The Book Cover -- Huge Basic Insight!!!

The book cover has really huge insight, right up front, on the incisive Logic of Flight, the Thinking Man's Way to Fly!

Notice the labeled Profile Drag Curve swooping up, a V^2, V Squared Curve, twice the speed, 4 times the Air Friction Drag, 3 : 9, 4 : 16, etc., the Profile Drag we usually hear about.

We're taught that Wing Lift happens because of a reduced pressure above the airfoil, but some hear about Induced Loss, or Drag, the cost of creating lift. What they should tell us is that Wings are also throwing down air, to create a Reaction Force Lift, *Newton's equal and opposite Reaction Force.* Induced is just the Energy Cost, the Loss of Throwing Down Air, Lift.

Look - Induced is a $1/V^2$ Curve, Swoops Down as we go Faster!!!

We simply add those two curves together, and get the "leaning Lazy J" Drag Curve that all planes have, some with more or less Induced, or Profile drag. Profile depends on how sleek, clean it is, also Speed. Induced depends on Aspect Ratio, Span / Average Chord, also Speed. Sailplanes best!

Big Spans involve a bigger Mass Flow Rate, $\dot{M}$, thus slower throwing!

We get Min. Drag, Max. Climb, nominally where the curves cross and are equal! Cruising Faster, Profile Swoops up, Induced Swoops Down, maybe 20, 25% of the Total Drag!

Ah, but now we can get really Smart! At the Tangent Point to the Drag Curve at Sea Level, we have the Max Speed vs. Drag - see, all other speeds, Drags above that tangent line!!!

But now, if we simply climb up, for High Altitude Cruise, in thinner air, we have to go faster to hold up the plane, TAS, True Airspeed, 21% faster at 12,500' vs. Sea Level IAS, Indicated Airspeed, but at Sea Level IAS Drag, Free Speed!

We can also much more safely Lean the Engine at the much lower High Altitude Power, unthrottled, win, win, win!!!! Get all that *"easy enough"* insight and you already grasp the core of The Logic of Flight, The Thinking Man's Way to Fly!

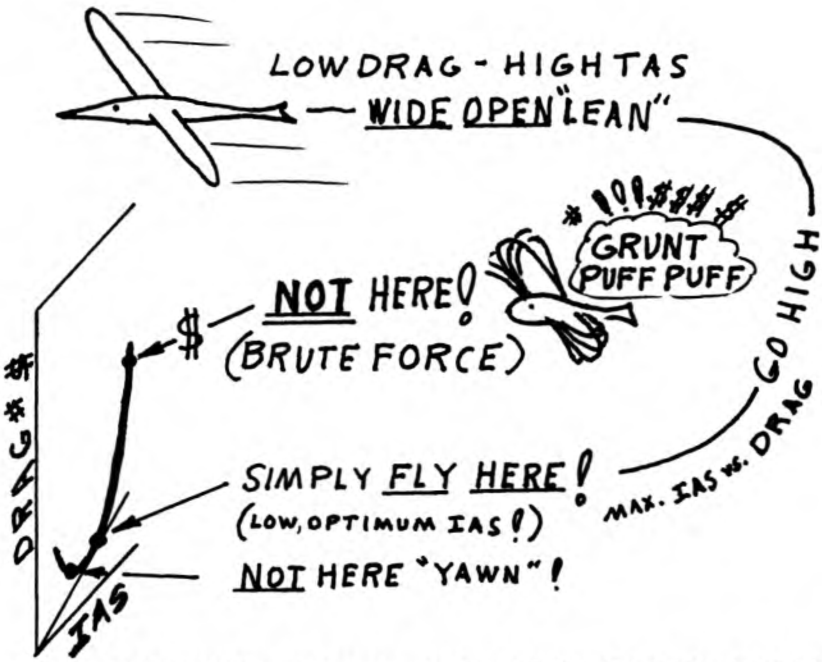
Dense, Incisive - Yes! The Core of Optimum Flight on One Page!!!

THE OBJECTIVE OF THIS BOOK IS TO **SHOW YOU** THAT THERE IS A BEAUTIFUL AND **AMAZINGLY SIMPLE LOGIC OF INTELLIGENT FLIGHT!**

IN FACT, THE CONCLUSIONS ARE SO SIMPLE THAT YOU CAN BEGIN TO LEARN THEM IN THE FIRST FEW MINUTES, IN THE FIRST FEW PAGES!

THE EVEN MORE VALUABLE FACT, HOWEVER, IS THAT WE CAN ***USE*** THE THINKING MAN'S LOGIC OF INTELLIGENT FLIGHT, ***AS A TEACHING TOOL***, TAKE YOU THROUGH THE WHOLE CENTRAL CORE OF AERODYNAMICS, OF ENGINES, OF HOW IT ALL WORKS AND TIES TOGETHER. YOU CAN SEE IT ALL BETTER THAN MOST EXPERTS, WHO NEVER SEEM TO GRASP, TO CLARIFY AND STATE THE WHOLE INTEGRATED LOGIC! IT'S FUN TO GRASP IT ALL!

IT'S JUST A MATTER OF **MAXIMIZING IAS VS. DRAG**, FOR YOUR GROSS WEIGHT, CLIMBING, GETTING **FREE TAS** **AT** **HIGH ALTITUDE**, (THAT DOES NOT HURT MPG) -- THEN SIGNIFICANTLY IMPROVING MPG, BY OPTIMIZING ENGINE EFFICIENCY, OPTIMALLY MATCHING YOUR **ENGINE** TO YOUR PLANE, BY SIMPLY GETTING IT **WIDE OPEN**, **PROPERLY LEANED**, AT THAT OPTIMUM IAS, AND OPTIMUM WIDE OPEN ALTITUDE, ***REAL INSIGHT!!!***



YOU WILL HAVE FOUND THE <u>OPTIMUM L/D</u>, <u>ANGLE OF ATTACK</u> AND "<u>DECK ANGLE</u>", THAT WORKS AT <u>ANY</u> GROSS WEIGHT, <u>ANY</u> ALTITUDE!! YES, THERE IS A "**<u>MAGIC ANGLE OF ATTACK</u>**", THAT WORKS AT <u>EVERY WEIGHT</u>, <u>EVERY ALTITUDE</u>! **<u>IT'S</u> <u>ALL</u> <u>HERE</u>**!

YOU'LL BE AMAZED AT YOUR NEW INSIGHT, YOUR INCISIVE GRASP OF AERODYNAMICS AND ENGINES, HOW LAUGHABLY SIMPLE IT ALL IS IN HINDSIGHT!! YOU'LL SOON REALIZE YOU FOUND THE **BEST LEARNING OPPORTUNITY OF YOUR LIFETIME**!! YOU'LL FIND THE BOOK SET UP FLEXIBLY, FOR YOU TO LEARN JUST AS DEEP AS YOU WISH. IT <u>ALWAYS COMES BACK TO THE SIMPLE CENTRAL THEME</u>, SO **<u>YOU CAN'T POSSIBLY GET LOST</u>**!

THE WISE OLD BIRD

THE LOGIC OF FLIGHT

"THE THINKING MAN'S WAY TO FLY"

INTELLIGENT, EFFICIENT FLIGHT

FEATURING

MAX SPEED / $

BY JACK NORRIS

Jack Norris Publisher

The Logic of Flight
The Thinking Man's Way to Fly

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Jack Norris

Price purposely kept low to spread the insight!

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PREFACE

Pilots LOVE TO FLY, love planes, the freedom, adventure, the elation of conquering the sky. The novice, eager, learns "to pilot" the plane, so he too can enjoy. The pro, still challenged by flight's many aspects, becomes professionally adept, "at operating" the plane, the machine, learns almost all of flights many aspects. But there is almost always at least one knowledge gap, that causes pilots, to be more "driver", perhaps "master driver" than real master! The pilot seldom learns or understands, the logic of the Aerodynamics that the plane itself senses, flies on, **its logic!** That is unfortunate, and unnecessary!

Without a really good, EASY EXPLANATION of the hidden technical basis of THE LOGIC OF EFFICIENT FLIGHT, pilots are denied a clear insight into how the *airplane itself* really works, what *it* senses, what ITS LOGIC is!

Pilots are "doers", not "students". There is a barrier that is part "technical", part the lack of a good teacher, part the personality difference between an engineer and a pilot, who'll "skip the theory"! HOWEVER, the thought that a truly competent pro, who can, for instance, safely fly into the New York air traffic complex, with terrible weather, with a "Jet load" of people, for an entire lifetime, yet fail to master his subject, for the lack of a really good explanation, is just ridiculous! Our objective is to provide THE ENGAGING SOLUTION, for the novice and the master as well, using the basic *classic plane* as a teaching tool!!

