

Airplane Flying Handbook (FAA-H-8083-3C)

Chapter 4: Energy Management: Mastering Altitude and Airspeed Control

Introduction

This chapter is all about managing the airplane's altitude and airspeed using an energy-centered approach. Energy management can be defined as the process of planning, monitoring, and controlling altitude and airspeed targets in relation to the airplane's energy state in order to:

1. Attain and maintain desired vertical flightpath-airspeed profiles.
2. Detect, correct, and prevent unintentional altitude-airspeed deviations from the desired energy state.
3. Prevent irreversible deceleration and/or sink rate that results in a crash.

Importance of Energy Management

Learning to manage the airplane's energy in the form of altitude and airspeed is critical for all new pilots. Energy management is essential for effectively achieving and maintaining desired vertical flight path and airspeed profiles, (e.g., constant airspeed climb) and for transitioning from one profile to another during flight, (e.g., leveling off from a descent).

Proper energy management is also critical to flight safety. Mistakes in managing the airplane's energy state can be deadly. Mismanagement of mechanical energy (altitude and/or airspeed) is a contributing factor to the three most common types of fatal accidents in aviation: loss of control in-flight (LOC-I), controlled flight into terrain (CFIT), and approach-and-landing accidents. Thus, pilots need to have:

1. An accurate mental model of the airplane as an energy system.
2. The competency to effectively coordinate control inputs to achieve and maintain altitude and airspeed targets.
3. The ability to identify, assess, and mitigate the risks associated with mismanagement of energy.

Viewing the Airplane as an Energy System

The total mechanical energy of an airplane in flight is the sum of its potential energy from altitude and kinetic energy from airspeed. The potential energy is expressed as mgh , and the kinetic energy as $\frac{1}{2} mV^2$. Thus, the airplane's total mechanical energy can be stated as:

$$mgh + \frac{1}{2} mV^2$$

Where,

m = mass
 g = gravitational constant
 h = height (altitude)
 V = velocity (airspeed)

A flying airplane is an “open” energy system, which means that the airplane can gain energy from some source (e.g., the fuel tanks) and lose energy to the environment (e.g., the surrounding air). It also means that energy can be added to or removed from the airplane’s total mechanical energy stored as altitude and airspeed.

A Frame of Reference for Managing Energy State

At any given time, the energy state of the airplane is determined by the total amount and distribution of energy stored as altitude and airspeed. Note that the pilot’s frame of reference for managing the airplane’s energy state is airplane-centric—being a function of indicated altitude and indicated airspeed, and not height above the ground or groundspeed.

The indicated altitude displayed in the altimeter and its associated potential energy are based on the height of the airplane above a fixed reference point (mean sea level or MSL), not on the height above ground level (AGL), which changes with variations in terrain elevation. Likewise, the indicated airspeed displayed in the airspeed indicator and its associated kinetic energy are based on the speed of the airplane relative to the air, not on the speed relative to the ground below, which varies with changes in wind speed and direction.

Note that changes in indicated altitude and airspeed are attained through forces resulting from the pilot's direct manipulation of the controls. These direct control inputs determine the airplane's ability to climb/descend or accelerate/decelerate. In contrast, changes in AGL-altitude and groundspeed are affected by "external" factors, such as varying terrain elevation and wind, which the pilot cannot alter. Of course, the pilot should manipulate the airplane's energy in such way as to minimize any risks associated with terrain or wind. For example, the pilot may seek to manipulate energy state so as to maximize the airplane's energy gains and minimize energy losses when faced with rising terrain. A safer heading may also be an option.

Once airborne, the airplane gains energy from the force of engine thrust (T) and it loses energy from aerodynamic drag (D). The difference between energy in and out ($T - D$) is the net change, which determines whether total mechanical energy—stored as altitude and airspeed—increases, decreases, or remains the same.

When thrust exceeds drag ($T - D > 0$), the airplane's total mechanical energy increases. The pilot can store the surplus energy as increased altitude or airspeed. For example, if the pilot decides to put all the surplus energy into altitude, the airplane can climb at a constant airspeed. [Figure 4-1A] If the pilot opts to place all the surplus energy into airspeed, the airplane can accelerate while maintaining altitude. [Figure 4-1B]

When drag exceeds thrust, ($T - D < 0$), the airplane's total mechanical energy decreases. The pilot has two sources of stored energy to tap into. For example, the pilot may choose to let the airplane descend at a constant airspeed [Figure 4-1C] or slow down while maintaining altitude [Figure 4-1D] as stored energy is withdrawn to deal with the energy deficit. When energy gained equals that lost ($T - D = 0$), all thrust is spent on drag. In this case, the total amount of mechanical energy and its distribution over altitude and airspeed does not change. Both remain constant as the airplane maintains a constant altitude and airspeed. [Figure 4-1E]

Energy can also be exchanged between altitude and airspeed. For example, when a pilot trades airspeed for altitude, as altitude increases, airspeed decreases. In other words, when energy is exchanged, altitude and airspeed always change in opposite directions (absent any other energy or control inputs). As one goes up, the other one comes down. Also note that even though the distribution of energy over altitude and airspeed may change dramatically during energy exchange, the total amount of mechanical energy can remain the same at the end of the exchange maneuver [Figure 4-1F], as long as thrust is adjusted to match drag as the latter varies with changes in airspeed.

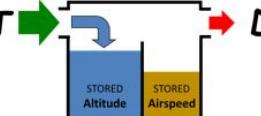
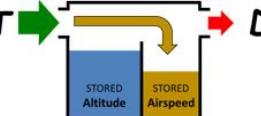
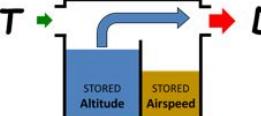
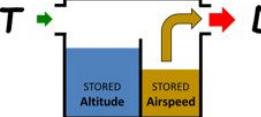
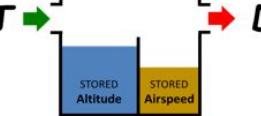
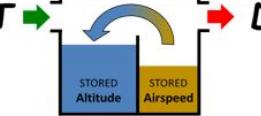
Energy Transaction Examples		Net Energy Change ($T - D$)	Change in Stored Energy		Resulting Aircraft Condition
			Altitude	Airspeed	
A		> 0	Increase	No change	Climb at constant airspeed
B		> 0	No change	Increase	Acceleration at constant altitude
C		< 0	Decrease	No change	Descent at constant airspeed
D		< 0	No change	Decrease	Deceleration at constant altitude
E		= 0	No change	No change	Constant altitude and airspeed
F		= 0	Increase	Decrease	Climb and deceleration

Figure 4-1 A-F. Examples of typical energy transactions.

Managing Energy is a Balancing Act

Since the airplane gains energy from engine thrust (T) and loses energy through aerodynamic drag (D), energy flows continuously into and out of the airplane while in flight. Usually measured as *Specific Excess Power* (P_S), or rate of energy change, the net energy flow is a direct function of the difference between thrust and drag.

$$P_S = (T - D)V/W$$

Where,

T = Thrust

D = Drag

V = velocity (airspeed)

W = aircraft weight

More importantly, there is a fundamental relationship between changes in the airplane's total energy resulting from this net energy flow on one hand, and changes in the energy stored as altitude and airspeed on the other. This fundamental relationship can be summarized through the airplane's energy balance equation. [Figure 4-2]

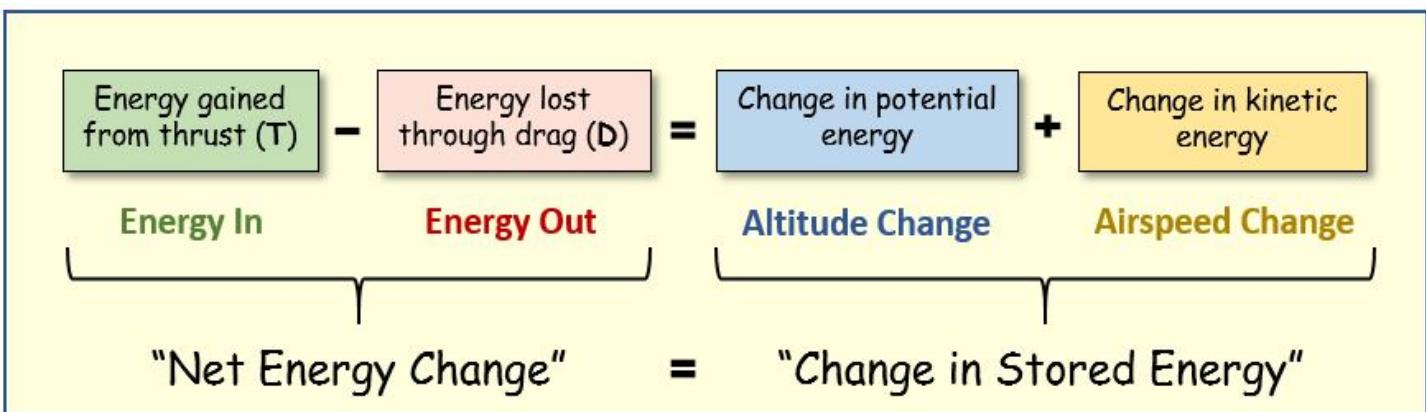


Figure 4-2. The energy balance equation.

The left side of the energy balance equation represents the airplane's net energy flow, while the right side reflects matching changes to the energy storage. Thus, changes to the airplane's total energy affect the left side of the equation, while the right side shows possible changes in energy distribution between altitude and airspeed.

