8 SpinLaunch is a California-based company established in 2014 with the goal of building an alternative method of lauching spacecraft into Low Earth Orbit (LEO). Instead of burning through massive amounts of rocket fuel at lift-off to gain altitude, the company is developing a launch system which uses kinetic energy as its primary method. The advantages include reducing the costs of launching satellites and having an environmental impact that is smaller than traditional rockets, as it avoids fossil fuels as well as the exhaust gases emitted as a result of fuel combustion. In addition, since the projectile doesn't have to carry much fuel, more of the mass can be dedicated to the transport of payloads such as satellites.

Scaled Down Prototype

The most recent accelerator prototype from the company is located in New Mexico, United States of America and is a one-third scale of the eventual accelerator. Designated as the A-33, the prototype accelerator cost USD $38 million and has a height of 50.4 m, as shown in Fig. 8.1.

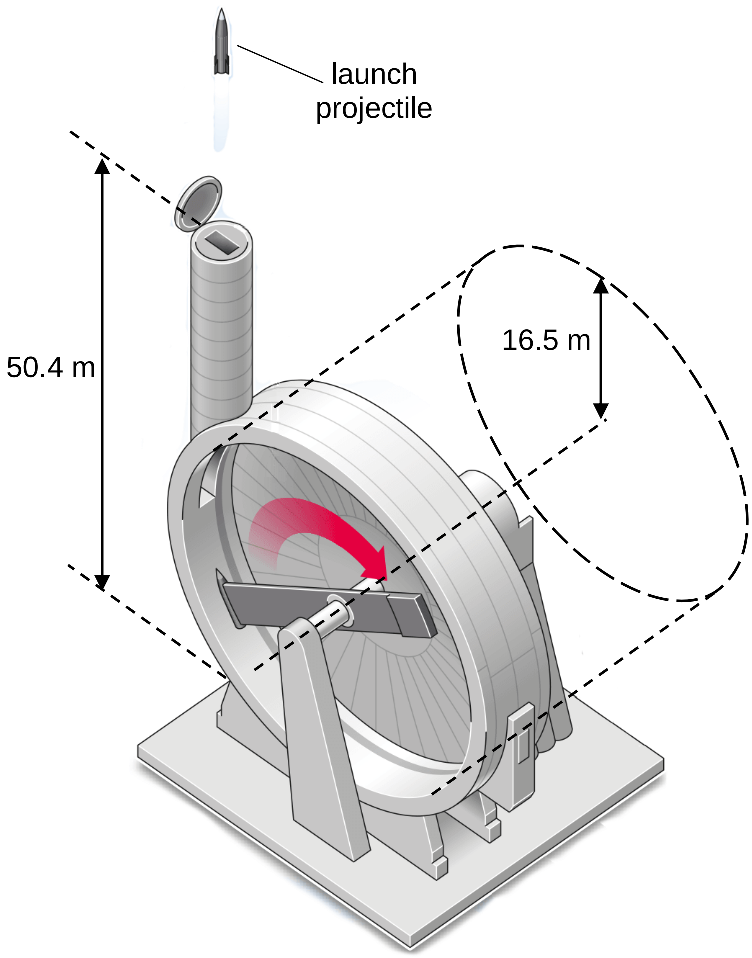

Fig. 8.1

For the latest test launch held in April 2022, the accelerator launched a 50.4 kg projectile at a maximum speed of 536 m s^{-1}, and reached a maximum height of 9300 m. The prototype accelerator required an hour to evacuate air out of the vertically-oriented centrifuge chamber, and then took an additional hour to gradually increase the rotational speed of the arm before releasing the launch projectile at an angle of 86.7° from the horizontal.

