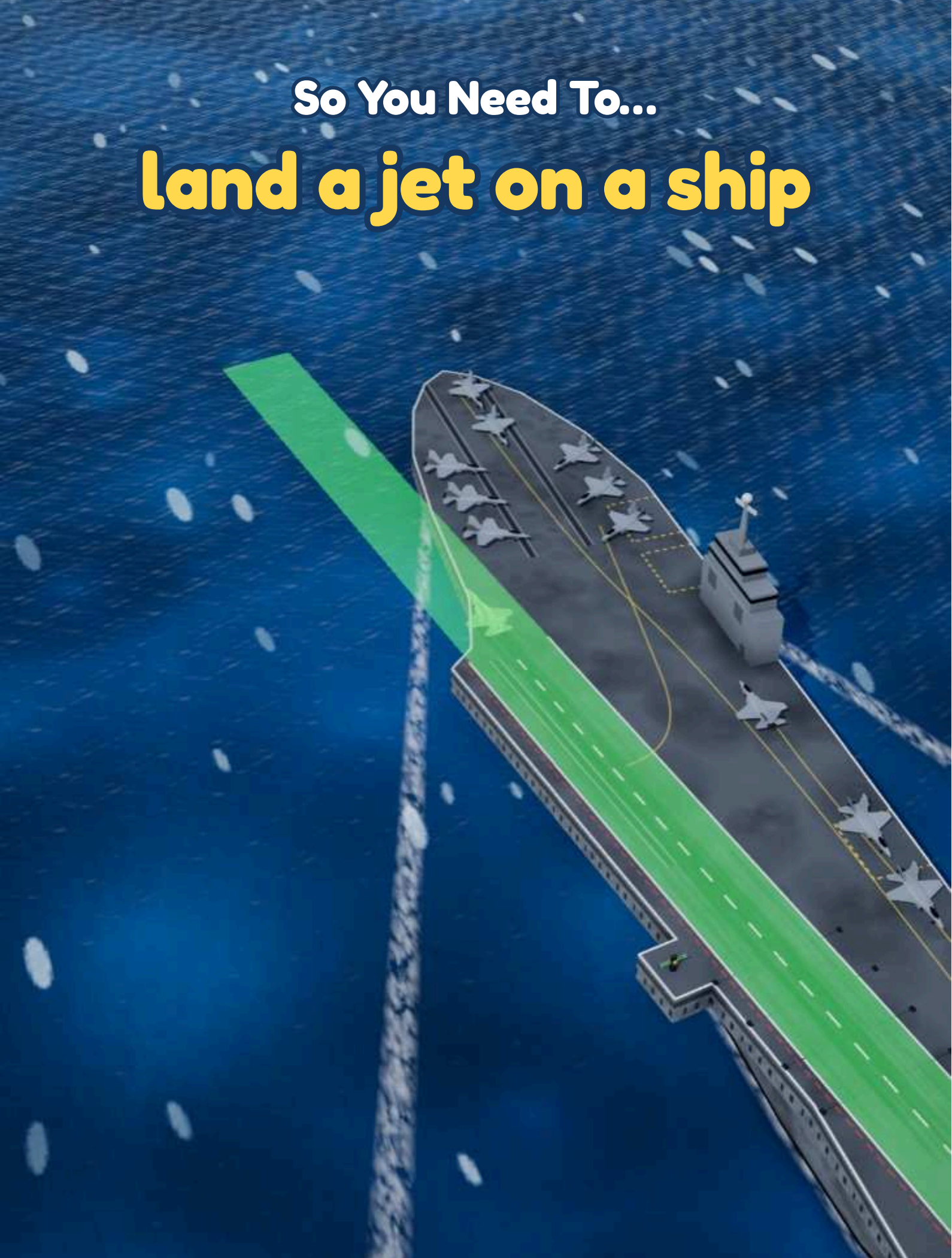


So You Need To...
land a jet on a ship



The science of how to land a jet on a ship

On an aircraft carrier, a fighter jet has to stop in about a hundred metres instead of the kilometres it would use on land. These pages explain the science that makes it possible: the energy that has to be stopped, the arresting gear that turns it into heat, why pilots go to full power as they land, the angled deck, the lens that guides them down, and landing on a deck that moves.