Note that a change in total energy resulting from the difference between thrust and drag (left side) always matches the change in total energy redistributed over altitude and airspeed (right side). Although rate of energy change, expressed as specific excess power (P_S), varies during flight—becoming positive, negative, or zero—both sides of the equation are inexorably balanced regardless of whether the airplane is accelerating, decelerating, climbing, descending, or maintaining constant altitude and airspeed. (*Note: This simplified balance equation does not account for long-term changes in total mechanical energy caused by the reduction in aircraft weight as fuel is gradually burned in flight. Although the effect of weight loss on total energy becomes critical when solving long-term aircraft performance problems such as range and endurance, it is negligible when considering short-term flight control problems.*)

Of course, the pilot controls the change in total energy on the left side of the equation, as well as the distribution of any changes in energy over altitude and airspeed on the right side. How the pilot coordinates the throttle and elevator to achieve and maintain desired altitude and airspeed targets as well as avoid energy "crises" is at the core of energy management and is elaborated in the rest of the chapter.

Role of the Controls to Manage Energy State

An energy-centered approach clarifies the roles of the engine and flight controls beyond the simple "pitch for airspeed and power for altitude" by modeling how throttle and elevator inputs affect the airplane's total mechanical energy. From an energy perspective, the problem of controlling vertical flight path and airspeed becomes one of handling the airplane's energy state—the total amount of energy and its distribution over altitude and speed. Thus, rather than asking what controls altitude and what controls airspeed, a pilot can now ask what controls total energy and what controls its distribution over altitude and airspeed.

Primary Energy Role of the Throttle and Elevator

The throttle, by increasing or decreasing engine thrust against drag, regulates changes in total mechanical energy. As illustrated above, changing total energy is a function of both thrust and drag ($T - D$). However, drag mainly varies long-term due to airspeed changes, or by using high lift/drag devices which can only increase drag. Therefore, changes in total energy are normally initiated by changing thrust, not drag. When the throttle setting makes thrust greater than drag, an increase of total mechanical energy is the result. When the throttle setting makes thrust less than drag, a decrease of total mechanical energy is the result. Once the desired path-speed profile is established, the throttle sets engine thrust to match the total energy demanded by vertical flight path and airspeed combined. The throttle then is the *total energy controller*.

On the other hand, the elevator is an energy exchanger and distribution device whose primary job is to allocate changes in total energy between vertical flight path and airspeed by adjusting pitch attitude. Here, once the chosen path-speed profile is achieved, the elevator sets the appropriate pitch attitude to maintain the demanded distribution of total energy over vertical flight path and airspeed. Thus, the elevator is the *energy distribution controller*.

The throttle and elevator then are really energy state controls—neither one controls altitude nor airspeed independently since these two variables are inherently coupled through the airplane's total mechanical energy. Instead, to control altitude and airspeed effectively, the pilot coordinates the use of both devices to manage the airplane's energy state.

The reservoir analogy [Figure 4-3] illustrates the energy-based role of the throttle and the elevator. In this analogy, the throttle controls the “valve” regulating the net total energy flow while the elevator controls the “valve” regulating the distribution of energy into and out of the altitude and airspeed “reservoirs.” Referring back to the energy balance equation [Figure 4-2], it becomes clear then that the throttle controls the left side of the equation (total energy) and the elevator controls the right side (energy distribution).

As illustrated in Figure 4-3, when the throttle increases thrust above drag ($T - D > 0$) the airplane gains total energy, and when the throttle reduces thrust below drag ($T - D < 0$) the airplane loses total energy. The elevator then distributes this increase or decrease in total energy between altitude and airspeed. Finally, when the throttle adjusts thrust equal to drag ($T - D = 0$), there is no change in total energy, but the energy stored as altitude and airspeed can be exchanged between the two reservoirs using the elevator, while total energy, at least short-term, remains constant.

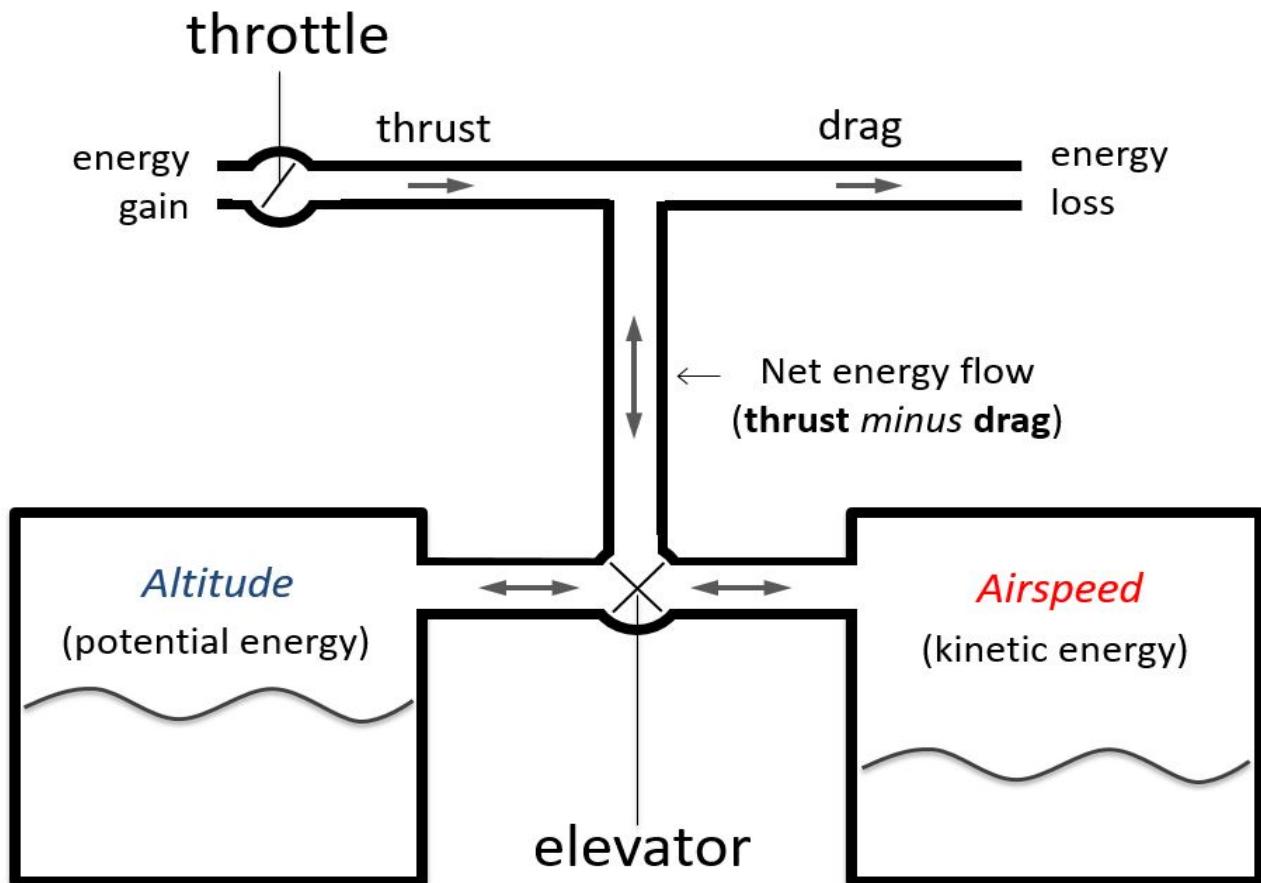


Figure 4-3. The reservoir analogy illustrating the primary role of the throttle and elevator to manage the airplane's energy state.

Additional Role for the Elevator

On the front side of the power required curve, where the airplane cruises at high speed (1 in *Figure 4-4*) and a low angle of attack (AOA) with little or no excess power or excess thrust (A in *Figure 4-4*), pulling back on the yoke or stick (elevator up) will result in a brief energy exchange climb, causing the airplane to slow down from 1 to 2 toward the center of the power curve [*Figure 4-4*]. This decrease in airspeed results in a reduction in total drag; hence available energy in the form of positive excess power ($P_S > 0$) where thrust exceeds drag ($T - D > 0$). With this excess power (B in *Figure 4-4*) the airplane can now climb at a constant airspeed or turn in level flight while maintaining a constant airspeed at an increased load factor.

On the backside of the power required curve, where the airplane flies at low speed (3 in *Figure 4-4*) and high AOA with little or no excess power or excess thrust (C in *Figure 4-4*), pushing forward on the yoke or stick (elevator down) will result in a brief energy exchange descent, causing the airplane to accelerate from 3 to 2 toward the center of the power curve [*Figure 4-4*]. This increase in airspeed results in a reduction in total drag; hence available energy in the form of positive excess power ($P_S > 0$) where thrust exceeds drag ($T - D > 0$). With this excess power (B in *Figure 4-4*) the airplane can now climb at a constant airspeed or turn in level flight while maintaining a constant airspeed at an increased load factor. This role of the elevator is critical to prevent unintentional, excessive deceleration or sink rate as illustrated later in the chapter (refer to *Preventing Irreversible Deceleration and/or Sink Rate* section).

