by the braking system to bring the space shuttle to a stop from 21 m/s?

G. Is the force provided by the braking system conservative or non-conservative? Justify your answer.

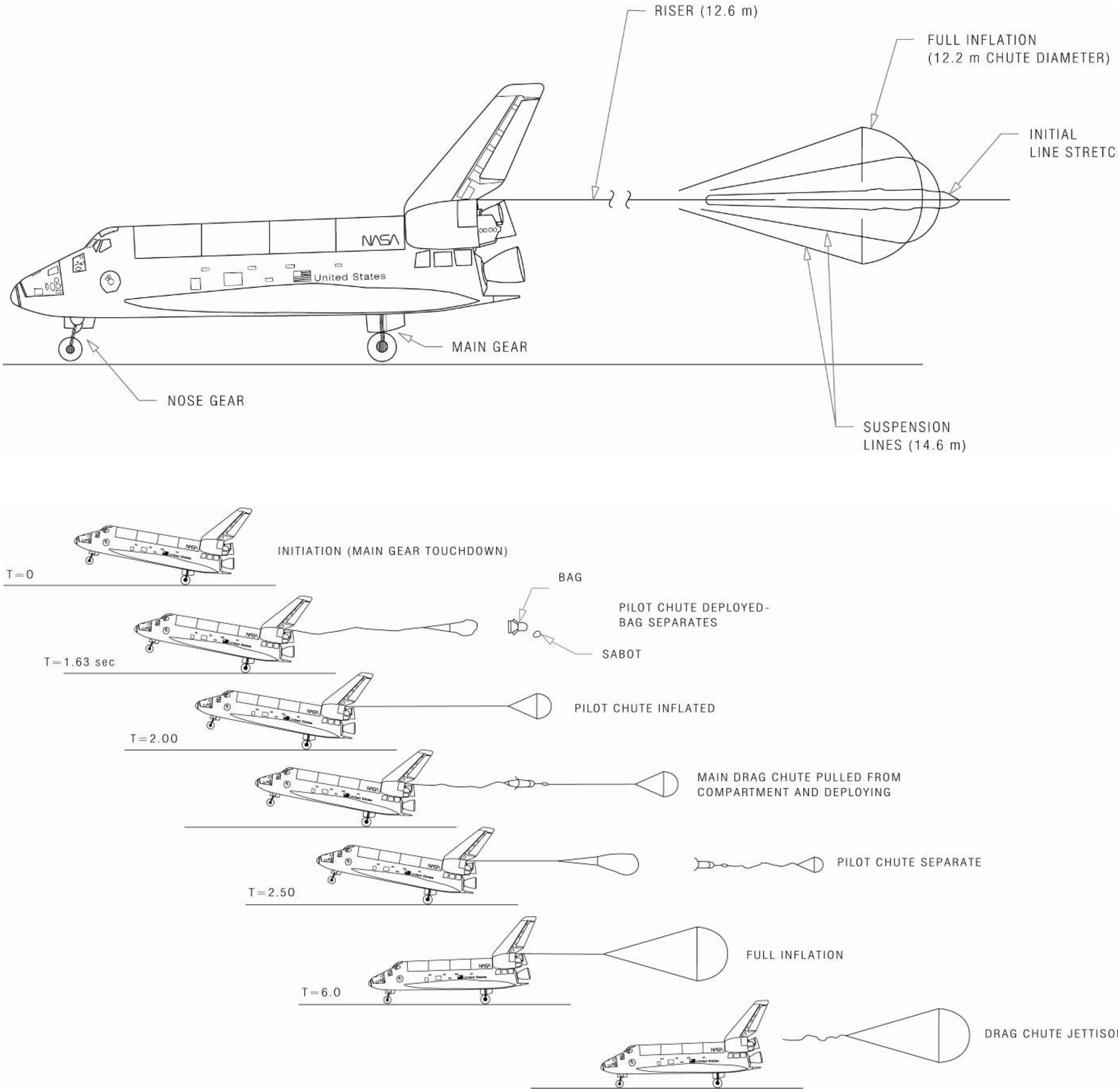


Figure 2: Space shuttle main gear touchdown through chute jettison.

Solution Key (One Approach)

A. The main landing gear tires each have a mass of 105 kg and are 1.2 m in diameter. At main gear touchdown, how much force does the runway exert on one tire to get it to rotate at speed? The tires have an initial rotation speed of zero at touchdown and are rotating at speed 0.50 seconds after touchdown. Assume that one tire can be approximated as a disk.

I. Find the rotational inertia.

$$I = \frac{1}{2} m r^2$$
$$I = \frac{1}{2} \cdot 105\,\text{kg} \cdot (0.6\,\text{m})^2$$
$$I = 19\,\text{kg} \cdot \text{m}^2$$

II. Find the angular acceleration.

First find the angular velocity then use it to find the angular acceleration

$$\omega = \frac{v}{r} \qquad \alpha = \frac{\Delta\omega}{\Delta t}$$
$$\omega = \frac{110\,\frac{\text{m}}{\text{s}}}{0.60\,\text{m}} \qquad \alpha = \frac{180\,\frac{\text{radians}}{\text{s}}}{0.50\,\text{s}}$$
$$\omega = 180\,\frac{\text{radians}}{\text{s}} \qquad \alpha = 360\,\frac{\text{radians}}{\text{s}^2}$$

III. Find the torque.

$$\tau = I\alpha$$
$$\tau = \left(19\,\text{kg} \cdot \text{m}^2\right) \cdot \left(360\,\frac{\text{radians}}{\text{s}^2}\right)$$
$$\tau = 6800\,\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} \text{ or } 6800\,\text{N m}$$

IV. Find the force.

$$F = \frac{\tau}{r}$$
$$F = \frac{6800\,\text{N m}}{0.60\,\text{m}}$$
$$F = 11{,}000\,\text{N}$$

B. When the space shuttle reaches about 72 m/s ground speed, braking begins. The crew should maintain a deceleration rate of 2.5 m/s^2 by using a combination of the drag chute and the braking system until a speed of about 21 m/s is reached. How far does the space shuttle travel during this portion of the landing?