Inside

1. The energy you have to stop	3
2. The arresting gear: turning motion into heat	4
3. Full power, and the angled deck	5
4. The meatball: a light that shows your height	6
5. Landing on a moving runway	7
6. By the numbers	8
7. Words to know	9
8. Think about it, and try it	10
9. Sources	11

For students and teachers. Every fact was checked against the sources at the back.

The energy you have to stop

A landing fighter carries as much energy of motion as about forty cars on a motorway.

20 t jet, 200 km/h



31 MJ

car, 100 km/h



0.6 MJ

Kinetic energy, in millions of joules (MJ). The jet's speed is measured against the deck.

Anything moving has kinetic energy, and to stop it, all of that energy has to go somewhere. Brakes on a car turn it into heat in the brake discs. A jet landing on a runway does the same with its wheel brakes, but it needs a kilometre or more to do it.

Kinetic energy grows with the square of speed, so doubling the speed matters more than doubling the weight. A jet twice as fast carries four times the energy, and needs four times the distance to stop with the same force.

On a carrier there's only about a hundred metres. So the jet doesn't rely on its brakes at all. A hook on the jet catches a wire, and machinery below the deck takes the energy instead.

Rough numbers

Kinetic energy = $\frac{1}{2} \times \text{mass} \times \text{speed}^2$. A fighter of about 20 tonnes, closing on the deck at 200 km/h (55.6 m/s): $\frac{1}{2} \times 20,000 \times 55.6^2 \approx 31$ million joules.

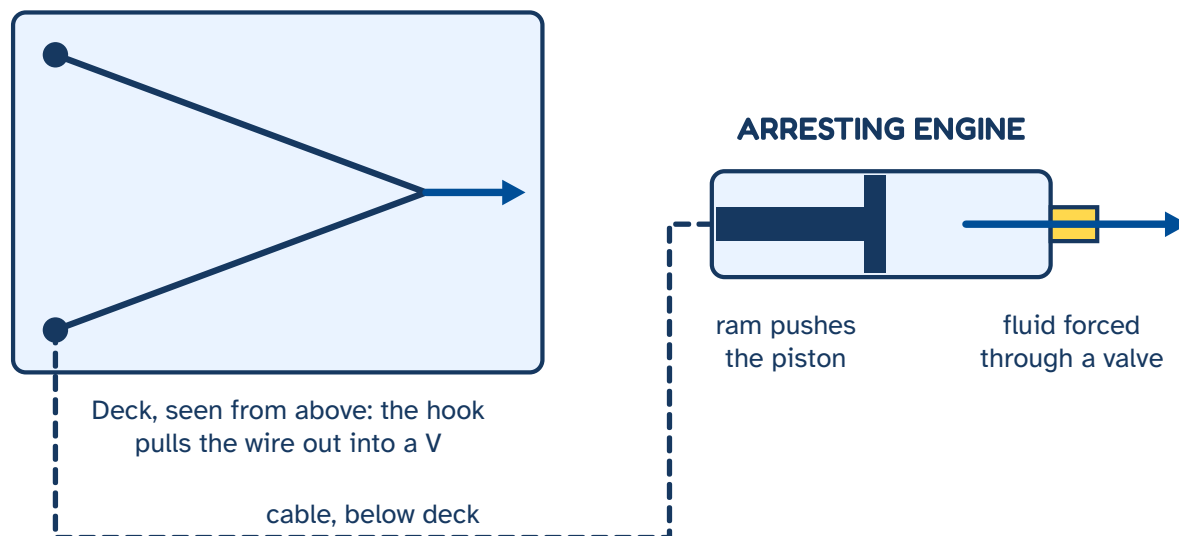
Stopping in about 2 seconds at a steady rate: deceleration = $55.6 \div 2 \approx 28 \text{ m/s}^2$, close to 3 g. The jet would roll about 56 m (average speed $\times$ time = 27.8×2).

The force needed is mass $\times$ deceleration = $20,000 \times 28 \approx 560,000$ newtons. This is a simplification: real landings take more like 2 to 3 seconds and roll out up to about 100 m, partly because the engines are still pushing at full power.

Key idea To stop something, you have to get rid of its kinetic energy. On a carrier, that job moves from the jet's brakes to the ship.

The arresting gear: turning motion into heat

The wire gives way on purpose, under a carefully controlled pull.



Several steel wires, called cross-deck pendants, are stretched across the landing area several centimetres above the deck. A pilot aims for one of them. The hook on the back of the jet catches a wire and pulls it out into a V.