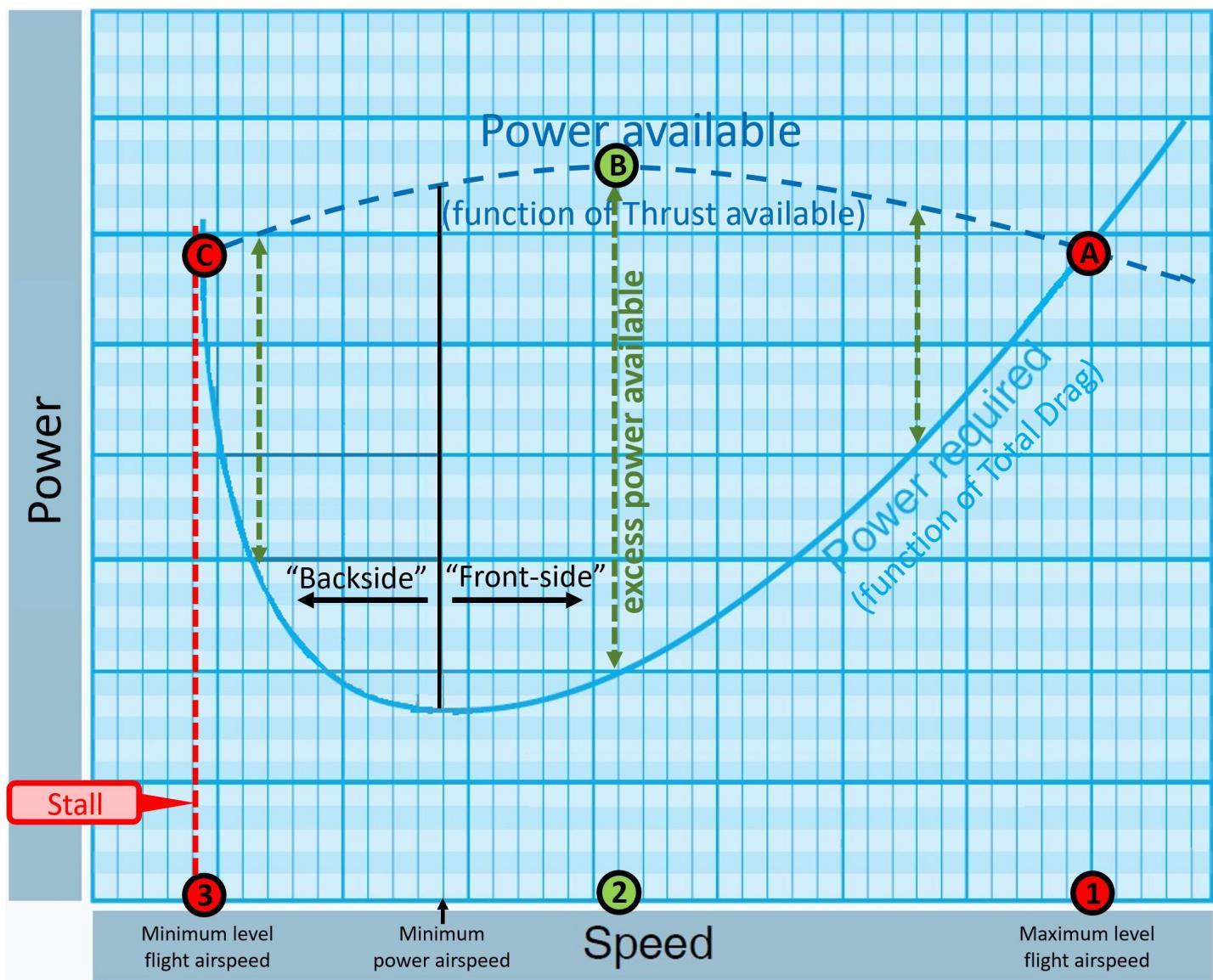


Figure 4-4. The front side and backside of the power required curve, the power available curve, and the relative excess power available (power available - power required) at different speeds.

While the elevator can assist the throttle in changing $T - D$ and P_s through changes in airspeed via energy exchange as described above, occasionally the elevator can directly increase the “D” in $T - D$ at any given speed during a level turn, thus helping the airplane rapidly bleed off total energy. As the airplane banks, load factor (lift/weight) increases because total lift has to increase to pull the airplane into the turn while simultaneously balancing its weight. This is accomplished by pulling back on the yoke (or stick) to increase AOA which results in increased induced drag and power required at any given speed. This action will quickly slow the airplane down and decrease total energy more rapidly than by just reducing the throttle setting to idle. This additional role of the elevator is shown on the power curve. [Figure 4-5]

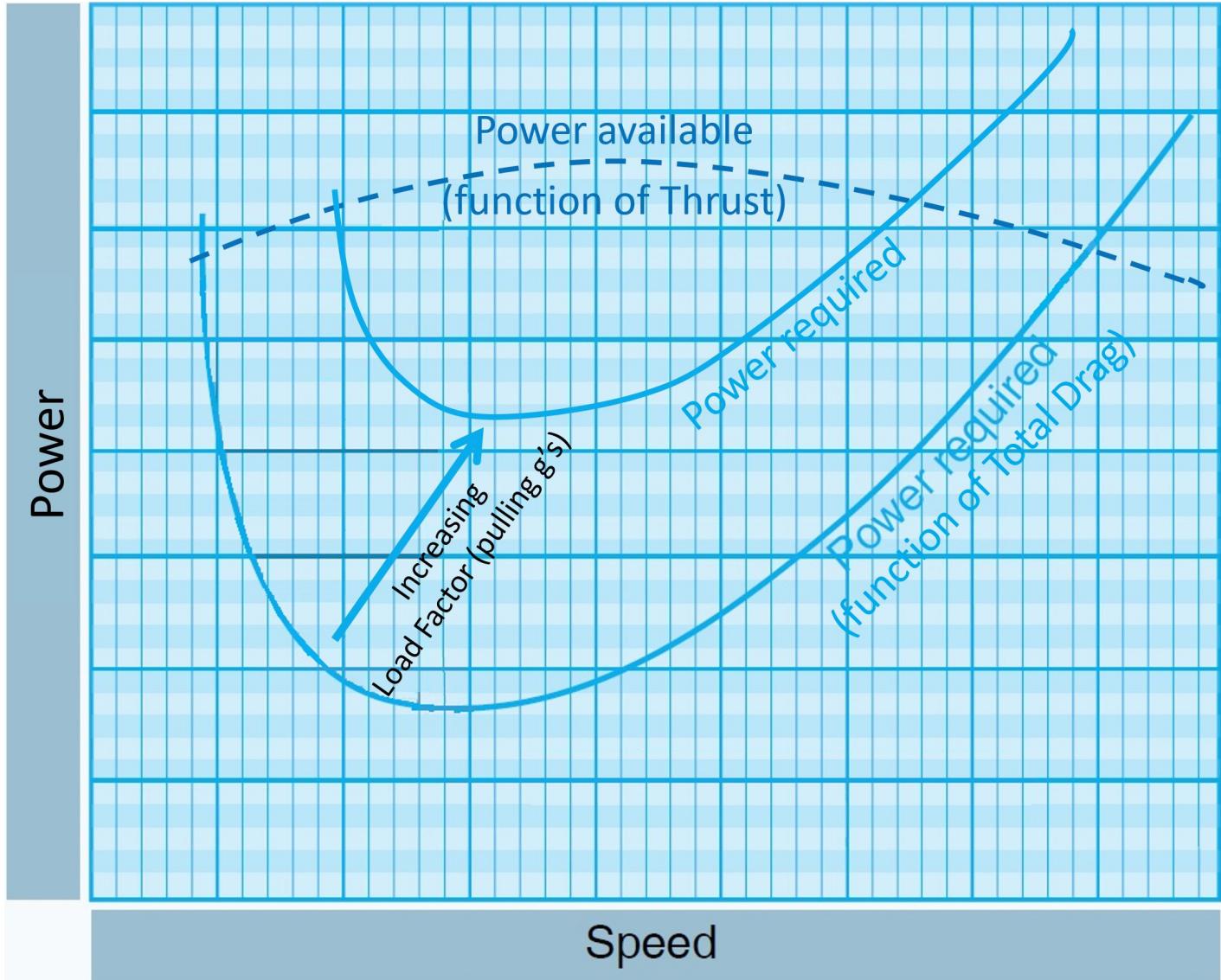


Figure 4-5. The effect of increased load factor on total drag and power required at different airspeeds.

Applying the respective role of the controls to manage the airplane’s energy state leads to a set of simple “rules” for proper throttle-elevator coordination to effectively control vertical flight path and airspeed. What are these basic rules of energy control?

Rules of Energy Control

The central principle encapsulating the role of the throttle and elevator for managing the airplane’s energy can be summed up as follows: coordinated throttle and elevator inputs control the airplane’s energy state. Modifying a popular adage, the principle can be restated as “pitch plus power controls energy state.” This central principle serves to guide a set of general energy control rules to achieve and maintain any desired vertical flight path and airspeed targets within the airplane’s energy envelope.

Visualizing the Airplane's Ability to "Move" Between Energy States

To better understand the basic rules of energy control, a pilot needs to visualize an airplane's energy state and its ability to switch from one energy state to another. In other words, how does an airplane "move" from an initial altitude and airspeed to any other target altitude and airspeed within its flight envelope, and how does the pilot control the process? A map should help, and in this case, it charts the status of the aircraft in terms of energy.