The *intended audience* for this book is ANYONE INTERESTED in INTELLIGENT FLIGHT, pilots, both novice and professional, people from all walks of life that find flight fascinating. Even the technical professional in the Aeronautical Sciences will find *incisive logic* and *insight* in this book that he had not thought to recognize and express!

The unabashed PURPOSE here, is to cut right through the complexity of Aerodynamics, the science of flight, put together the best, most UNDERSTANDABLE, TEACHING guide to THE BEAUTIFUL LOGIC of INTELLIGENT FLIGHT, with the magnificently SIMPLE CONCLUSIONS that lurk, hidden, like a Michelangelo sculpture, in an obscuring granite block.

It will purposely and specifically not be written in the arcane, terse, writing style that technical pros prefer in the obscure technical journal. In every way, using every mechanism, we will REACH OUT, MAKE CLEAR, BUILD the INSIGHTS to help the interested learner come aboard on the magnificent grasp that modern science makes possible. We'll use *italics*, capitol letters, **bold**, to emphasize, make CLEAR! The expert spent years learning, but fails to explain, forgets the learner doesn't "get it" the first time, certainly not the warm, incisive grasp, that *can be built*, by a good helpful teacher leading the way!

The learner needs HELP. Engineering formulas and Greek letters, scare off even intelligent, interested adults, PREVENT UNDERSTANDING! We will teach the beautiful logic and insight that the science exposes. We'll make the CONCLUSIONS CLEAR EARLY, show the INCISIVE PATH, the skeletal framework of the logic, BUILD, REFINE THE READERS GRASP. In the natural repetition, inherent in building and refining the grasp, everyone can "GET IT".

The main game is understanding the big difference, "where you fly on the drag curve", -- "How to also get the Engine efficient", SIMPLE!!! We'll make the INNER SECRETS of the Science of Flight **clear and understandable**, usable for **more intelligent, better informed flight** by any and all! As you come to grasp it all, you will be amazed by your incisive insight. You'll have **a good laugh** over the conclusions, the CLARITY, SIMPLICITY!!

FORWARD - FROM THE DARK AGES
- How We Got To This Point -

We are blessed to live in the greatest country in the greatest time in the history of man! We live in luxury, thermostatically controlled, buy a King's banquet, any product we wish, at the corner "horn of plenty". We have instant news, worldwide communication, entertainment, at the speed of light, navigation by satellite. With portable energy, we zip around in our own motorized chariots, FLY ourselves, FLY 900,000 pound jets. The *Wisest, Richest* man could not have that *one lifetime ago*! We even have the time, the opportunity to become whole happy people, who can grow in knowledge and wisdom, **true wealth**!

Recognize that a scant few generations ago, you might have been grubbing in the mud trying to grow your own food, hunting in a frigid winter, **just surviving**, a frontier sod buster here, a no chance serf in Europe, a *current* citizen of the third world, where they still haven't got the act together! **WHY**?

HOW did our fantastic modern world finally happen, and all in just a few hundred years? Do you realize that only a scant few hundred years ago, in the 1600's, Paris had but 40,000 people! That's only a lesser part of Kalamazoo, and with no sanitation they faced plagues with no known cause or cure, **died** helpless!

The History teachers completely missed the point. They teach us about battles, dates and treaties, the results of human ignorance! They should illuminate what really happened, a never ending succession of Genghis Khan types, power seekers, manipulative politicians, all with an excess of greed, and male hormones, and *a lack of real merit*, "true intelligence, wisdom".

One wonderful Professor at Ohio State, Sydney Fisher, miles ahead of his peers, understood, showed me how the human race kept fouling up for eons, the same flawed personalities going *nowhere*, that one should look to the negative and *positive* *"human movers"*, ***who*** and ***what kind*** of people were moving the human race ***backward, or ahead***. Humanity slowly managed three steps forward for every two backward, simply because there are the "*real movers*" who don't care about power or manipulation because they KNOW and CAN and DO! **LOOK**, recognize the ***genuine articles*** are ***always advancing*****!!**

People have been smart for a long, long time. The Greek Philosophers thought and wrote and created Euclidean Geometry. The Arabs had a better number system, still in use. The Egyptians built the Pyramids, better, the great Library at Alexandria. The Romans built great Aqueducts, roads and buildings. Their IQ's were just as high as ours! ***What was missing***? Why didn't the modern world happen sooner, why was progress so slow for eons, how come our progress and growth is suddenly so explosive? There is a ***specific reason!!!***

In the 1600's "men of intellect" came together in the great, if still prototype cities of Europe in "Philosophical Societies" to try to **define the basic "Natural Laws"**. They were really the **Prototype Scientists, Engineers**, and they ultimately found a number of very simple, but very *specific* little mathematical like formulas that ***exactly defined how the physical world works***. They "uncovered" the basic sciences of Physics and Chemistry, built on Mathematics, and the world was changed forever!!!

The great names, Galileo, Newton, Boyle, Charles, Bernoulli, Dalton, Kelvin, Avogadro, Priestley, Lavoisier, Thompson, Carnot, Watt, Cavendish, Coulomb, Ohm, Oersted, Joule, Gauss, Maxwell, Kirchhoff, Wheatstone, Faraday, d'Arsonval, carried the movement from the 1600's up through the 1800's and defined the physical world in a succession of fundamental, but strikingly SIMPLE relationships. There was not complexity, chaos, but **magnificent simplicity**, **precise logic**, in **nature**!

The Industrial Revolution was born, growing imperceptibly at first as the KNOWLEDGE GREW AND SPREAD. The ability to *manufacture products*, create usable engineering *materials* was born of opportunity and need. We've had vast advances in life, health, Pasteur 1857, products for living: The early mills, better cloth, more food, transportation, the "Iron Horses" of the 1800's (because there was not yet steel). Only as late as the end of the 1800's were there real steel mills, the first gas engines, early autos, *production* machines with the ability to manufacture *identical* parts in quantity -- and **progress just exploded!!**

The fundamental difference, the **pivital difference**, was now we could ***understand exactly how*** the physical world, the natural laws worked. We could **learn**, **solve** biological health problems, calculate precisely and design any product our need and imagination could **envision**. Sociologically it was the birth of **THE SCIENTIST, ENGINEER**, where the man that creates a nations destiny, is the creative man of intellect, not the obsolete Saddam Hussein type, the warrior, or the shallow power seeker.

We still have to corral the "power seekers", who still operate on hormones and manipulation from the bygone days, and learn to "move them out of the way" so society can move on to the next level! The people are catching on. The Swiss have a "citizen government"! We are into the age of **knowledge** and it **works**! It's **the Scientist Engineer** who has **created modern life**, our **"horn of plenty"**, and there **need be no negatives**, because the ***thinking man knows*** *how to clean, recycle, preserve, as well*!

Recognize in this book how the wonderful, **simple laws of nature** go to work to make "duck soup" of the complexities of Aerodynamics, **let <u>you</u> see right through it, own it - watch!**