(a) Assuming that air resistance on the launch projectile is negligible,

(i) show that the magnitude of the vertical component of the initial velocity is 535 m s^{-1},

[1]

(ii) determine the time taken for the launch projectile to reach the ground,

time taken = ………………………………… s [2]

(iii) find the maximum height attainable by the launch projectile with respect to the ground.

maximum height = ………………………………… m [2]

(b) (i) Find the ratio of $\dfrac{\text{maximum gravitational potential energy attained in real life}}{\text{maximum gravitational potential energy in absence of air resistance}}$.

ratio = ………………………………… [1]

(ii) Suggest if the ratio in **(b)(i)** is larger or smaller for a traditional fuel-combustion rocket.

....

....

....

.... [2]

Full Scale Design

SpinLaunch's design for the eventual full-scale accelerator will involve a Kevlar-carbon-fiber rotating arm within the circular vacuum chamber, as shown in Fig. 8.2. The launch projectile is expected to have a mass of 200 kg and will be flung above the stratosphere. Thereafter, a rocket will fire to provide the final velocity boost necessary for positioning into LEO. At those altitudes, there is hardly any atmosphere and therefore there is minimal drag on the launch projectile. Hence, a couple of minutes of fuel combustion will be sufficient to boost the launch projectile's speed to sufficiently high orbital speeds.