In a navigation map, such as an aeronautical sectional chart, the geographic position of an airplane is determined by two variables—latitude and longitude. Likewise, in an "altitude-airspeed" or "energy" map the energy position of an airplane, its energy state, is defined by two variables—altitude and airspeed. [Figure 4-6]

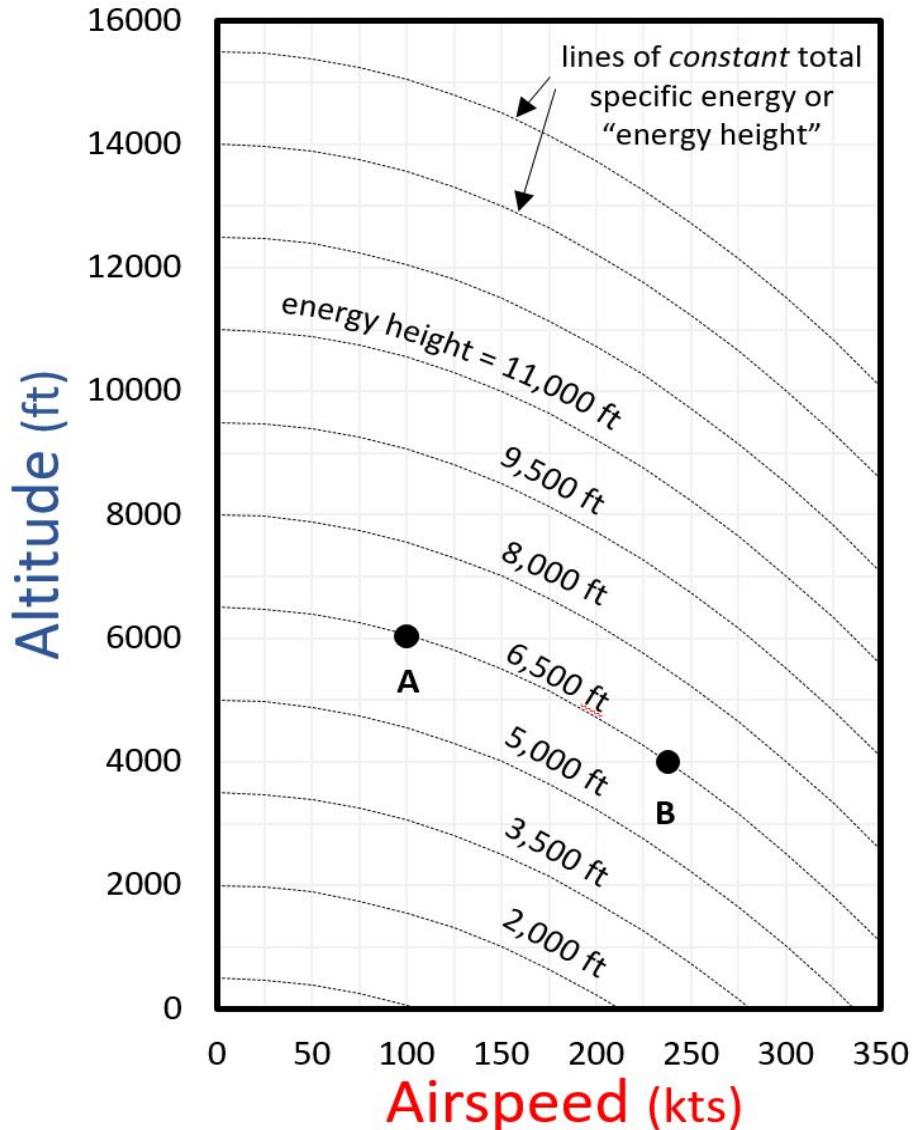


Figure 4-6. The altitude-speed "map" showing lines of constant energy height.

The position of an airplane in the altitude-airspeed map represents its total specific energy or E_S (which is simply the sum of its potential and kinetic energies divided by aircraft weight) as determined by its current altitude and airspeed.

$$E_S = h + \frac{V^2}{2g}$$

Where,

g = gravitational constant
 h = height (altitude)
 V = velocity (airspeed)

Since the total specific energy, E_S , has the units of height (e.g., feet), it is usually called energy height. It also gets this name from the fact that energy height is the *maximum* height that an airplane would reach from its current altitude, if it were to trade all its speed for altitude. *Figure 4-6* shows lines of constant total specific energy or energy height. Different positions of an airplane along a given energy height line have the same total energy regardless of their location on the line (e.g., A and B).

Thus, even though the airplane in point A is cruising at 100 knots and 6,000 feet, it has the same total specific energy expressed in height (6,500 feet) when cruising at 240 knots and 4,000 feet (B). This also means that the airplane in either position, A or B, would be able to “zoom” to the same maximum altitude of 6,500 feet by trading all its speed for altitude. The lines of constant energy height can be used as idealized trajectories to depict an airplane moving from one energy state to another solely through energy exchange (e.g., A to B). If the airplane rapidly exchanges altitude and airspeed, it would follow along the energy height line while, in the short term, maintaining constant total energy.

In addition to showing energy height lines, the energy map can also depict available specific excess power (P_S) contours, as well as energy trajectories of an airplane moving from one energy state to another. [*Figure 4-7*] The airplane can move along energy height lines by simply exchanging energy (e.g., A to B). However, to move across energy height lines, the airplane needs to increase or decrease total energy while distributing the energy change between altitude and airspeed. Thus, the ability of an airplane to go from one energy height to another (e.g., from A to positions C, D, or E) is a function of specific excess power (P_S), measured in rate of change in distance or height (e.g., feet per minute).

Examine the energy positions depicted in *Figure 4-7*. The airplane in position A is flying at 4,000 feet and 150 knots with a total energy equivalent to 5,000 feet. Since positions C, D and E are located at higher energy heights (11,000, 9,500, and 6,500 feet respectively), the only way for the airplane to reach them from position A is by increasing its total energy (i.e., increasing thrust above drag, or $P_S > 0$). The reverse is also true. If the airplane is in position C, D or E, the only way for it to get back to position A is by decreasing its total energy (i.e., decreasing thrust below drag, or $P_S < 0$). In other words, the rate at which the airplane can move from one energy height to another—e.g., how swiftly it can climb/descend at a steady speed, or accelerate/decelerate in level flight—is a function of specific excess power, which can be positive ($P_S > 0$) or negative ($P_S < 0$) depending on whether the airplane needs to move to an energy height that demands more or less total energy.

At the edge of the energy envelope, where available $P_S = 0$ at full throttle, the airplane can no longer climb while maintaining airspeed or accelerate without descending. Inside this envelope, inner contours increase in value, reaching a “peak” where available P_S is maximized. Notice that P_S at full throttle is maximized at a specific airspeed (V_Y) decreasing in value at slower or faster airspeeds. At V_Y then, the airplane can attain the maximum rate of climb while maintaining airspeed or the maximum acceleration without descending [*Figure 4-7*].

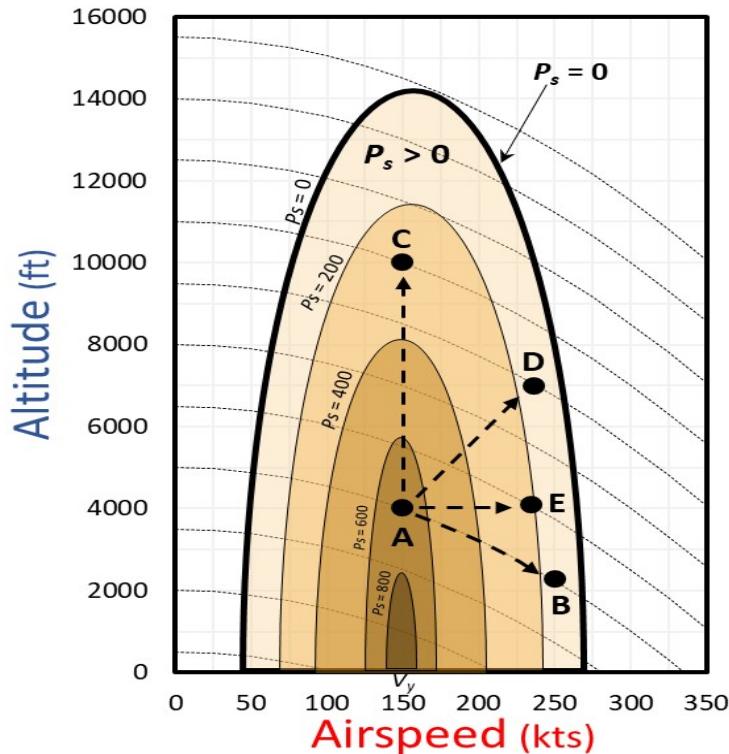


Figure 4-7. Energy map depicting specific excess power (P_S) contours (shown in feet per minute) and energy trajectories for a hypothetical airplane.

Three Basic Rules of Energy Control

An “energy-control” map can help visualize the basic energy control rules. [Figure 4-8] The energy-control map depicts not only the trajectories of an airplane transitioning from an arbitrary initial energy state (1) to other target states (2, 3, 4, 5, 6, and 7), but also the changes in energy caused by the throttle (blue/red arrows) and the elevator (green arrows). In other words, it allows pilots to visualize the basic control rules for moving an airplane from any state to another. The edge of the sustainable energy state envelope (where $P_S = 0$ at full throttle) is also illustrated.

Note that the line of constant total energy (dashed line) that divides the area in the map requiring more total energy (blue area) from that which requires less energy (red area) is depicted relative to the arbitrary initial energy state (1). The throttle adds (blue arrow) or subtracts (red arrow) the amount of total energy demanded by the new target energy state, while the elevator (green arrows) distributes the correct amount of total energy between potential and kinetic energies. By balancing the simultaneous actions of the controls, the airplane can follow the desired energy trajectory.

As illustrated in *Figure 4-8*, moving the airplane from position 1 to the energy states in 2 and 3 calls for a higher throttle setting to increase total energy by the same amount (in this example, positions 2 and 3 are located at the same higher-energy height). The difference between these two energy trajectories (1-to-2 and 1-to-3) lies in the way the total energy change is distributed by the elevator through changes in pitch attitude. As can be seen in *Figure 4-8*, changes in total energy by adjusting throttle setting (blue/red arrows) extend across lines of constant total energy (dashed line), while changes in energy distribution by adjusting the elevator deflection (green arrows) extend along the lines of constant total energy (equal energy height). Appropriate changes in total energy via the throttle and/or changes in energy distribution via the elevator, depicted by their respective energy “arrows,” determine the direction of a given energy trajectory between two energy states. To visualize this effect, compare the trajectory from 1-to-2 with that from 1-to-3 and notice the way the corresponding elevator energy arrows (left green arrow = up-elevator; right green arrow = down-elevator) are positioned in relation to the throttle energy arrow (blue arrow = increased throttle).