Each end of the wire joins a longer cable that runs below deck to an arresting engine. In the arresting gear used on most carriers, the cable is wound back and forth around sets of pulleys. As the jet pulls the cable out, the pulleys drive a ram into a cylinder full of hydraulic fluid.

The ram forces the fluid through a control valve. Pushing a liquid through a narrow gap takes a lot of force, and that work turns into heat in the fluid. Before each landing, the crew sets the engine for the type of aircraft and its weight, so a light jet and a heavy one both stop smoothly.

The newest US carriers use a different system that slows the cable with water turbines and an electric motor, controlled by computer.

Work and heat

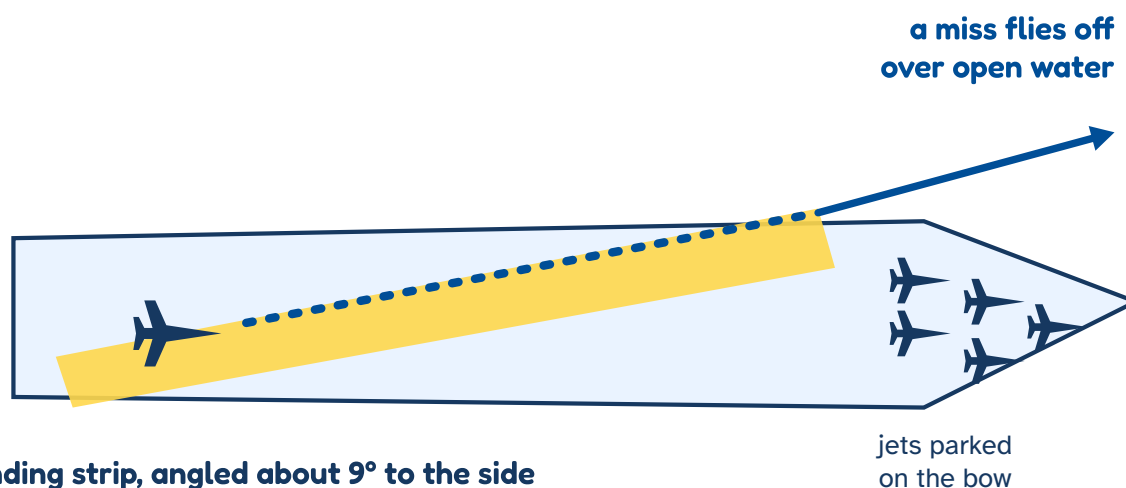
Work done = force × distance. Nearly all of the 31 million joules from the last page, plus the extra push from the engines at full power, ends up as heat in the arresting engine.

Heating water takes 4,186 joules per kilogram per degree. So 31 MJ could heat about 90 litres of water from 20 °C to boiling ($31,000,000 \div (4,186 \times 80) \approx 93$ kg).

Key idea The arresting gear works like a syringe pushed by the jet. Forcing the fluid through a valve turns the jet's motion into heat.

Full power, and the angled deck

A pilot landing on a carrier pushes the throttles forward at the moment of landing.



Seen from above. A jet that misses the wires keeps going straight along the angled strip and flies off over the water, clear of the parked jets.

If the hook misses every wire, the jet has to take off again straight away. This is called a bolter. But a jet engine can't jump from low power to full power instantly. Its spinning parts need time to speed up, and then the jet needs time to gain speed.

So the pilot goes to full power the moment the wheels touch. If the hook catches a wire, the arresting gear is strong enough to stop the jet anyway. If it misses, the thrust is already there.

Early carriers had a straight deck, so a jet that missed could crash into aircraft parked at the front. In 1951, British naval officer Dennis Cambell and engineer Lewis Boddington came up with angling the landing strip off to one side. The first true angled deck went on the US carrier *Antietam* in 1952. Now a jet that misses flies off the end over open water, and the bow is free for parking and launching aircraft.