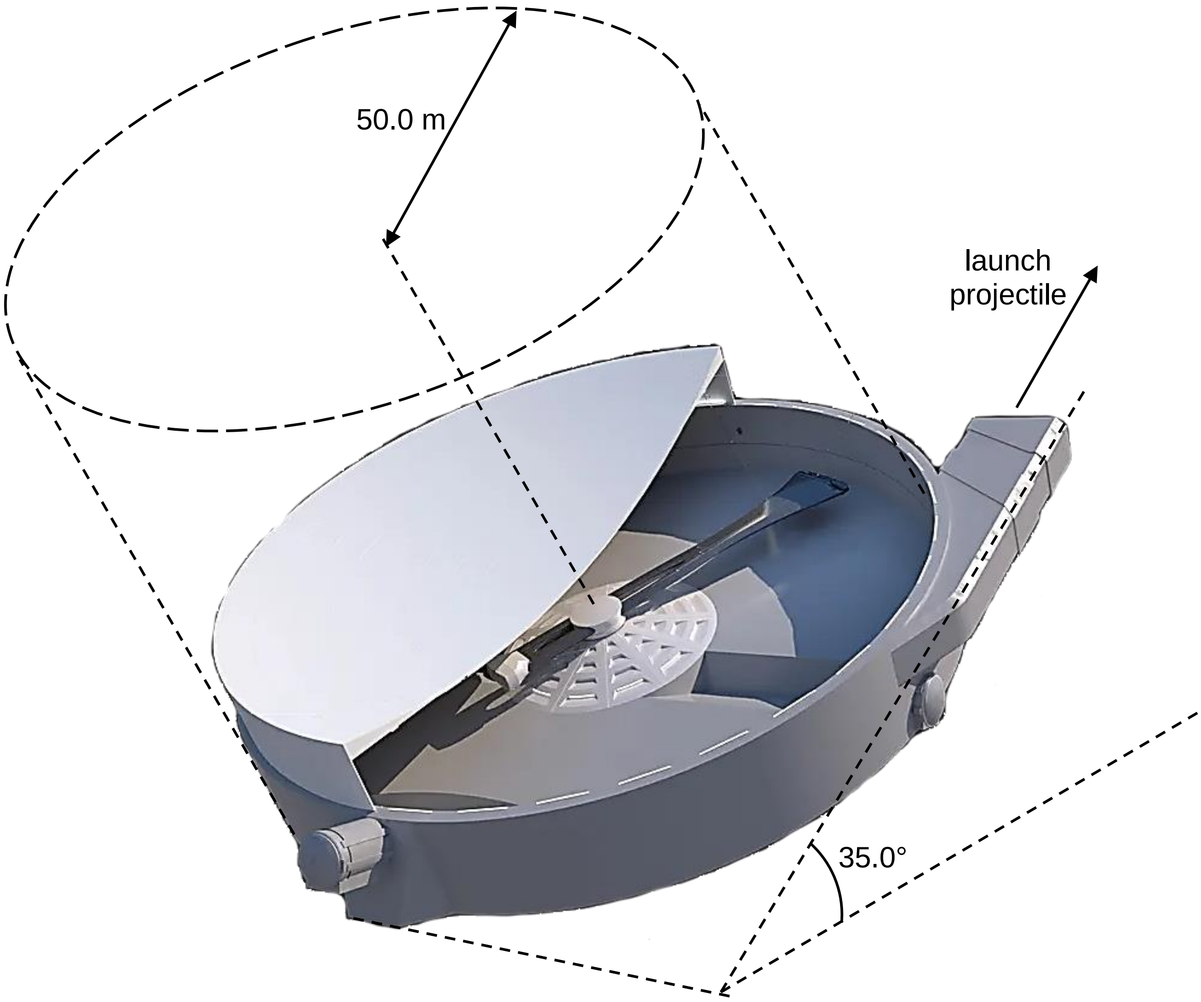

Fig. 8.2

The full-scale accelerator will feature a vacuum chamber that spins the launch projectile around a radius of 50.0 m. It will gradually ramp up the rotational speed to 450 revolutions per minute before launching the projectile at speed of 8000 km per hour, directed 35.0° above the horizontal.

Once the launch projectile reaches an altitude of 61 000 m, a traditional fuel-combustion rocket ignites in order to accelerate to the desired speed of 28 200 km per hour.

(c) (i) Determine the angular speed of Earth's rotation about its own axis.

angular speed = ………………………………… rad s^{-1} [1]

(ii) To allow for a more efficient launch, the accelerator should be sited somewhere along the equator of the Earth.

State and explain the direction that the launch projectile be directed towards, in order to achieve further energy efficiency.

....

....

.... [2]

(d) (i) Show that the linear speed of the launch projectile in the full-scale design just before launch is 2360 m s^{-1}.

[1]

(ii) Find the ratio of $\dfrac{\text{kinetic energy of launch projectile at launch}}{\text{kinetic energy of launch projectile just before launch}}$.

ratio = ………………………………… [1]

(iii) Using energy considerations, explain why the interior of the accelerator has to be in vacuum.

....

.... [1]

(e) **(i)** The effective power supplied in spinning up the launch projectile is 100 kW.

Determine the amount of time (in minutes) required to spin the launch projectile up to launch speed from rest.

time = ………………………………… min [2]

(ii) Humans can briefly survive being subject to accelerations of up to 9 *g*'s.

Suggest if this method of launch is suitable for sending humans up to satellite bodies such as the International Space Station.

....

.... [2]

Low Earth Orbit (LEO)

Low Earth Orbit (LEO) is an orbit around Earth with a period of 128 minutes or less. This is a region of Earth's atmosphere that is below an altitude of 2,000 km, about one-third of Earth's radius. Fig. 8.3 shows the variation of gravitational potential ϕ with distance from Earth's surface. The Earth has a radius of 6400 km.