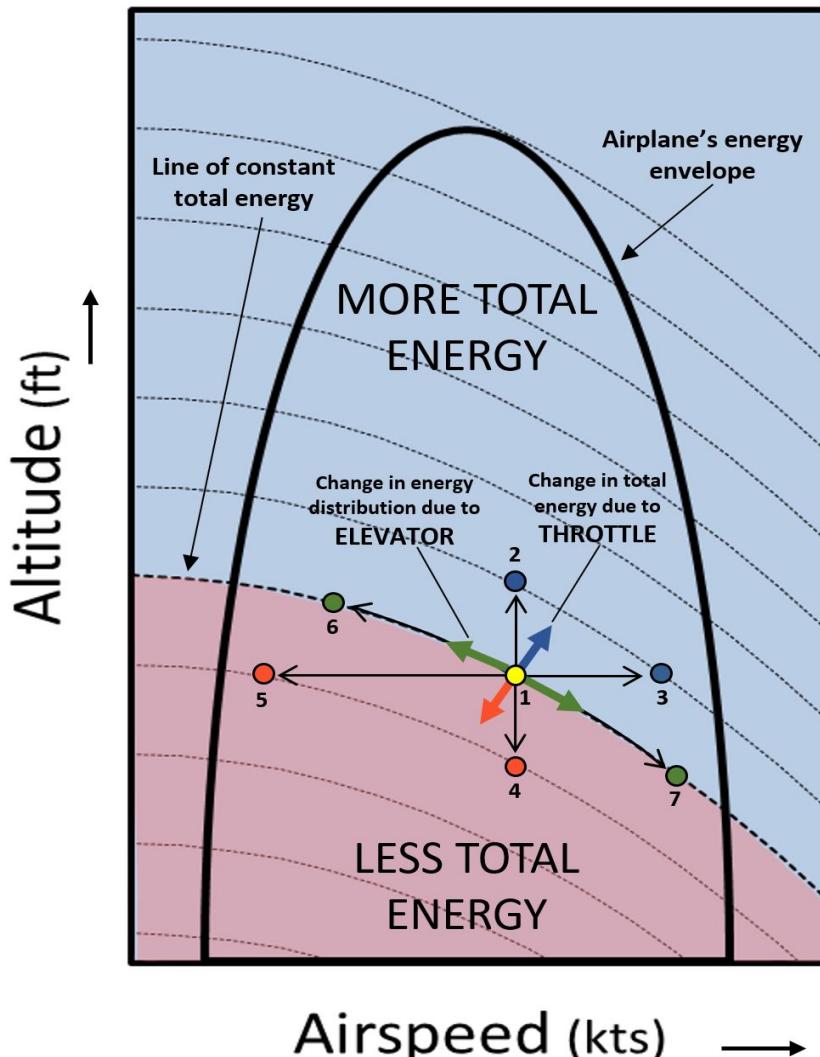


Figure 4-8. The energy-control map helping to visualize the basic energy control rules.

Thus, transitioning to a higher altitude at a constant speed (1-to-2) requires increased throttle and up-elevator to stay on speed, while transitioning to a faster airspeed at a constant altitude (1-to-3) demands increased throttle and (gradual) down-elevator to stay on path, re-trimming as needed to relieve elevator control pressures.

Transitioning to a lower altitude at a constant speed (1-to-4) requires decreased throttle and down-elevator to stay on speed, while transitioning to a slower airspeed at a constant altitude (1-to-5) demands decreased throttle and (gradual) up-elevator to stay on path, re-trimming as needed to relieve elevator control pressures.

Finally, transitioning to a higher altitude by trading speed for altitude (1-to-6) requires up-elevator without initially changing throttle setting, while transitioning to a faster airspeed by trading altitude for speed (1-to-7) requires down-elevator without initially changing throttle setting. In both cases, at the end of the energy exchange maneuver, the elevator will need to be re-trimmed and throttle setting adjusted to match drag at the new speed in order to maintain total energy constant while remaining at the new altitude-airspeed target.

As can be visualized in *Figure 4-8*, there are three general energy control rules for coordinating the throttle and elevator to move the airplane from one energy state to another:

Rule #1: *If you want to move to a new energy state that demands more total energy, then:*

Throttle: increase throttle setting so that thrust is greater than drag, thus increasing total energy;

Elevator: adjust pitch attitude as appropriate to distribute the total energy being gained over altitude and airspeed:

- a. To climb at constant speed, pitch up just enough to maintain the desired speed;
- b. To accelerate at constant altitude, gradually pitch down just enough to maintain path.

Upon reaching new desired energy state, adjust pitch attitude and throttle setting as needed to maintain the new path-speed profile.

Rule #2: *If you want to move to a new energy state that demands less total energy, then:*

Throttle: reduce throttle setting so that thrust is less than drag, thus decreasing total energy;

Elevator: adjust pitch attitude as appropriate to distribute the total energy being lost over altitude and airspeed:

- a. To descend at constant speed, pitch down just enough to maintain the desired speed;
- b. To slow down at constant altitude, gradually pitch up just enough to maintain path.

Upon reaching new desired energy state, adjust pitch attitude and throttle setting as needed to maintain the new path-speed profile.

Rule #3: *If you want to move to a new energy state that demands no change in total energy, then:*

Throttle: do not change initially, but adjust to match drag at the end of maneuver as needed to maintain total energy constant;

Elevator: adjust pitch attitude to exchange energy between altitude and airspeed:

- a. To trade speed for altitude, pitch up;
- b. To trade altitude for speed, pitch down.

Upon reaching new desired energy state, adjust pitch attitude and throttle setting as needed to maintain the new path-speed profile.

Note that control rules 1 and 2 allow the elevator to distribute the change in total energy in different ways. For example, using rule 1.a the pilot may choose to adjust the pitch-up attitude to climb at a slower (or faster) airspeed. Other situations may require combining two control rules. One example is when, at maximum cruise airspeed in level flight, thrust has reached its maximum limit (i.e., $P_S = 0$) but the target energy state is at a higher altitude and total energy within the airplane's envelope. At maximum level airspeed, there is no excess thrust available to increase the airplane's total energy needed to climb. One solution is to initially trade kinetic for potential energy (rule 3.a), slowing down to an airspeed where drag is reduced below thrust, thus allowing the airplane to increase its total energy and climb at that slower airspeed (rule 1.a).

Mitigating Risks from Mismanagement of Energy

Besides learning the proper use of the controls for normal energy management tasks, pilots should be equipped with the ability to identify, assess, and mitigate two major risks associated with mismanagement of energy: 1) unwanted deviations from the desired energy state; and 2) unintentional, irreversible deceleration and/or sink rate causing depletion of mechanical energy. The first risk involves unintended altitude-airspeed deviations (refer to *Managing Energy Errors* section). The second risk entails unforeseen, continuous airspeed and/or altitude loss coupled with little or no available excess power in a given flight condition (refer to *Preventing Irreversible Deceleration and/or Sink Rate* section).

Two Energy Management Scenarios

Two flight scenarios illustrate the two major risks associated with failure to manage the airplane's energy state and how a pilot can identify, assess, and mitigate those risks.

Scenario 1

Unintentionally descending below the desired glideslope on final approach to landing and failing to make the proper correction. [Figure 4-9] To bring the airplane back to the desired glideslope, should the pilot pitch up, throttle up, or both?

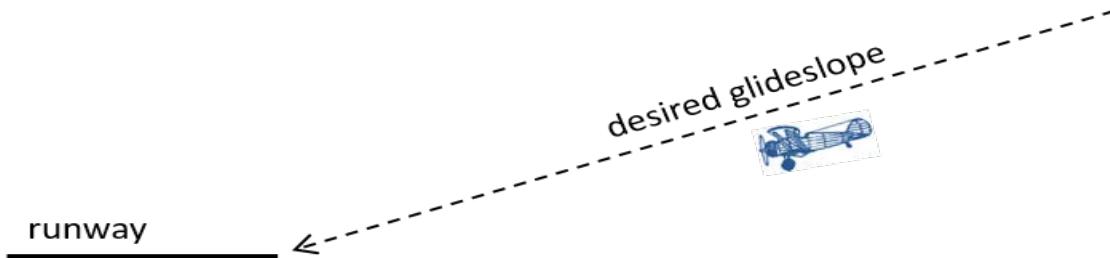


Figure 4-9. Descending below the desired glideslope.

Scenario 2

Flying toward rising terrain and not being able to fly up and over it before impacting terrain. [Figure 4-10] Note the rising terrain all along the departure corridor. What can the pilot do to prevent an impending crash?



Figure 4-10. Departing from Runway 33, Aspen/Pitkin County Airport (KASE), elevation 7,820 feet.

For both scenarios, this section will demonstrate how proper energy management can provide the pilot with the skill to manage the associated risks and avoid tragic results.

Managing Energy Errors

In addition to learning effective techniques for maintaining stabilized path-speed profiles (e.g., tracking the glideslope) and transitioning from one profile to another during flight (e.g., leveling off from a descent), pilots should develop skills for managing unwanted deviations in vertical flight path and airspeed—returning the airplane to its target energy state. Since many inflight “energy crises” start as undetected, ignored or poorly managed path-speed deviations, pilots need the skills to recognize, correct and prevent these deviations.

Although the intention is to correct altitude and airspeed deviations, the pilot is always acting on the airplane’s energy state. Thus, it is important to translate altitude-speed deviations into energy errors. [Figure 4-11] Because the airplane’s total energy is distributed over altitude and airspeed, there are two types of energy errors: 1) total energy errors and 2) energy distribution errors.