THE SCIENCE OF FLIGHT, SUCCESSFULLY TAUGHT

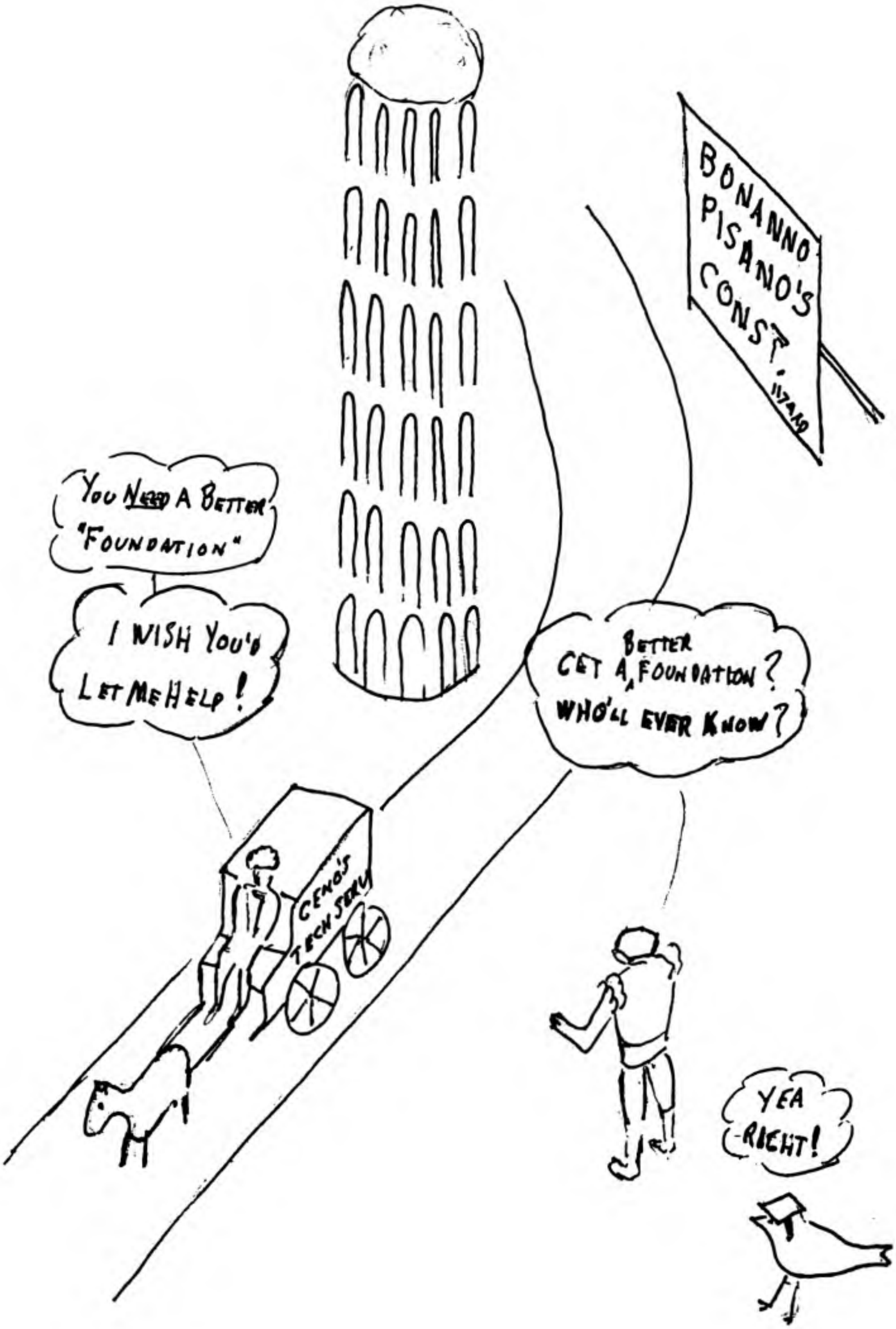
The barrier between what I know about The Science Of Flight and the great fun and satisfaction that you too can have in grasping the core of Aerodynamics, as it applies to intelligently flying an airplane - is - can we successfully **TEACH, LEARN**?

If I were just the engineer who understood the Science, the Engineering, we'd both be in big trouble here. The task at hand is as much about successfully teaching, and learning what is otherwise a complex morass, as it is about the science of flight.

There are three reasons why we're going to succeed here.
1. I **really understand** how airplanes work!
2. I see a **simple, clear logic path** through Aerodynamic complexity, that is essentially never completely grasped.
3. I am going to **teach it in a unique way** -- so you can't possibly fail to "get it", even if you normally shy away from things technical or mathematical, **<u>and</u> you'll get plenty of help**!

I've had a wonderful and unique education and career, a unique "forced education", that at various times required me to learn how to be: 1. A very good deep digging engineer who learned how to get to the very essence of any technology. 2. A leader who could "create", "lead", "teach", "sell" as the occasion required. 3. A consultant, who could accurately assess what a situation lacked, needed, and like a chameleon, fit, or teach, or provide, what the situation required. I <u>HAD</u> TO LEARN **a lot**!

With over 100 of my Spacecraft Control Products on the Spacecraft in the Milestone Of Flight Gallery, the central hall of the National Air and Space Museum, millions of dollars of leading edge products all over the world, there's a bunch I can teach you, and I know how to make it CLEARER, EASIER!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YOU NEED A BETTER "FOUNDATION"
I WISH YOU'D LET ME HELP!
GET A BETTER FOUNDATION? WHO'LL EVER KNOW?
CENO'S TECH SERV
YEA -RIGHT!

Our brains work quite differently than a computer. They work "**by association**", by "relating knowledge" in layers. Thus, if we have something to learn, **IF**, it is presented to us in "**a logical way**", if, we can see a "logic path" that "makes sense to us", if, we can see "an integrated story building on a central logic tree", we can learn quickly, easily, and cope with far more than we could ever sort out on our own! **I'll make it all clear to you!**

You will be amazed here to find that in just a few chapters you will already be seeing through the Aerodynamics of intelligent flight. It won't be an accident. We're going to be doing it differently than it's normally done. We'll be using quite a different writing style, quite a bit more emphasis, CLARITY, than the terse technical journal writer, the editor practiced in "good writing". The objective here is quite different than in a novel, a journal. It is to "show the clear path", "to lead", "TO TEACH", To HELP, a broad spectrum of "learners".

It would be wonderful, if I could write this individually for the many levels of interested intelligent people who will want to read and learn here. Of course you realize we must make it work for the beginner, right up through the pro who's looking to see if there's really something new here. (there are, things not quite grasped and said clearly yet!) To the potential critics, cut me a bit of slack, my objective is worthy, bigger, and different than what's been accomplished yet. I'm after a big, worthy goal, AN UNDERSTANDING FOR EVERYONE, OF THE THINKING MAN'S, LOGIC OF INTELLIGENT FLIGHT.

I'll introduce myself to you a bit as we go, tell you an anecdote here and there, along with the central story, that will give you extra insights you would not otherwise have. You may think, that I digress, but then quickly find that I'm teaching you HOW we'll be teaching you the subject at hand. HAVE FAITH. You'll even find it's a surprisingly EASY READ, even **fun**!

DEFINITION OF BASIC TERMS

A ready reference to clarify, stop confusion on abbreviations.

"q" -- The "Ram Dynamic Pressure" in psf, pounds per square ft., (#/ft.^{2} in engineering terms), sensed by the "pitot tube", after subtracting the "static pressure", sensed by the "static port". It operates the Airspeed Indicator. It turns out that airplanes fly on "q", Lift and Drag equally affected, "energized" by it. Constant "q" flight, at a given weight, becomes constant L/D flight, a fundamental of HUGE Importance, that permits A SIMPLE, LOGIC OF INTELLIGENT FLIGHT!

IAS -- Indicated Airspeed: The readout of the Airspeed Indicator in Knots, nautical miles per hour, or MPH, statute miles per hour, from sensing "q". IAS reads erroneously low at altitude as air density decreases, which turns out to be **good**, not bad because "it's sensing what the airplane is flying on"!

CAS -- Calibrated Airspeed: True IAS, corrected for any error in the instrument, or the static pressure pickup, or the Pitot location. Pilots tend to not use this term, though they certainly should. To keep the explanation simple, especially in the first part of the book, we'll just use IAS as pilots do, but what we'll mean is CAS, correct Calibrated IAS!

TAS -- True Airspeed: Literally the true speed after IAS, CAS, are corrected for the drop off at altitude due to the air density, ρ, decreasing at altitude. TAS = True IAS $(\rho_{SL}/\rho_{Alt})^{1/2}$

Lift -- L: The *pounds* of lifting force generated *perpendicular to the flight path angle*. Generally taken as equal to the weight in level and near level flight, though thrust or drag help hold up the weight as climb or glide steepens.

C_L -- Coefficient of lift: A simple dimensionless coefficient, or "multiplying factor", that shows the relative ability of an "airfoil" to lift, as its relationship with the angle of attack of the airstream changes. Used in the basic Lift and Drag Formulas.

α^o -- Alpha, Angle of attack: The angle between the flight path angle, and the mean chord line of the airfoil, a simple line drawn from the very nose of the airfoil to its trailing edge.

Drag -- D: The *pounds* of all types of drag generated *parallel to the flight path angle*. There are two basic kinds of Drag, **Parasite Drag** resulting from surfaces being pulled through the Airstream, and **Induced Drag**, the drag due to generating lift. (A third type, Profile Drag is simply the parasite drag of the wing area.) Two (or three) basic drag curves can be drawn, and/or be combined into a classic **leaning "J" shaped total drag curve**.