Why there's no time to wait

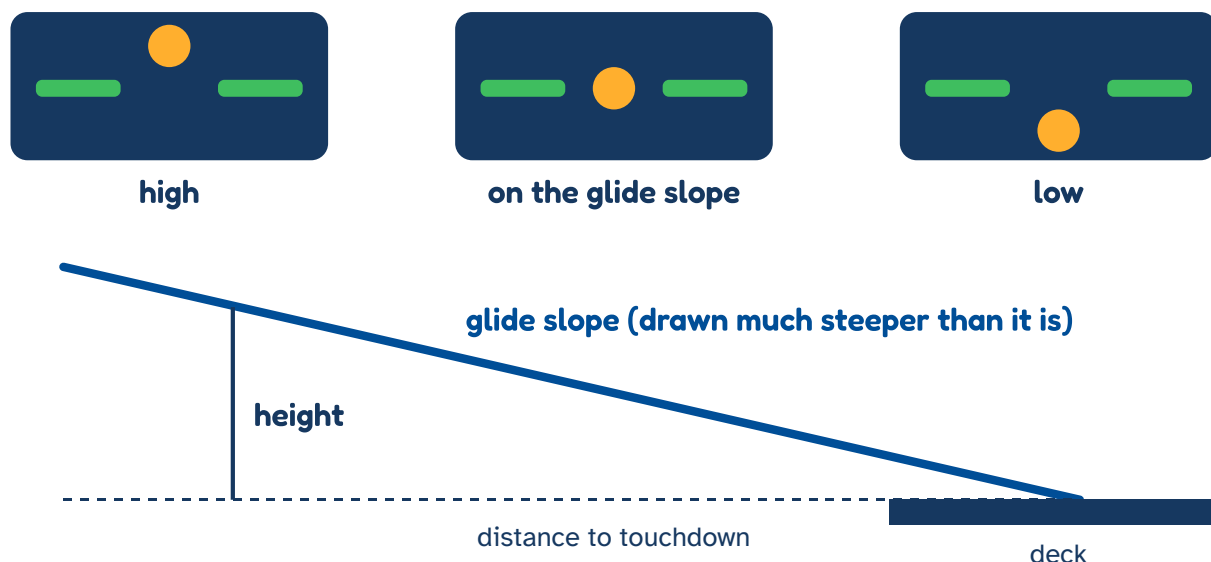
Suppose 150 m of deck is left ahead of the jet when the hook misses, and it's moving at 55 m/s relative to the deck.

Time to the end = distance ÷ speed = $150 \div 55 \approx 2.7$ seconds. An engine needs a moment to reach full power, and the jet then needs time to speed up, so the power has to be on already.

Key idea Pilots plan for a miss on every landing. Full power on touchdown makes a miss safe instead of a crash.

The meatball: a light that shows your height

A lens beside the landing strip tells the pilot, at a glance, whether the approach is too high or too low.



Top: what the pilot sees in the lens. Bottom: the glide slope, the straight line the jet follows down to the deck.

Pilots follow a glide slope: a straight path down to the deck at a shallow angle, usually about 3.5° . Judging that by eye, on a small moving deck, is very hard, so the ship shows it with light.

The landing lens is a column of lights behind Fresnel lenses. Each one sends its light out in a narrow band of angles, so from any height the pilot sees only one of them lit: the 'meatball'. Beside it are fixed rows of green datum lights.

Ball level with the green lights: on the glide slope. Above them: too high. Below: too low. Very low, the ball turns red. The lens is stabilised against the ship's pitching, rolling and heaving.

Carrier pilots don't flatten out before touchdown as they would on a runway. They keep the same path so the hook lands in the right place, and the landing gear takes the bump.

Trigonometry on the approach

Height = distance $\times$ $\tan(\text{angle})$. At 1 km from touchdown on a 3.5° slope: $1,000 \times \tan 3.5^\circ \approx 1,000 \times 0.061 \approx 61$ m.

Sinking speed = closing speed $\times$ $\sin(\text{angle})$. At 200 km/h (55.6 m/s): $55.6 \times 0.061 \approx 3.4$ m/s, about the speed you'd hit the ground after jumping off a 0.6 m wall (height = $\text{speed}^2 \div 2g$).

Key idea The lens turns a hard judgement, the angle of your path, into an easy one: is the light above, level with, or below the green row?

Landing on a moving runway

The ship helps by driving into the wind.

the jet's speed through the air: 250 km/h



air flowing over the deck: 50 km/h



what the wire has to stop: 200 km/h



The ship steams into the wind, so air flows over the deck from bow to stern. The jet needs speed through the air to fly, but the wire only has to stop its speed relative to the deck.

A wing makes lift from its speed through the air, not its speed over the ground or the sea. A fighter on approach needs about 250 km/h of airspeed to keep flying.

When a carrier is launching or landing aircraft, it turns into the wind and speeds up, so air flows down the deck. If 50 km/h of air flows over the deck, a jet with 250 km/h of airspeed only closes on the deck at about 200 km/h. That's less for the arresting gear to stop.