Airspeed				
	Slower	Desired Airspeed	Faster	
Altitude	Higher	(1) Total Energy: OK Potential energy: high Kinetic Energy: low	(4) Total Energy: high Potential energy: high Kinetic Energy: OK	(7) Total Energy: very high Potential energy: high Kinetic Energy: high
	Desired Altitude	(2) Total Energy: low Potential energy: OK Kinetic Energy: low	(5) Desired Energy State Total Energy: OK Potential energy: OK Kinetic Energy: OK	(8) Total Energy: high Potential energy: OK Kinetic Energy: high
	Lower	(3) Total Energy: very low Potential energy: low Kinetic Energy: low	(6) Total Energy: low Potential energy: low Kinetic Energy: OK	(9) Total Energy: OK Potential energy: low Kinetic Energy: high

Figure 4-11. An energy state matrix that translates the main altitude-speed deviations into energy errors relative to the desired energy state (5).

Monitoring the altimeter (or other flight path reference) and airspeed indicator allows the pilot to distinguish these two types of energy errors. In total energy errors, the airplane has too much energy (blue boxes) or too little energy (red boxes). The pilot will notice that altitude and speed deviate in the same direction (“lower-and-slower” or “higher-and-faster”). On the other hand, in energy distribution errors the airplane may have the correct amount of total energy (green boxes) but its distribution over altitude and speed is incorrect. Here, altitude and speed deviate in opposite directions (“higher-and-slower” or “lower-and-faster”). In this case, the pilot deals with relative deviations—not absolute altitude and speed.

Following energy management principles, total energy errors are corrected by increasing or decreasing energy using the throttle, while energy distribution errors are corrected by exchanging energy between altitude and speed using the elevator. To correct a combination of total energy and distribution errors, both controls need to be used simultaneously. *Figure 4-12* summarizes the control skills needed to correct total energy and energy distribution errors.

Scenario 1 [*Figure 4-9*] is a good example to illustrate energy errors and the skills needed to correct and avoid them. *Figure 4-13* actually depicts three possible scenarios (B, C, and D) where an airplane on final approach to land has descended below its intended flight path. Should the pilot pitch up, throttle up, or both? It depends. The airplane is lower than desired, but the pilot should check the airspeed as well. Relative to the target airspeed, the actual speed may be slower (B), faster (D), or on target (C). In all three cases, the goal is to return the airplane to its correct energy state (A), following a deviation in altitude and/or airspeed.

Lower-and-slower (B) is fundamentally different from lower-and-faster (D). The former requires advancing the throttle forward to regain total energy (3 in *Figure 4-12*), while the latter requires pulling back on the yoke/stick to null the energy distribution error (9 in *Figure 4-12*).

Airspeed				
	Cautions when Very Slow	Slower	Desired speed	Faster
Altitude	Higher	Relatively safe. Surplus altitude is available to gain speed by pushing the elevator forward.	(1) Exchange energy by pushing the elevator forward to accelerate and descent simultaneously. Maintain the throttle setting.	(4) Reduce throttle setting to reduce total energy. Use elevator to maintain correct airspeed and allow the airplane to descend.
	Desired altitude	Risky. Consider gaining speed at the expense of some altitude initially to improve climb performance with full throttle.	(2) Increase throttle setting to gain total energy by accelerating. Use elevator to maintain the desired altitude.	(5) DESIRED ENERGY STATE Maintain both throttle and elevator (trim) settings.
	Lower	Dangerous! Apply full throttle to resolve this condition. Avoid pitching up, which would increase drag and reduce or impede climb performance when on the backside of the power required curve.*	(3) Increase throttle setting significantly to gain total energy. Push elevator forward gradually to accelerate to correct airspeed and then climb.	(6) Increase throttle setting to gain altitude and pull back on elevator to maintain correct airspeed.
* Depending on aircraft type, as full throttle is applied at the start of correction maneuver, slight forward or aft elevator pressure may be needed to maintain a constant pitch attitude. As the airplane gains total energy, use the elevator to accelerate to correct airspeed and then climb.				

Figure 4-12. The control skills needed to correct total energy and energy distribution errors identified in Figure 4-11 with an additional column giving caution to the “very slow” condition where careful AOA management is needed in addition to energy management.

Note that in the scenario depicted in B in *Figure 4-13*, advancing the throttle forward to increase energy would only succeed if excess thrust is available ($P_S > 0$). This may not be the case if the pilot has badly mismanaged energy and slowed down to a speed where induced drag is so high that even applying full throttle would result in no surplus energy (see column “Cautions When Very Slow” in *Figure 4-12*). Depending on the flight condition, available excess power at full throttle may be negative ($P_S < 0$). In this case, the only recourse is to first trade altitude for speed by pushing forward on the yoke/stick, reducing AOA and induced drag, and only then advancing the throttle forward to regain total energy. But if the airplane is too close to the ground, there may not be enough room to reverse the negative energy rate and prevent the airplane from striking the ground.

Now consider the scenario depicted in C in *Figure 4-13*, where the airplane has descended below the desired flight path but is flying at the correct speed. Here, even though there is no speed deviation, the pilot is faced with a combination of total energy and distribution errors. Regaining altitude without changing speed requires advancing the throttle forward while easing aft on the yoke/stick (6 in *Figure 4-12*). In other words, decoupling altitude and airspeed (i.e. changing one without changing the other) demands the use of both controls simultaneously.

In all cases, path and speed should be monitored carefully as they are corrected, adjusting pitch attitude and throttle setting as appropriate. Once short-term deviations are corrected, the airplane will need to be trimmed for long-term control to maintain the desired path-speed profile (5 in *Figure 4-12*).

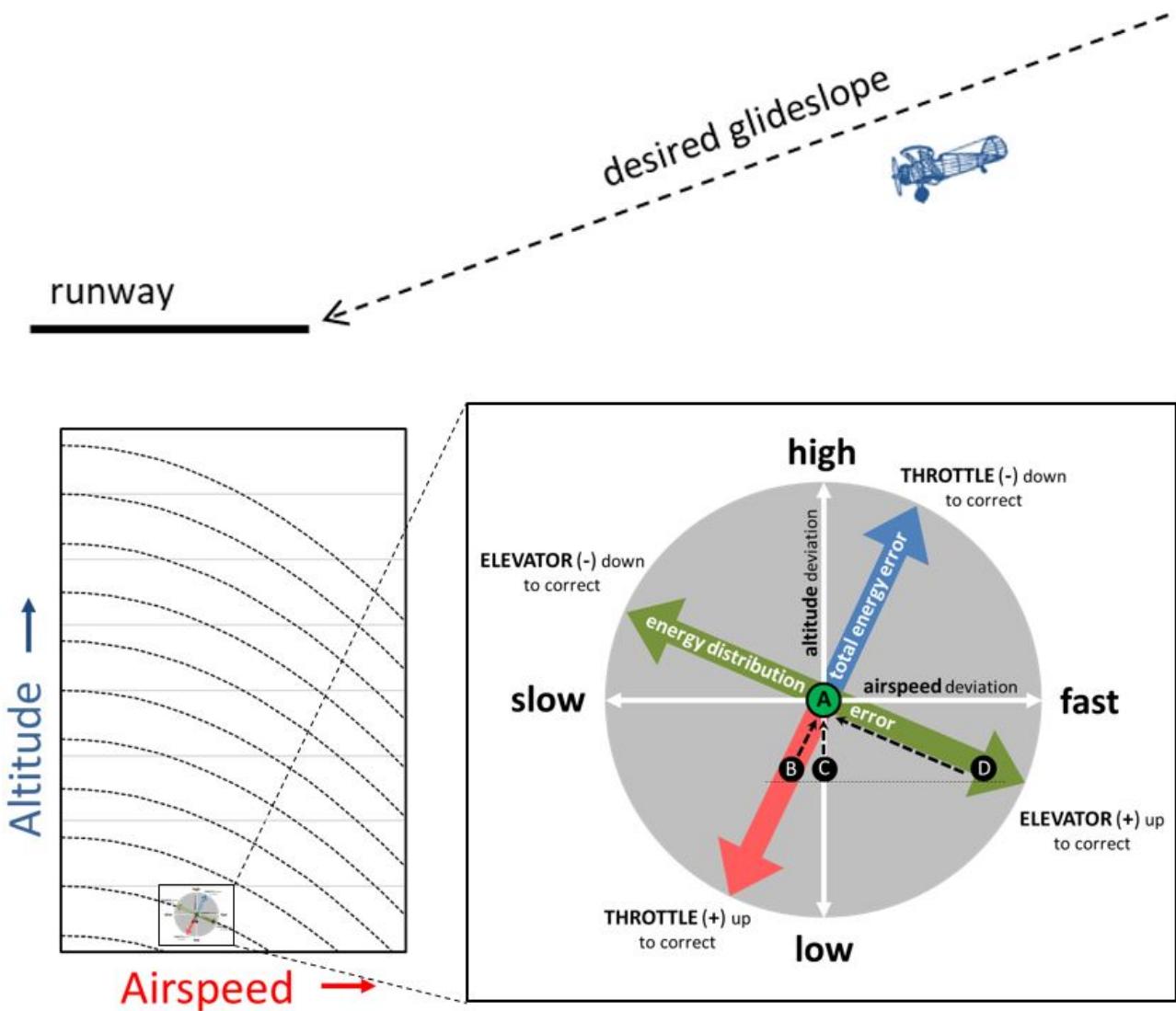


Figure 4-13. Energy error management.

The above approach-to-landing scenario is just one example illustrating the risk of mismanaging altitude-speed deviations. Pilots need to be able to identify, assess, and mitigate altitude and/or airspeed deviations during any phase of flight, including traffic pattern operations, take-offs and climbs, cruise flight, descending flight, and any procedure or maneuver involving turns.

Clearly, skills for promptly correcting path-speed deviations can enhance flight safety but the pilot should also be aware of the risk of unrecoverable depletion of the airplane's mechanical energy, especially as the airplane approaches the edges of its flight envelope where available excess power is zero.