C_D -- C sub D: The overall total Coefficient of Drag, at any given speed, which is made up of two parts, C_{Do}, a constant, representing the Parasite Drag, and C_{Di}, the highly variable Induced Coefficient, actually dependent on $C_L{}^2$ and *aspect ratio*, used to create the **two basic drag curves**, and/or the classic *composite*, leaning "J", **total drag curve**.

Aspect Ratio -- A_R: The wing span divided by the chord or the average chord of a tapered, or shaped wing. That is also mathematically equivalent to $Span^2/Area$. Used in calculating theoretical Induced Drag.

e -- Oswald Span Efficiency Factor: A high class "fudge factor", nominally about .8 used to increase theoretical Induced Drag up to its actual value. Actual = Theoretical / e

FPA -- Flat Plate Area: The equivalent flat plate Drag Area, of the Parasite Drag of the entire plane. Numerically equivalent to C_{Do} x S, the wing area. Thus, Parasite Drag equals FPA x q.

S -- Wing Area: Simply the wing area in square feet.

ρ -- Rho (row): The "mass density" of air at a given altitude. Equal to the density of air at any given altitude in pounds/ $ft.^3$, divided by g, the acceleration of gravity, 32.174 ft./ sec^2.

L/D -- Lift over Drag Ratio: The ratio of Lift to Drag that separates "clean" planes from "draggy" designs, but also in the most fundamental way defines the "flight condition" that, if held constant, permits a simple, essentially exact, LOGIC OF FLIGHT! L/D is also equivalent to C_L/C_D numerically.

MPG -- Miles Per Gallon: Every bit as applicable to your plane as it is to your car, except that in your plane you have much more intellectual control over what it actually is, and it in turn "tells" whether you are a really smart pilot, or just another driver, who doesn't understand yet how the airplane works!

N_R -- Reynolds Number: A rather esoteric engineering term that actually relates the "size and speed" of the plane to the "density and viscosity" of the air. You might realize that would be significantly different for a "bee" than a 747, with model airplanes, sailplanes, personal planes in between, seeing different effects that vary from quite significant to a part of a percent. Generally larger faster planes have a 30% *max* C_L and a smaller C_D advantage, less so at high altitudes. HOWEVER, smaller chord, slower sailplanes more easily maintain low drag LAMINAR FLOW. Interestingly, models, too slow, too small, can build stagnant laminar wakes, sometimes use "turbulators", turbulent flow, to energize, shrink the wake.

GW -- Gross Weight: Simply the "total weight" of the plane at takeoff, or any given time under consideration. (See CG)

CG -- Center of Gravity: Simply the balance point of the airplane with its load. Actually, the plane can fly heavier than it actually is, if the CG, the "center of gravity" is far forward of "the Center of Lift", requiring the tail to exert a large downward balancing force, that acts like "extra weight", and furthermore causes extra "trim drag". However, that extra downward force is usually ignored in basic discussions! Clearly, a rearward CG is better for efficient flight, but too far aft is unstable, dangerous, prone to "flat spins", not smart, at all!

Center Of Lift -- C_p, Called the Center Of Pressure: Moves forward at higher angels of attack, *particularity on highly cambered airfoils*, which, as above requires excess downward tail balancing loads, which in turn favors more symmetrical, well designed airfoil sections.

η_p -- Propulsive Efficiency. "Eta" Sub p, the Greek Letter "h": Simply the "Power Required" for the *real* Drag of the airframe (multiplied by the true speed) divided by the *"actual* power" supplied by the engine. The subject was never adequately understood, because there was never a real test for full scale propeller airplane drag, other than free glide testing of a propellerless plane. Now with <u>Zero Thrust Glide Testing</u>, for REAL drag, and level flight Speed Power Testing, many old planes show poor η_p, that degrades with increasing power, whereas current tests of carefully designed leading edge homebuilts show good η_p, a valuable insight and design criteria.

Leaning -- Changing the Air:Fuel Ratio from the nominal13:1, or less, Max Power mixture, to the nominal 16:1 Max Economy mixture, that is usually done manually, to give the pilot *control*!

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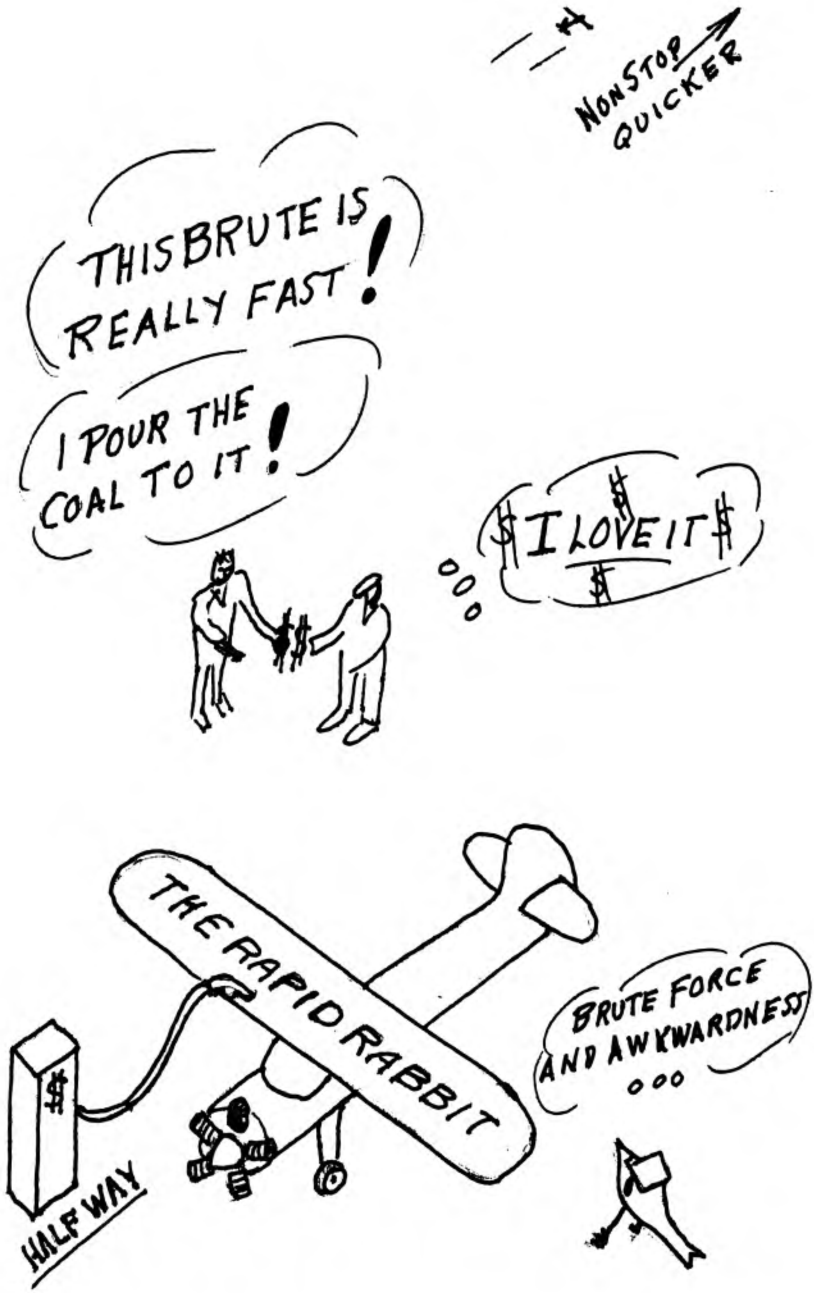

NONSTOP
QUICKER
THIS BRUTE IS REALLY FAST!
I POUR THE COAL TO IT!
$ I LOVE IT $
THE RAPID RABBIT
BRUTE FORCE AND AWKWARDNESS
HALF WAY

CHAPTER 1: INTRODUCTION

The Simple Insight

There is a BEAUTIFUL LOGIC to flight, to the way that airplanes work. It is beautiful because it is so logical, cuts right through the core of complex Aerodynamics, is so easy to grasp and use, has final conclusions that are GENUINELY SIMPLE!

Indeed, the great good feeling, and the funny insight into THE THINKING MAN'S WAY TO FLY, is the real intellectual satisfaction in actually seeing through the complexities of Aerodynamics, that perhaps you thought you could never really grasp, and find that all the important final conclusions on how to fly a plane efficiently, intelligently, are so **laughably simple**.

We can teach you the major bottom line conclusions in five minutes, and we will, just a few paragraphs down, so you *know at the beginning where you're going!* But, the true beauty and value is that in going through the whole logic, and making it your own, you can gain a wonderfully incisive grasp of how **Aerodynamics, Engines,** and **Flight** really work, -- and easily!