Since the acceleration is considered constant, we can use the equations for constant acceleration and solve for displacement.

$$v^2 = v_0^{\;2} + 2a\Delta x$$

$$(21\,\tfrac{\text{m}}{\text{s}})^2 = (72\,\tfrac{\text{m}}{\text{s}})^2 + 2(-2.5\,\tfrac{\text{m}}{\text{s}^2})\Delta x$$

$$950\text{ m} = \Delta x$$

C. Assume that the chute is jettisoned at the instant the shuttle has slowed to a speed of 21 m/s. After it has reached this speed, assume that additional deceleration is only caused by braking on the main gear. After the chute is jettisoned, flight rules call for a deceleration rate of less than 1.8 m/s^2. If the crew uses the maximum braking deceleration of 1.8 m/s^2, what is the time required for the space shuttle to come to a stop from a speed of 21 m/s?

Use the standard kinematics equation for velocity and solve for time.

$$v = v_0 + at$$

$$0 = 21\,\tfrac{\text{m}}{\text{s}} + (-1.8\,\tfrac{\text{m}}{\text{s}^2})t$$

$$12\text{ s} = t$$

D. Using the information from questions B and C, sketch a graph of space shuttle velocity versus time, starting from when braking is initiated to the point at which the shuttle comes to a stop (assuming the drag chute is jettisoned at 21 m/s).

Using the standard kinematic equation for velocity, $v = v_0 + at$, the velocity of the space shuttle from the time braking is initiated until it reaches 21 m/s can be described by the equation:

$v = 72 – 2.5t$

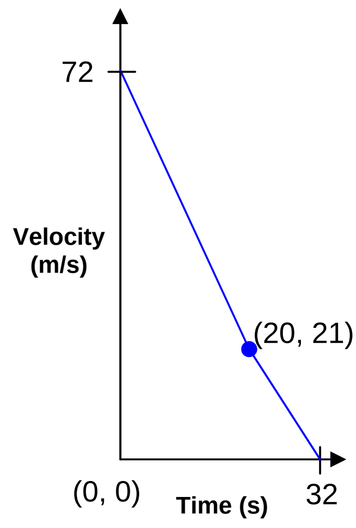
Substituting 21 m/s into the equation we can find the elapsed time at that velocity.

$21 = 72 – 2.5t$

t = 20 seconds

At this point, the deceleration changes to -1.8 m/s and it will take the space shuttle an additional 12 seconds to come to a stop (found in question C)

Student’s graphs will vary but should be similar to the one shown.



E. The mass of the space shuttle is approximately 90,800 kg at landing. Find the braking force after the chute is jettisoned. Use the maximum deceleration rate as defined by the flight rules.

Since we are ignoring air resistance and other frictional forces, the braking system is the only force acting in a horizontal direction. Use Newton's second law to find the average force.

$$F_{braking} = ma$$

$$F_{braking} = (90{,}800\text{ kg})(1.8\ \tfrac{\text{m}}{\text{s}^2})$$

$$F_{braking} = 160{,}000\text{ N}$$

F. How much work is done by the braking system in bringing the space shuttle to a stop from 21 m/s?

Use the work-kinetic energy theorem to solve.

$$W = K - K_0$$

$$W = \tfrac{1}{2}mv^2 - \tfrac{1}{2}mv_0{}^2$$

$$W = \tfrac{1}{2}(90{,}800\text{ kg})(0\ \tfrac{\text{m}}{\text{s}})^2 - \tfrac{1}{2}(90{,}800\text{ kg})(21\ \tfrac{\text{m}}{\text{s}})^2$$

$$W = -2.0 \times 10^7\text{ J}$$

G. Is the force provided by the braking system conservative or non-conservative? Justify your answer.

The force is non-conservative.

The force provided by the braking system is due to friction. Friction is a non-conservative force. Mechanical energy is not conserved. The kinetic energy is converted to thermal energy in the braking system. (Justification will vary)

Scoring Guide

Suggested 15 points total to be given.

Question		Distribution of points
A	*4 points*	1 point for correct rotational inertia 1 point for correct angular acceleration 1 point for correct torque 1 point for correct force
B	*2 points*	1 point for correct kinematics equation 1 point for correct answer
C	*1 point*	1 point for correct kinematics equation
D	*3 points*	1 point for correct initial velocity 1 point for correct time at zero velocity 1 point for general concave-up shape of graph
E	*1 point*	1 point for correct answer
F	*2 points*	1 point for correct work-kinetic energy equation 1 point for correct answer
G	*2 points*	1 point for correct answer 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

Greg Mattes—MMACS Flight Controller, NASA Johnson Space Center, Houston, TX

AP Physics Instructors

Brenda Pinchbeck—Clear Lake High School, Clear Creek Independent School District, TX

Doug Fackelman—Liberty High School, Academy District 20, CO