Preventing Irreversible Deceleration and/or Sink Rate

During normal flight, the airplane experiences many instances of negative energy rates (negative specific excess power or $P_S < 0$) while decelerating at a constant altitude or descending at a constant airspeed; these are intended energy bleed rates. However, one of the greatest dangers from mismanaging the airplane's energy state is encountering unintended, excessive deceleration and/or sink rate coupled with little or no positive excess power available under a given flight condition. Failure to recover above a certain critical altitude results in depletion of mechanical energy. Regardless of what the pilot does past that point, the airplane will hit the ground.

To help pilots understand the risk of unintended energy depletion, let's take a closer look at Scenario 2 [Figure 4-10]. This flight scenario illustrates a situation that is all too common in general aviation: flying toward rising terrain and not being able to fly up and over it before impacting terrain.

As shown in Figure 4-10, there is rising terrain all along the departure corridor. The scenario is as follows:

1. A pilot of a normally-aspirated, twin-engine airplane departs out of Rocky Mountain Metropolitan airport (KBJC) in the morning on a nice summer day and flies into Aspen/Pitkin County airport (KASE).
2. The pilot enjoys the scenery around Aspen, eats lunch, and decides to return home in the early hot afternoon.
3. The pilot departs KASE off of runway 33. At full throttle/power the airplane takes longer to accelerate but rotates at the normal speed.
4. The pilot pitches to the normal pitch target, retracts the gear, and initiates a climb.
5. The pilot notices the airplane isn't performing as desired. The pilot checks to see if the gear is up and adjusts the mixtures to try and get a little more power.
6. The terrain is rising, the pilot gradually pitches up, and the airplane starts losing airspeed.
7. The airplane quits climbing.
8. The stall horn begins to sound.

The above scenario is hypothetical, but there have been very similar situations that have ended tragically.

The airplane in the above scenario has encountered an unintended deceleration and impending sink rate that could rapidly become irreversible. This can be shown in two ways, using the traditional power curve [Figure 4-14] and the energy map [Figure 4-15]:

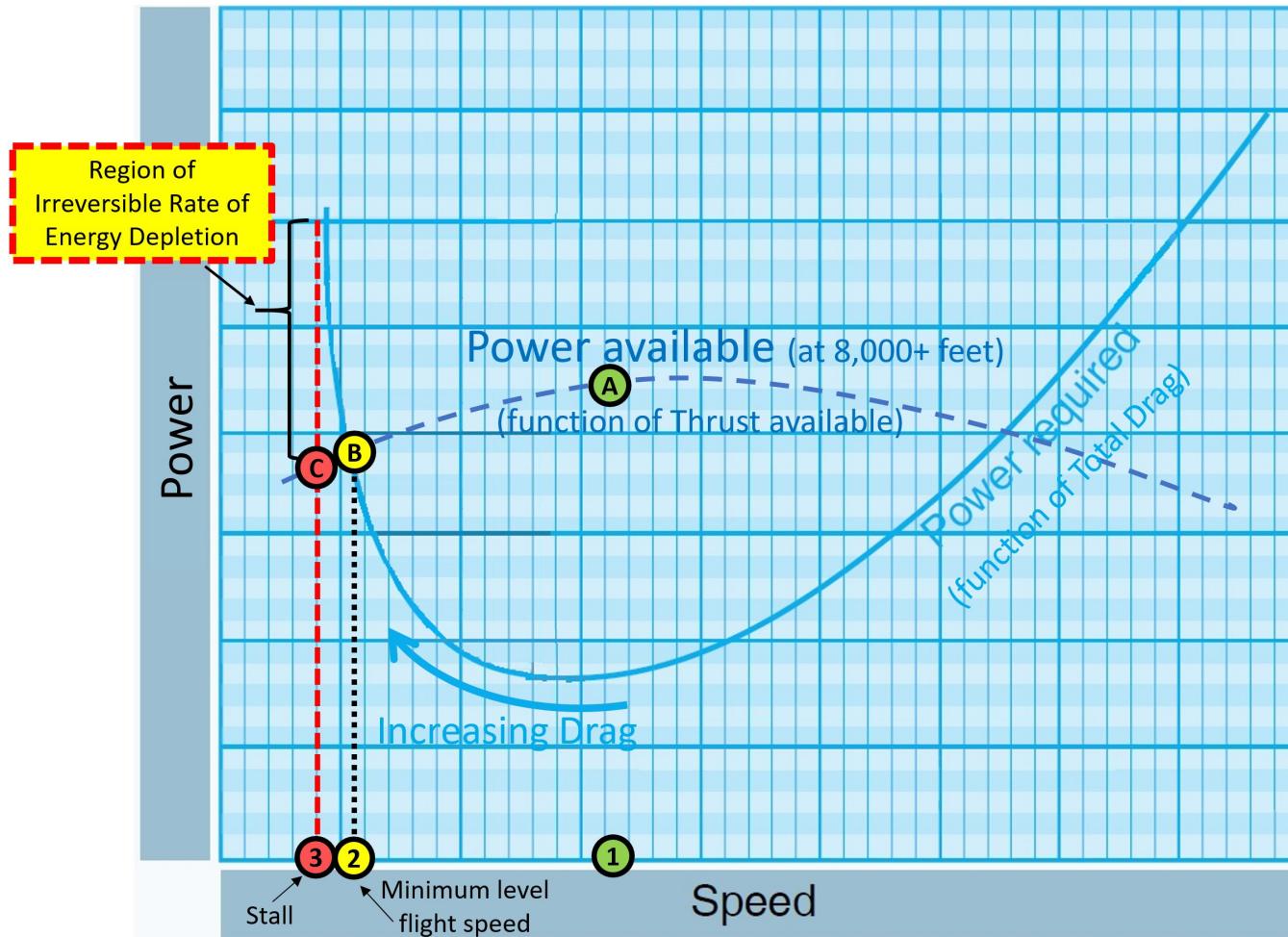


Figure 4-14. The energy depletion scenario viewed in the power required and available curve. Compared with the power available curve depicted in Figure 4-4, note the lower power available curve at this high elevation (7,820 feet at the departure airport) and higher density altitude than standard during a hot afternoon.

As illustrated in the airplane's power required and available curves [Figure 4-14], the airplane slows down, going from speed 1 where it is climbing (A: power available greater than power required), to speed 2, where it stops climbing (B: power available equal to power required), and continuing to speed 3 where the stall horn sounds (C: power available less than power required). The energy map [Figure 4-15] tells the same story from a total mechanical energy standpoint: the airplane has positive P_S at point 1 and climbs to point 2 where it stops climbing since $P_S = 0$, then continues to point 3, where the $P_S < 0$ and the stall horn sounds.

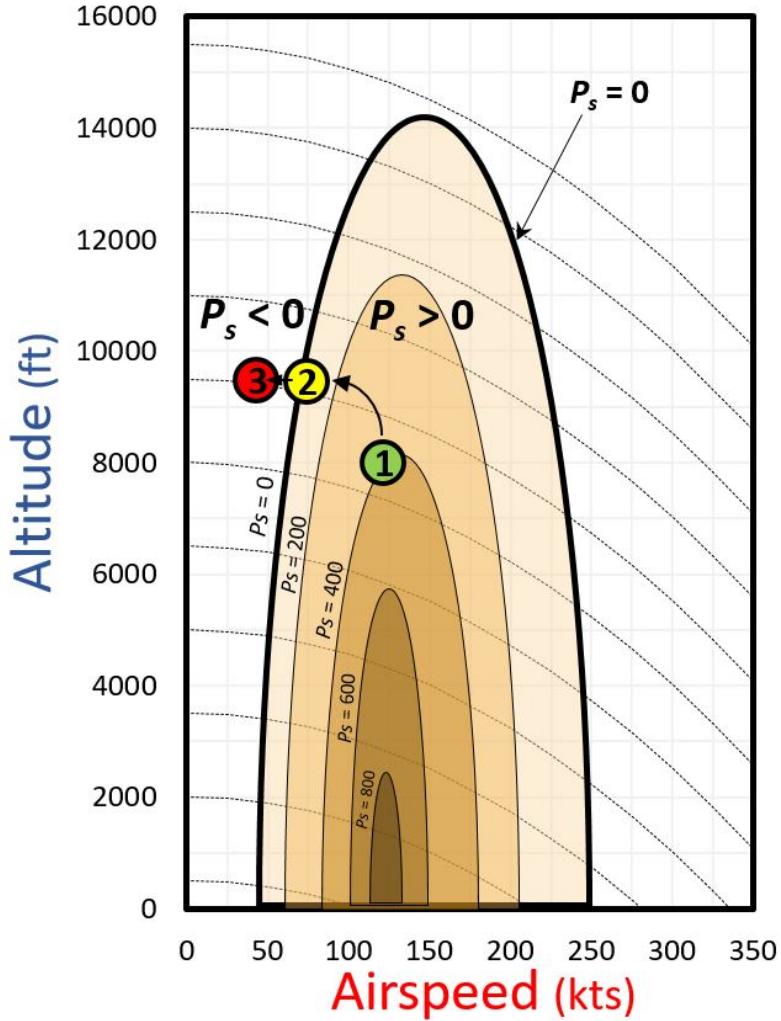


Figure 4-15. The energy depletion scenario viewed in the energy map. Specific excess power (P_S) contours are labeled in units of feet per minute.

The question then is: what does the pilot do to recover from this predicament? The answer is proper energy management. The airplane needs to move to a different place on the energy map that will allow the airplane to begin climbing. So, what does that mean?

- As can be seen in Figure 4-12, the pilot is in a scenario akin to that at the desired altitude, but with cautions when very slow.
- The pilot then has to do something that is not intuitive; consider gaining speed at the expense of some altitude initially to improve climbing performance with full throttle.
- Once the airplane accelerates to an airspeed in which the $P_S > 0$, it can begin to climb again.

The above recovery scenario is shown in the energy map Figure 4-16, which illustrates the important role of the elevator in assisting the pilot to recover from unintentional and dangerous deceleration and/or sink rate (refer to *Additional Role for the Elevator* section).