The problem has been that there has been no one to explain it to us in the clear, logical, comprehensive way that is possible! One might think that the real pros in Aerodynamics could do it easily. The problem is, a pro forgets to say and tie together the fundamentals that the learner needs, doesn't grasp what a pilot needs to know, gets lost in minutiae, seldom grasps the logic that integrates efficient operation of the plane and the engine.

Though the intent is "SIMPLE", don't underestimate what we're after here. This will be a book for the learner, but it will be much more. It will teach professionals *incisive* logic that they had not thought to tie together. The OBJECTIVE here is nothing less than **the definitive book** on THE BASIC LOGIC OF FLIGHT, that will work **for a broad range of readers**!!!

How does one set out to make a complex technical morass like Aerodynamics simple, logical, easy to follow and grasp, with very simple conclusions? Well, there is a *very specific way*. It only takes a lifetime of experience and knowledge to grasp the simple way to see through Aerodynamics complexity, and see how to teach it simply! We began to explain in the "Forward" that the modern age began when the first Philosopher, prototype Scientists and Engineers, first started to pin down the fundamental laws of nature, of Physics, in the 1600's.

They found *very simple*, *logical*, mathematical relationships, the Natural Laws of Physics and Chemistry, easy, but very specific little formulas underlying *everything*! You'll see that even though the basic formulas are very simple, the fact that they are very specific, allows us to draw multiple, very incisive insights, from each part of what is there! It's quite amazing really!

The genius, that we hope to pull off in this book, is to: 1. let the laws themselves show us the logical way to proceed, to teach you. 2. very carefully follow that simple, *incisive path* so that the relationships *stay simple*, *logical* and essentially *exact*. You may not even be aware that we'll be following a very specific disciplined path, based on a lifetime of experience and insight, you'll just be amazed by the clarity. We do warn you that you can learn a whole lot, so keep your receiver turned on high!!

Here's that early insight we promised you. There are <u>three</u> ideal flight modes, but for most flying, the only one that makes sense is the one that minimizes drag vs. speed, **maximizes speed vs. drag**, or **fuel** required, or fuel **cost**. Drag, gallons, cost, are all equivalent, decrease MPG!! For *a given gross weight*, there is an **ideal indicated airspeed, IAS** that **stays ideal** *at* **any altitude**, because constant IAS *means constant drag*!!! Now all you have to do to *optimize engine efficiency*, and *optimally match the engine and plane*, is to **climb** to the altitude where your engine is *just wide open*, ***unthrottled***, and ***lean** it properly*, holding that *magic IAS*!!! Naturally your True Airspeed will have greatly increased, you will have good speed, you will have optimized speed vs. trip cost, and optimally matched your engine and plane! IT'S THIS EASY! 1. **AN OPTIMUM IAS** (vs. GW). 2. **CLIMB, GET UNTHROTTLED**. 3. **LEAN**!

Believe it or not, there is an even easier way, that's even more all encompassing! Constant, ideal, IAS, Drag, vs. weight, lift, found IDEAL TRAVELING L/D, C_L, *angle of attack*, fuselage deck angle!! That means you can mount a small "level" on the cabin wall, at the *magic angle*, call it the "Super Science Flight Optimizer", and use it for any altitude, any gross weight!!! You climb up to where the engine is ***wide open***, ***(leaned)***, at the **MAGIC ANGLE OF ATTACK**, bubble in the middle. That's it, everything is optimum!! Do **not lean** in climb, **low**, at high power, where the engineers intended a **cool richer** mix!

Do you see that I wasn't kidding you? We're, going to have fun here, learning! You're going to get **as smart as you wish**, and the way we're going to do the explanation, it will work for first time learners as well as professionals looking for more insight!

Yes there are some subtleties that have minor effects, like Reynolds number. We'll cover those too, but not let them obscure the central truths!! There is indeed a BEAUTIFUL, and SIMPLE logic to the way that airplanes work, and it's all going to be laid out so everyone can grasp it!!! ENJOY!!!

It's always easier to learn something if, before you start, you get a feel for what the final conclusion is, where you're going, how you're going to get there, so we're going to build that into our presentation! That's why we already told you a concise version of the major conclusions of the book! Quickly now, we're going to start showing you the first look at how we're going to get there, an **early outline of how** we'll make a complex subject like the aerodynamics of intelligent flight, logical, easy, fun and satisfying! But **first** there's something about **how we learn**!

Looking back, I was fortunate to have some great teachers. Sylda Smith, red hair, school marm bun and all, was one of those wonderful high school teachers who cared, who was not about to let any of us dumb kids fail math, before we were mature enough and organized enough to know what was good for us! If you weren't up to her standards, you would, by command, be in for her special 7 AM class for "laggards". If it happened to be a frigid Cleveland morning, tough, that was just another part of the necessary growing up process, and she told us so! Abby Rush, signed Ab^2y, the other Algebra teacher, was a close second, won honorable mention.

Ohio State, one of the "Land Grant" Universities, at $47 a quarter, did a fantastic job, targeted "a broad engineer" in a five year program with the (3) quarter system, 15 sets of subjects, rather than 8 with a four year semester system. Somehow they all succeeded, because for a kid who started as a pretty unpromising student, I certainly had a fantastic career. It included, jet landing gears, complex servo flight control packages, spacecraft rocket maneuvering system controls, nuclear power plant earthquake protection, analytical instrumentation, and much more. In all, a whole fistful of technology, and not just as engineer, but as company founder, general manager, salesman, program manager, the whole game.

What I've really always been about is creating successful, leading edge, high technology products. That very specifically includes learning, solving the problem, teaching and leading the organized solution. Our task here is very much about complex technology, and specifically, **clarifying, simplifying, teaching**, and **learning, complex technology**. Those are pages right out of the book that I've been dealing with for a lifetime.

I've had the great fun and challenges of the major multi billion dollar complex technical programs, Aircraft, SPACE et al! That can be as important, challenging, interesting as any profession there is. You have to bring everything together, the entire human, technical, business spectrum, and prevail over any and all competition. There is no second place prize. What that takes, is really having the right answers, proving *absolute credibility*, and surprise, **teaching**, that is, leading intellectually! What you will see herein is the result of **a lifetime of experience**, not only with complex technology, but in making complexity clear, understandable, agreeable to deal with, *user friendly*!!

To learn complex subjects, you **need a better way**, and if you're **lucky**, someone to figure it out and **simplify** it **for you**. You'll see *both* here. Somewhere back there some enlightened soul taught me the classic old, and well proven **SQ3R** method of learning: **Scan - Question - READ - Recite - Review.**

SCAN what's coming. QUESTION. Get in mind what's apt to be involved, so you "start anticipating a pattern", a frame of logic and facts to learn on. READ it, RECITE it, the key facts, as you go, then REVIEW it -- and you got it. The central core of this classic method is SEEING EARLY -- WHAT THE PATTERN IS. **We adults both learn and remember by seeing the pattern, how everything in a subject fits together, interrelates. IF, it makes sense to us. we learn it quickly, easily -- we remember it. and we USE IT**!!!

That's the game we both want to play here, so I'll do my part, if you'll do yours. So, here goes, **here comes the pattern**.

As introduced in the Foreword to the book, the basic natural laws are very simple, and all tie together in a neat orderly way once you have enough experience to see the pattern. Thus, the way to see through the complex mix of science here, is to let the **natural laws show us** the **logical, incisive, exact, easy** way!

● ENERGY, is what makes airplanes fly! Looking at energy gives us a very enlightening fundamental grasp of how DRAG, INEFFICIENCY, HEIGHT, and DISTANCE eat energy, and launches us on the logical understanding of the whole subject of flight! DRAG and INEFFICIENCY become the twin enemies!!

● LIFT and DRAG. One simple little formula, gives us the first picture of how *both* lift and drag work, is the key to grasping several fundamentals of the logic of flight, including WHY AIRPLANES FLY ON IAS, so it will be the first and only formula we'll take the first time novice through!! ✓

● DRAG is the chief culprit that eats energy! There are **TWO** basic types of drag. They are quite **opposite** in the way they change with speed, and they **add together** in a way that causes all airplanes to have the **same shaped drag curve**, but with important *rotation* differences. LEARN ONE, LEARN ALL! You begin to see through all planes as this picture emerges!

● THREE OPTIMUM FLIGHT MODES. Minimum power gives maximum endurance, minimum drag yields max range, but MAX SPEED / $ becomes THE THINKING MAN'S WAY TO FLY, where we learn how to purchase speed wisely!!!