The deck also moves up and down and rolls with the waves. This is one reason the glide slope is shown by a stabilised lens, and why landing signal officers on the deck watch every approach and can wave a pilot off.

Relative speed and energy

Closing speed = airspeed – wind over the deck = $250 - 50 = 200$ km/h.

With no wind over the deck, the jet would close at 250 km/h. Energy goes with speed squared, so it would carry $(250 \div 200)^2 \approx 1.56$ times as much energy, over half as much again.

Key idea What matters for flying is speed through the air. What matters for stopping is speed relative to the deck. Wind over the deck helps both.

By the numbers

A large US aircraft carrier (Nimitz class)

Length	about 333 m
Flight deck width	about 77 m
Angle of the landing strip	about 9°
Arresting wires	3 or 4, roughly 12 to 15 m apart
Top speed	more than 30 knots (56 km/h)

An arrested landing

Fighter landing weight	up to about 20 tonnes
Approach airspeed	about 250 km/h
Glide slope	about 3.5°
Time to stop	about 2 to 3 seconds
Distance the wire pulls out	up to about 100 m

Handy numbers

1 knot	1.852 km/h
1 g	9.81 m/s ²
Heating water	4,186 J per kg per °C

Figures vary between ships, aircraft and landings.

Words to know

Kinetic energy	Energy of motion: $\frac{1}{2} \times \text{mass} \times \text{speed}^2$.
Deceleration	How quickly something slows down, in m/s^2 or in g.
Tailhook	A strong hook under the back of a carrier jet that catches an arresting wire.
Cross-deck pendant	One of the steel wires stretched across the landing area.
Arresting engine	The machinery below deck that pulls back on the wire and absorbs the jet's energy.
Trap	Pilots' word for a landing where the hook catches a wire.
Bolter	A landing where the hook misses every wire, so the jet takes off again.
Wave-off	An order to abort the approach and go around before touching down.
Angled deck	A landing strip set at an angle to the ship, so a missed landing clears the bow.
Glide slope	The straight, shallow path a landing aircraft follows down to the deck.
Fresnel lens	A flat lens made of thin rings or strips, used to aim light in a narrow beam.
Meatball	The amber light in the landing lens that shows whether the jet is high or low.
Datum lights	The fixed green lights beside the meatball, marking the correct glide slope.
Landing signal officer	A pilot on deck who watches each approach and talks to the landing pilots.
Wind over deck	The speed of the air flowing along the flight deck, from the ship's speed plus the wind.

Think about it

1. Kinetic energy goes with speed squared. How many times more energy does a jet carry at 300 km/h than at 200 km/h?
2. If the arresting gear pulled with the same force, how much farther would that faster jet roll before stopping?
3. On a 3.5° glide slope, how high is the jet 2 km from touchdown? ($\tan 3.5^\circ \approx 0.061$)
4. Why does the ship turn into the wind before aircraft land?
5. A runway landing usually ends with a gentle flare. Why do carrier pilots fly straight into the deck instead?
6. Why would a straight deck be more dangerous than an angled one?

Answers. 1: 2.25 times ($(300 \div 200)^2$). 2: 2.25 times as far. 3: about 122 m. The others are for discussion; the pages before have the clues.

Try it: an arresting wire for a toy car

You need: a toy car, a bent paper clip, sticky tape, a thick rubber band, two heavy books, a long board or a large book for a ramp, a ruler.

1. Tape the bent paper clip under the back of the car so it hangs down like a hook, almost touching the floor.
2. Stand the two books on the floor a little wider apart than the car, and stretch the rubber band between them, low enough for the hook to catch. Keep your face and fingers clear of the band: when it springs back, it flings the car backward.
3. Make a ramp, roll the car down from a marked height (measured straight up from the floor) and let it catch the band. Measure how far past the books the car goes before it stops.
4. Roll it again from twice the height, and measure again.

What's happening: Rolling down the ramp turns height into kinetic energy, so twice the height gives twice the energy. The band stretches to soak up that energy. With more energy it stretches farther, though not twice as far: a stretchy band soaks up energy faster the more it stretches. A real arresting engine does the same job, but it turns the energy into heat instead of storing it in a stretch, so the jet doesn't bounce back.

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Watch the video: youtube.com/shorts/aE1hRZieCng

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