The airplane needs to gain speed at the expense of some altitude, moving from point 3 where the $P_S < 0$ to point 4 where the $P_S > 0$. The airplane can then initiate a constant airspeed climb to point 5, at the desired target altitude and airspeed [Figure 4-16]. Note that the desired target climb airspeed in the presence of rising terrain may be V_X , the speed for best angle of climb. V_X is slightly slower than V_Y , the speed for best rate of climb, and will result in a lower climb rate but steepest climb angle. Once the airplane has recovered from the unintentional airspeed loss and begins climbing at V_X , the pilot should assess the situation and make an important decision to mitigate further risk—either continue climbing or do something else. Should the airplane not have the needed performance to safely clear the rising terrain on its intended course, the pilot has at least another available option: make a 180 degree turn and return to land at the departure airport until temperature and density altitude conditions improve.

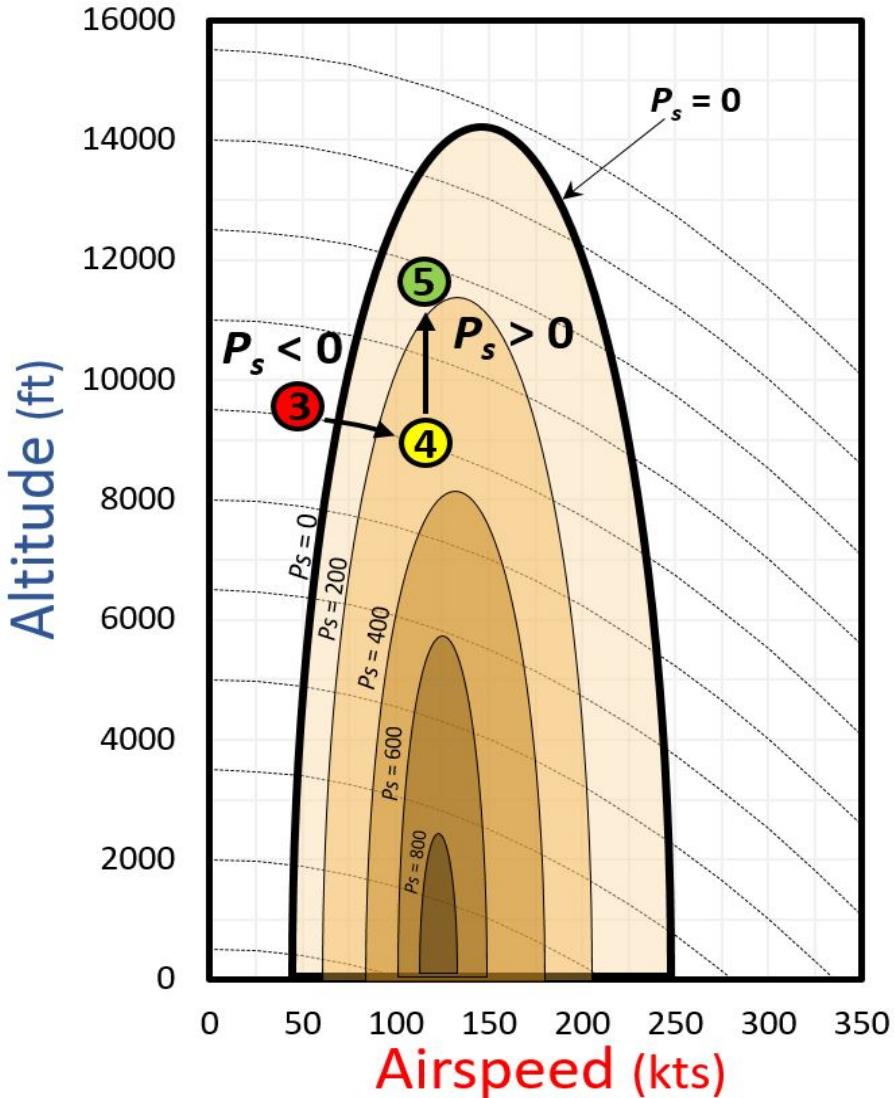


Figure 4-16. The energy loss scenario recovery viewed in the energy map. Specific excess power (P_S) contours are labeled in units of feet per minute.

The above rising terrain scenario is just one example illustrating the risk of irreversible deceleration and/or sink rate. Pilots need to be aware that unintentional depletion of mechanical energy can happen in various instances, especially as the airplane approaches the slow edge of its energy envelope at low altitude, where available specific excess power (P_S) is zero. Examples include unstable/slow approaches to landing; high-drag go-arounds where the pilot neglects to raise the gear and/or flaps; and steeper-than-normal turns in the traffic pattern. Note that irreversible sink rates do not necessarily involve exceeding the critical AOA resulting in a stall and spin. The airplane can be unstalled and still experience unrecoverable sink rates near the high-speed edge of its energy envelope, where available specific excess power (P_S) is also zero. Two examples are high-speed steep spirals following botched steep level turns, and high-speed dives too close to the ground.

The bottom line? Should the airplane ever experience unintended excessive negative energy rates with little or no excess power available under a given flight condition, the pilot needs to use proper energy management allowing a prompt recovery and a suitable follow-up action.

Review of Terms and Definitions

The terms and definitions specific to this chapter appear below.

Aircraft Energy Management

The process of planning, monitoring and controlling altitude and airspeed targets in relation to the airplane's energy state. Note that this definition is concerned with managing mechanical energy (altitude and airspeed) and addresses the safety (flight control) side of energy management. It does not address the efficiency (aircraft performance) side of energy management, which is concerned with how efficiently the engine generates mechanical energy from fuel and how efficiently the airframe spends that energy in flight.

Energy System

A flying airplane is an *open* energy system. That means that the airplane can gain energy from some source (e.g., fuel) and lose energy to the environment (e.g., surrounding air). In addition, energy can be added to or removed from the airplane's total mechanical energy stored as altitude and airspeed.

Total Mechanical Energy

Sum of the energy in altitude (potential energy) and the energy in airspeed (kinetic energy).

Kinetic Energy

Amount of energy due to the airspeed, expressed as $\frac{1}{2}mV^2$, where m = airplane's mass, and V = airspeed.

Potential Energy

Amount of energy due to the altitude, expressed as mgh , where m = airplane's mass, g = gravitational constant, and h = altitude.

Energy State

The airplane's total mechanical energy and its distribution between altitude and airspeed.

Energy Exchange

Trading one form of energy (e.g., altitude) for another form (e.g., airspeed).

Energy Balance Equation

According to this equation, the net transfer of mechanical energy into and out of the airplane (a function of thrust minus drag) is always equal to the change in its total mechanical energy (a function of altitude and airspeed). Note that this simplified definition does not account for long-term changes in total mechanical energy caused by the reduction in aircraft weight as fuel is gradually burned in flight.

Power Available

The airplane's rate of energy gain due to maximum available engine thrust at a given airspeed. Expressed as TV , where T = engine thrust and V = airspeed. Usually measured in horsepower, foot-pound per minute, or foot-pound per second.

Power Required

The airplane's rate of energy loss due to total drag at a given airspeed. Expressed as DV , where D = total drag and V = airspeed. Usually measured in horsepower, foot-pound per minute, or foot-pound per second.

Specific Excess Power (P_s)

Measured in feet per minute or feet per second, it represents rate of energy change—the ability of an airplane to climb or accelerate from a given flight condition. Available specific excess power is found by dividing the difference between power available and power required by the airplane's weight.

Energy Height or Total Specific Energy (E_s)

Measured in units of height (e.g., feet), it represents the airplane's total energy per unit weight. It is found by dividing the sum of potential energy and kinetic energy by the airplane's weight. It also represents the maximum height that an airplane would reach from its current altitude, if it were to trade all its speed for altitude.

Energy Error

An altitude and/or airspeed deviation from an intended target expressed in terms of energy. Depending on the airplane's total amount of energy and its distribution between altitude and airspeed, energy errors are classified as total energy errors, energy distribution errors, or a combination of both errors.

Total Energy Error

An energy error where the total amount of mechanical energy is not correct. The airplane has too much or too little total energy relative to the intended altitude-speed profile. When this error occurs, the pilot will observe that altitude and airspeed deviate in the *same* direction (e.g., higher and faster than desired; or lower and slower than desired). An example would be an airplane on final approach that is above the desired glide slope and at a faster airspeed than desired.

Energy Distribution Error

An energy error where the total mechanical energy is correct, but the distribution between potential (altitude) and kinetic energy (airspeed) is not correct relative to the intended altitude-speed profile. When this error occurs, the pilot will observe that altitude and airspeed deviate in *opposite* directions (e.g., higher and slower than desired; or lower and faster than desired). An example would be an airplane on final approach that is above the desired glide slope and at a slower airspeed than desired.

Irreversible Deceleration and/or Sink Rate

Unrecoverable depletion of mechanical energy as a result of continuous loss of airspeed and/or altitude coupled with insufficient excess power available under a given flight condition. Failure to recover above a certain critical AGL altitude results in the airplane hitting the ground regardless of what the pilot does.

Chapter Summary

Every pilot is an energy manager—managing energy in the form of altitude and airspeed from takeoff to landing. Proper energy management is essential for performing any maneuver as well as for attaining and maintaining desired vertical flightpath and airspeed profiles in everyday flying. It is also critical to flight safety since mistakes in managing energy state can contribute to loss of control inflight (LOC-I), controlled flight into terrain (CFIT), and approach and landing accidents. The objectives of this chapter are for pilots to: 1) gain an understanding of basic energy management concepts; 2) learn the energy role of the controls for managing the airplane's energy state; and 3) develop the ability to identify, assess, and mitigate risks associated with failure to manage the airplane's energy state.