● THE IMPLICATIONS. OPTIMUM, CONSTANT IAS for a given gross weight, at any altitude, better still, OPTIMUM, CONSTANT ANGLE OF ATTACK at *any gross weight*, any altitude, both yield IDEAL CONSTANT L/D, (LIFT/DRAG), flight. The **effect of weight** on drag and required IAS, of **lower air density** increasing True Airspeed at **high altitude**, **free speed** with ***higher* TAS** that doesn't hurt MPG, are all central to understanding! You really begin to grasp the whole subject!

- THE ENGINE. Understanding why your engine must be too big for your plane, and why that causes it to be even more inefficient, teaches you WHY you need to understand HOW to maximize engine efficiency and optimally match it to your plane. The key, **HIGH**, **UNTHROTTLED**, **LEAN.** Q. HOW HIGH?

- THE THINKING MAN'S WAY TO FLY. The amazingly simple conclusions on how you can fly intelligently, efficiently easily, and why it all works out so neatly! OPTIMIZING ENERGY USE vs. SPEED, sets up the CORRECT LOGIC OF FLIGHT, where BASIC DRAG CONCEPTS set up simple specific logic that obeys the controlling natural laws!!!

- THE GRADUATE COURSE. It's possible to explore lots of subtleties, and we'll do a good deal of that for those who want to have it all precisely correct. Of even greater value however, is to recognize the simple orderly relationships between everything, *intelligently ignoring minutiae*. A few extra Chapters and Appendices with worthwhile insights for those who choose, and we'll have a flexible presentation for all!

Now just how do we propose to teach the whole logic of flight, deal with the complexities of aerodynamics, make it easy for the novice and satisfying for someone much more knowledgeable? FIRST, we're going to attempt to write it in understandable English and understandable logic, in big enough type that it's an EASY READ, but that's not all.

SECOND, we are going to carry along a **deeper**, more probing, narrative, with more detail, the complete formulas, in slightly **smaller print**, for the advanced people who want it all together. That way the novice can simply skip what is too much for him, at least on the first pass, and the more technically inclined can go as deep as he wishes the first time, and be satisfied! Either way the novice will see and understand.

With due apologies to the more technical reader, we are going to try to write the finer print version in English as well, not "Greek Tech.", to encourage the novice to come back for a second pass after he grasps the basic picture, get an even better, deeper grasp, hopefully answer what questions he may develop.

THIRD. Purposely sacrificing what is properly considered "good normal writing style", we will use every available method to EMPHASIZE, TO CLARIFY, TO HELP the learner. If we succeed in our objective of making the complexities of Aerodynamics, "duck soup" for a broad audience, a task never accomplished, that's a miniscule sacrifice. We'll even have some sentences that are too long when we need to tie a whole logic string together, TO HELP the learner! I've taken bigger risks than that, for lesser goals, so be forgiving, if you're a pro!

You are going to end up clearly understanding that: 1. AIRPLANES FLY ON "q", IAS, INDICATED AIRSPEED! *but* that 2. ENGINES FLY ON TAS, TRUE AIRSPEED! and WHY those two fundamental facts are true. They are ***both*** fundamental to both THE LOGIC OF FLIGHT, and THE THINKING MAN'S WAY TO FLY, but you won't find that grasp, that concept in any other book!

Our fond hope is that even a pro will find some thoughts outside his usual thinking that will prove interesting, give him an insight, here and there, that he hadn't thought of.... On the Voyager World Flight, we found very competent people missing some key fundamental points!! Many years in the high technology business taught me the REALLY smart guys learn from everyone, even the sweeper, because everyone sees a different facet of the problem at hand!

I once saw my ace machinist solve an obscure metallurgical problem that had stumped me, my chief engineer, and every pro I could reach on the phone! Denby Karaharawa, our experimental machinist saved an Apollo contract that really had the best metallurgical experts in the country stumped! I long ago learned to respect the other guy. I found he can be very smart in ways that I and you are not, in areas, where we may not even recognize that there is something to be understood!

It is a huge misfortune that many highly intelligent people in the technical fields just love to make things obscure, complex, arcane, to write in technical Swahili, unfortunately like guys in a private clique, looking for elite stature! The technical journals can be awash in it! NEWTON'S TRUE GENIUS WAS CLARIFYING THE OBSCURE, FOR ALL TO USE!

WHAT IS TRULY VALUABLE IS TO DO PROFESSIONAL WORK TO SEE THROUGH COMPLEXITY WITH X-RAY VISION, THEN MAKE THE COMPLEX CLEAR AND EASY, SO IT CAN BE GRASPED BY ALL, PUT TO BROAD INTELLIGENT USE! THAT'S HOW THE REAL ORIGINALS DID IT. THAT'S HOW PROGRESS HAPPENS. **That's what we're after here!**

SUMMARY INSIGHT

Since the basic natural laws of Physics are so remarkably simple and logical, if we are only wise enough to follow the logic trail that the simple laws and formulas set up, we have found the ***magic way to decipher*** a complex subject like Aerodynamics, find remarkably simple concepts and conclusions! (Indeed, the engineering formulas, with those scary Greek letters that so quickly put off everyone not trained in the sciences, are the very mechanism that, in the right hands, make the complexities simple and understandable. ***Watch it happen — for you!!!***)

In this book you will come to understand that an airplane is a "flying machine" that converts *energy*, fuel energy, into flight!

If **energy** is the fundamental commodity used to create flight, the lead we should look to is what are the basic laws governing energy. That quickly teaches us about big INEFFICIENCY, and that we need to come to UNDERSTAND DRAG, how to minimize it, how to get the least drag for the most speed, to intelligently fly any given trip!

That leads to **a remarkably easy and interesting logic path, a long list of equally remarkable insights and conclusions**!!

We'll learn WHY it's proper to **FLY CONSTANT IDEAL IAS** for a given GROSS WEIGHT, at **ANY ALTITUDE**, A **CONSTANT IDEAL ANGLE OF ATTACK**, CONSTANT IDEAL L/D at ***any* altitude, *any* gross weight** -- WHY you CLIMB TO MAX ALTITUDE, MAX TAS, WITH THE **ENGINE WIDE OPEN**, ***LEANED*** **for** ***MAX ECONOMY!*** YOU HAVE the ***LOW IAS DRAG***, at the ***HIGH TAS SPEED!***

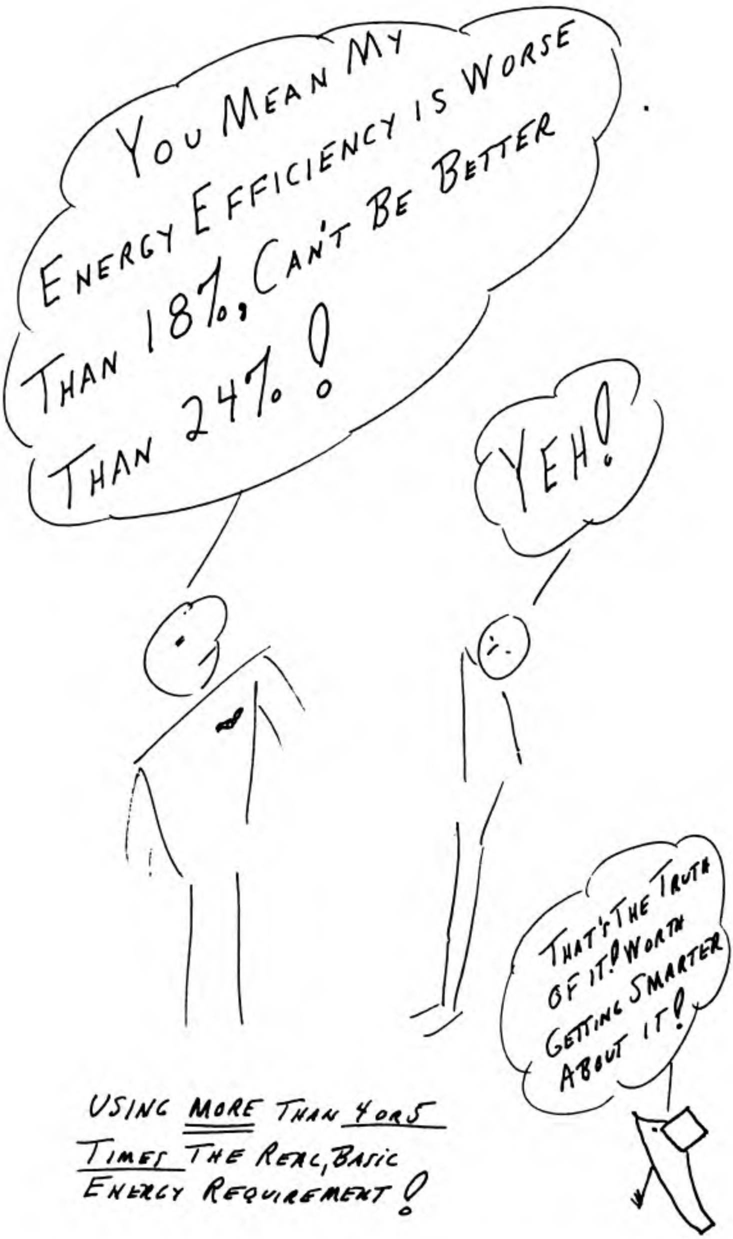
IT"S A CINCH TO LEARN THE THINKING MAN'S WAY TO FLY, **BUT**, THE REAL REWARD IS TO UNDERSTAND **WHY**, AND GRASP THE HEART OF AERODYNAMICS AND ENGINES IN THE PROCESS!!