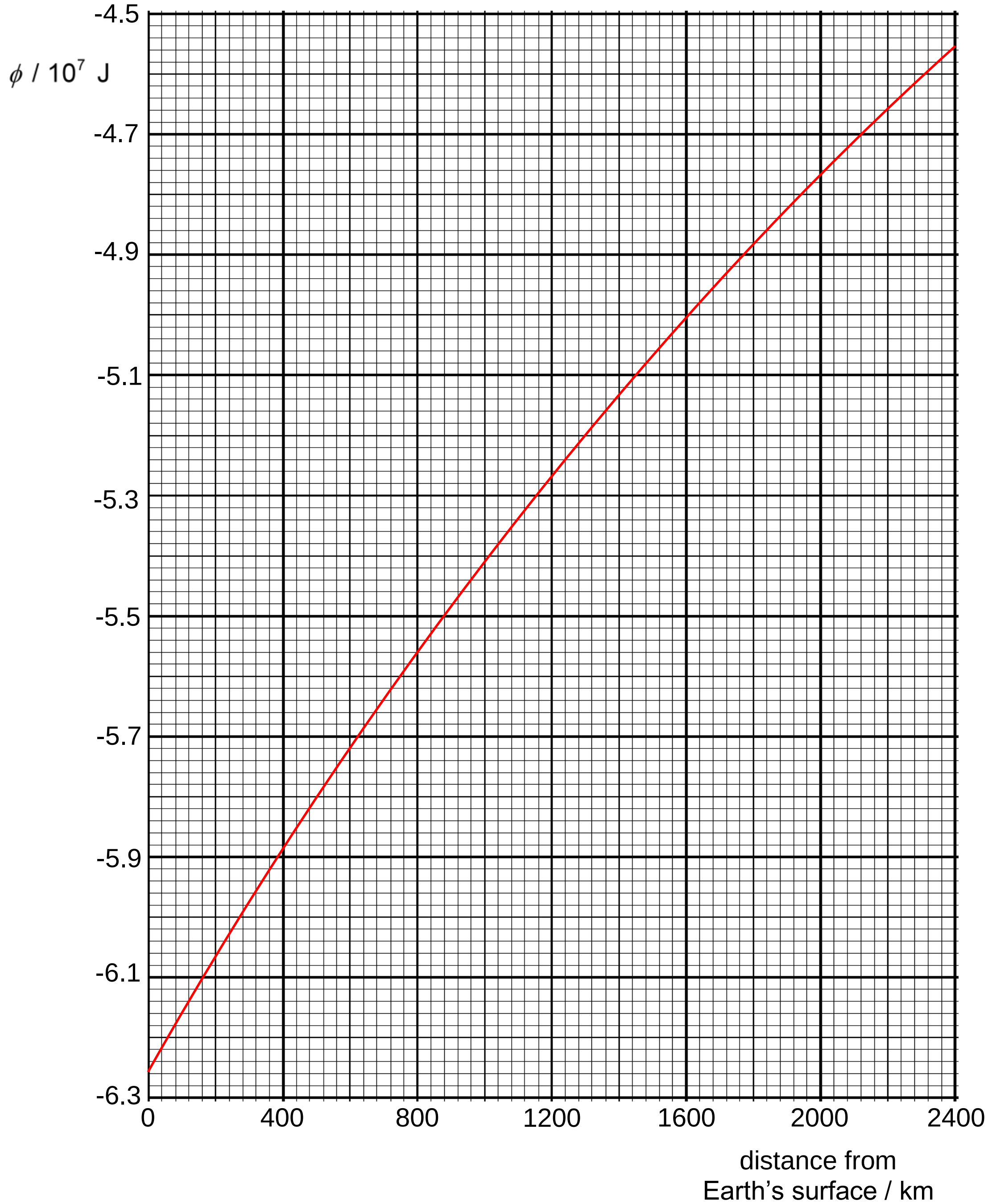

Fig. 8.3

(f) **(i)** State what is meant by *gravitational potential*.

....

....

.... [1]

(ii) Use Fig. 8.3 to determine the gravitational field strength g at an altitude of 2000 km.

Show your working clearly.

g = ………………………………… N kg^{-1} [2]

(iii) Your answer to part **(f)(ii)** is clearly non-zero.

Explain why astronauts onboard the International Space Station which orbit the Earth in a LEO, experience weightlessness despite being subject to Earth's gravitational field.

....

....

.... [2]

(iv) A launch projectile of mass 200 kg is launched via SpinLaunch and successfully docks with the International Space Station, which orbits the Earth at an altitude of 400 km.

Use Fig. 8.3 to find the work done against gravity in doing so.

work done = ………………………………… J [2]

[Total: 25]