The straightforward objective of this book is to take the complex subject's of Aerodynamics and Engines, make them fun and interesting, to understand and use advantageously in flight! We didn't initially intend to, but props are explained too, the ultimate morass challenge that took 138 years to explain here!

The subjects are: Understanding The Logic Of Intelligent Flight, and Grasping The Central Core Of Aerodynamics, and Engines, -- EASILY. The challenge is to do a better job of **TEACHING,** and **LEARNING**. We'll use every method to keep, you clear on WHERE we're GOING, HOW we're going to get there, every method to emphasize, make CLEAR. Since, you already have your first grasp of the **simple, final conclusions, you really can't get lost, because we'll keep coming back to the same central theme, building, refining your grasp.** *If you do get lost, or snowed, temporarily, don't panic*, because we'll be right back to the theme you already know. **1. Ideal IAS vs. GW, any altitude, (ideal α, any GW, any altitude!). 2. Climb, until wide open, 3. Leaned for Max Economy! --- EASY, in fact DEAD SIMPLE!!**

It's all set up to accommodate learners at any level. You need **only go as deep as you want to, and are able to**, but you have the option to get smarter than experts on how it all works and ties together. **The experts never state it clearly, completely! A learner needs that help to see it best, and easiest!**

My bet is that you'll be intrigued and challenged, get it in your own way, at your own speed, and end up smarter on how airplanes work, than you ever thought possible!!



USING MORE THAN 4 OR 5 TIMES THE REAL, BASIC ENERGY REQUIREMENT!

CHAPTER 2

ENERGY

The objective of this chapter is to show you, in a way that you will never forget, that the laws of thermodynamics are very unfriendly, that there is a gross inefficiency in the way that engines use fuel. That directly points a Thinking Pilot to get smarter on how to minimize drag vs. speed and optimize engine operation, to use fuel optimally, indeed to the entire CORRECT LOGIC OF FLIGHT -----

An airplane is a flying machine that converts energy, fuel energy, into flight, and thus it is bound by the simple laws of energy! Energy calculations can be SIMPLE ARITHMETIC, yet they PERMIT GREAT INSIGHT on matters that can be vastly more complicated analyzed by other means!

If you *push with one pound of force over one foot of distance*, or *lift a one pound weight one foot*, either way you have expended *one foot pound of energy*. There are 778.26 foot pounds of mechanical energy per BTU, British Thermal Unit of heat energy, (A BTU simply heats 1 pound of water 1° F)

Did you catch the clue there? Can you see where this simple logic is going, how easily we'll meaningfully interrelate drag, distance, fuel energy required, and even how much fuel it takes to hoist your plane up to 10,000 feet --- an answer you'll not easily or accurately get, by far more complicated means!

There is a BIG SURPRISE however, a very important insight that I'll bet you'll never forget, so we'll take you through a simple little example, and you can gain the insight just as I did!

Way back at Christmas 1950, driving home from college in my senior year, and looking for an airplane, knowing I was going to be called into Air Force Engineering at Wright Field, immediately upon graduation in June, I came across a beautiful 1947 Luscombe 8E for **$1225, *one third* of its new price!** As a mere student, it took nerve to buy an airplane with my model airplane winnings. With no income yet, it was a leap of faith. It became a real education flying back an forth, essentially every weekend, summer and winter, safely, not becoming a statistic!!!

As things turned out it became a lifetime, essentially free airplane, now a valued Classic, less than **22 dollars per year, 57 years later.** I got way too busy to have an airplane, but was not about to let go. The simple, reliable Luscombe, was practical to keep, always ready to go. It's been a lifetime escape vehicle that's been everywhere, every possible flying condition. It was the cover plane on the February, 1993 AOPA PILOT.

$1225 / 57 Years = $21.49 per year Capital cost!

By 1982, getting closer to retirement, and after years of just using the trusty, classic, Luscombe for R & R fun to get away from the hassles and stress of high tech. engineering work, my curiosity finally got the better of me, and I dove in to find out how THE LOGIC OF FLIGHT really worked!!!

I tried the very calculations we were getting into above and **found such a wild mismatch in the numbers** that it started an investigation that has yielded **a whole series of amazing results**, just one of which was my backing into being the **Technical Director in Mission Control on the world flight of the Voyager**. By 1986, I had a lot of insight others just didn't have, and it became amazingly easy to see through it all!!

Here's the simple enlightening calculation! To hoist a 1400 pound Luscombe up to 10,000 feet would require 14,000,000 ft. lbs. of mechanical energy. DIVIDING by the 778.26 ratio above (ft.lb./BTU), it would look like only about 17,989 BTU would be required, only about *one pound* of Av gas, at nominally ~19,600 BTU per pound. Any pilot with any feel for his plane would know that was not close to being enough!

Here is where we start getting smarter! The hooker is that there is a **huge efficiency problem!** The overall efficiency of a plane and engine combination which could fall in the range of 20% to 25% is actually most apt to fall well below 20%, *heavily throttled*, or in max power climb where the engine designer may dump in *more* than a max power mixture to cool the valves!

Thus, rather than requiring (17,989/19,000), .95 pounds of fuel to climb a small plane to 10,000 feet, it will take more like a 5.85 pound gallon of Av gas, which is lighter and has *less* energy than a heavier, 6+ pound broad cut auto gas, or Jet Fuel!

The main problem is that internal combustion engines are a disaster from an efficiency standpoint, 27% to 33%! To be efficient thermodynamically, you want the engine to burn hot, maybe ~4500°F, then dump its exhaust at absolute zero, -459°F below zero, after extracting *all* the available energy. In fact, the exhaust gets dumped *red hot*, maybe ~1500°F, for a number of reasons, so as an efficient heat engine it's a bigtime failure! Since the Aluminum/oil can't run above 460*/220°F, there's a big cooling loss as well, and in addition that adds a big cooling drag to the plane, which amounts to nominally 10% of the available horsepower, after it's generated at that terrible efficiency! It's a very unsatisfactory situation, not readily changed.

* Cylinders have a ~460 F° Red Line. Stay below 400, avoid cracked cylinders!

A really good engine requires about .4 pounds of fuel to develop one horsepower for one hour. If you run that through a calculator as above, and compare it to 33,000 ft. lbs /min. per HP you get only 33.5 % efficiency. A more common engine at a "specific fuel consumption" of .45#/ HP hr. would be only 29.7%, and a .5 engine, where **you** are operating it poorly, is but 26.8%. Engineers learn in college that Thermodynamics is a very inefficient process, and learn to accept it as inevitable, but if you look at those terrible numbers, there's a lot of argument for being a lot less accepting! There will be change, refinement.

I can get about 28.9% out of my 73 Octane Continental C 85!

So that's a quick look at the engine part of the efficiency problem, so you can start to get a little feel for what's really going on, and begin to recognize that if you can do something intelligent about how you fly your plane, to cut the fuel bill, mitigate the big fuel waste, you're making a right move. We'll look deeper into engines in a later chapter, so you can understand them even better. **You can make a big difference!**

Now to the airplane part of the game! Back in 1982 when I got curious about all this, I wanted to do a test and find out what the real drag and propulsion efficiency of my classic Luscombe was, just to really understand the *whole* LOGIC OF FLIGHT. I was told there was **no test**, I could *not* get a real answer! But pros told me props were about 80% efficient, so I could assume 80% propulsive efficiency, and calculate a drag considering .8 of my HP! Eight decades, into the age of flight and two decades into the space age, I saw the **inability** to get a REAL test answer as half **unacceptable** and half **ridiculous**.

The sailplane people, notably Dick Johnson, several times National Soaring Champion, get magnificent drag data on their craft by doing very carefully controlled, more than professional gliding sink rate tests.

$$\text{Drag} \times \text{TAS} = \text{Sink Rate} \times \text{Gross Wt.}$$

$$\text{Drag \#} = \text{Gross Wt.\#} \times (\text{Sink Rate} \ / \ \text{TAS})$$

To make that nifty, simple little formula and test work, and give correct answers, you keep drag and GW in pounds, and sink rate and TAS *both* in ft./sec. The very simple principle working there, is that the weight sinking at a rate of speed **releases vertical power**, to match the **flight path power required**. Power is force times speed, rate of use of energy, (ft. lbs./sec.)

It was never possible to do that glide testing on a propeller airplane because the propeller/windmill was always in the way, creating thrust or drag, providing or absorbing power! As we'll explain later in the book, we worked out a way, that, by sensing zero thrust, using the axial slop in the crankshaft thrust bearing, permitted glide tests, just like a propellerless sailplane! That solved the longest running, most fundamental gap in Aeronautical Engineering, 87 years after the first flight!

The results didn't agree with the party line at all, on my unsophisticated Classic plane. The **drag was much lower** than might have been predicted, but the **propulsive efficiency was far below a propeller's nominal 80%**. It had seemed completely illogical to me that a poor little propeller sitting in front of a less than perfect, classic airframe, blowing back on it, would still deliver a full 80% thrust efficiency. It did **not**! Testing showed it **got worse** as you increased thrust. **The prop was ~75%**, **another ~90% factor** in there at reasonable power, for **nominally 67% when both were multiplied together**. That would have been even lower if we would have installed closable cowl flaps, eliminated cooling drag, lowered the "real airframe drag" even more. Comparing low airframe drag and required power, with real engine power, would be **below 60%!**

In the process of working it all out, we learned of August Raspet's great work in 1954 at Mississippi State, where he did free glide testing of a *propellerless* Bellanca Cruisair, towed to 12,000 feet. Testing it with the engine cooling ducts sealed, he got such low drag, that, comparing it with the horsepower required in powered level flight, he found that propulsive efficiency, **airframe required power**, divided by **engine input power**, was only **58%**, **essentially, exactly what we found!**

1 /.58 = 172% more Power required, vs Gliding, WOW!!!

So, we have something like 30% engine efficiency, multiplied by roughly 60% propulsive efficiency, a *ridiculous* overall **<18%.** That means we may use more than FIVE TIMES the basic energy requirement!!! That number can float around between FOUR to SIX, depending on how smart your engine and airplane designer are, **and you**! **You can have a BIG effect!!**

HOMEBUILT planes have become A NEW LEADING EDGE OF FLIGHT! The slick, efficient, new homebuilt designs, with low drag and good propulsive efficiency, that are going faster, farther, on less fuel, are an IMPORTANT and necessary development for personal flight in this 21st Century. **YOU** knowing how to fly your plane intelligently, efficiently, is equally IMPORTANT. Challenging the laws of thermodynamics to yield more efficient engines is something you can bet on, as we better grasp the huge need, grasp that fuels may well be manufactured, not mined, in the new Century, that is here now! When the oil runs out we *better* have Fusion, liquid **H** fuel !!!

Before we finish, you'll understand that automobiles, which have been making great efficiency gains lately, are severely wounded by driving around **at low power, heavily throttled**, which requires them to **PUMP their air in**, which compromises their potential! The same problem occurs with your airplane engine, BUT, **if you grasp** the lessons in this book, you will understand that **you can fix** that problem by simply climbing up, flying at BOTH **low power** and **wide open**, in the thinner air!!

The engine is such an important item, learning how to very easily optimize engine performance, and optimally match it to your plane by simply flying it unthrottled, **wide open**, but at **low power**, **lean**, at the optimum altitude, IAS and α^{o} for your plane and engine combination, *is* **the major objective of this book!**

The way the logic develops, however, it's proper to learn the airplane logic first, **how you intelligently fly a Drag Curve**. As we already showed you, for a given weight, all you have to do is learn how to fly your plane smart, at optimum IAS vs. drag, fuel, and fuel cost, then simply climb up until your engine is wide open, or close enough that your efficiency is not wounded by throttling. Climbing **high** at **optimum IAS**, constant drag, constant angle of attack and L/D, you increase speed, TAS, *without* hurting drag or MPG, then *improve* MPG by *increasing* engine efficiency by unthrottling it, leaning! That is the core, of the entire CORRECT LOGIC OF FLIGHT!

YOU'LL COME TO SEE THAT THE MOST BASIC PART OF THE GAME IS COMING TO UNDERSTAND A DRAG CURVE AND WHERE A THINKING PILOT SHOULD FLY ON IT, SIMPLY BECAUSE THAT DRAG IS DRAGGING OVER YOUR ENTIRE TRIP LENGTH, EATING FUEL ENERGY, JUST LIKE YOUR ENGINE INEFFICIENCY IS! Climbing eats energy too, but it's a **good investment** with a big payoff in free speed, and increased engine efficiency. You can get some of it back in an efficient letdown, but the startling insight there is that you already wasted nominally 80% of the energy and can only recover the 20% left in your plane's height!

I Fly 2 Miles High. At 12: 1 L/D, 24 Miles Range, at ~ 70 MPH, ~ 20 Minutes!

You can actually do better than that makes it sound, because you can glide down at zero thrust, as I have, at ~Max L/D cruise speed for over 20 minutes, at as low as 5 HP and not burn the fuel you would have been burning, with its built-in big loss. It's an intriguing little fun puzzle you can see with a fuel flowmeter!

Hopefully you're seeing, agreeing, that, true to our promise, we're going to "teach you a bunch". ALL the conclusions are going to be SIMPLE, one step at a time, and LOGICAL, *but very incisive*, and build to a very complete understanding of the whole LOGIC OF INTELLIGENT FLIGHT, an understanding you'll USE and ENJOY for the rest of your life!

A huge accolade is due the late August Raspet, head of the Aerophysics Lab at Mississippi State U. in the 50's, and mentor of many successful Aeronautical Engineering Graduates such as Richard Johnson, of Sailplane Fame. An activist, maverick, he **challenged his students to get out, creatively use their brain!**

Raspet began free glide testing propellerless personal airplanes in the early 50's, to get the first factual drag and propulsive efficiency data to evaluate and refine the breed. His data stood as the best and only REAL data on propeller airplanes. He clearly showed the real drag, and inferior propulsive efficiency of several planes of that time. Oddly that insight did not seem to be picked up by the industry when it was clearly, important, meriting further work and product improvement.

Richard Johnson became known worldwide for his refinement of his R J 5 sailplane, working with Raspet, his many soaring accomplishments, and finally, his ultra sophisticated glide testing of the ultra sophisticated **world class 60 : 1 Sailplanes**.

His work raised sailplane testing to an art form, and inspired our work which led to the development of **Zero Thrust Glide Testing.** Most significantly, whereas ZTGT would seem to be less pure and sophisticated, the availability of the engine makes it **possible to go find "perfect air"** for near-perfect test results. Such is the way that progress is made, the Science advanced. **This book is possible because we have real drag curves !!**

CHAPTER 2, ENERGY, (IN A NUTSHELL)

If a Flying Machine converts energy into flight, it is logical that we look to the basic laws of energy to find the start of the logic trail to decipher the basic and correct LOGIC OF FLIGHT!

We find a pound of Gross Weight lifted 1 foot is 1 ft. lb. of vertical ALTITUDE ENERGY, and a pound of DRAG flown one foot is 1 ft. lb. of FLIGHT PATH ENERGY!!

This can be related directly to fuel required, if we know the efficiency of the engine and propulsion system, since there are 778.26 ft. lbs per BTU of heat (fuel) energy, and nominally 19,600 BTU per pound of 5.85#/Gal. Av Gas. (Jet = 6.5#/Gal.)

Heavier Auto Gas, ~ 6#/gal., is generally above 20,000 Btu/pound.

As pilots we would never try an engineering calculation. BUT, doing that simple arithmetic calculation immediately provided our first major reward, the shocking insight that engines may only be 27% to 33% efficient, our propulsion efficiency perhaps as low as 58%, that we use FOUR to SIX times the basic energy requirement. We can get HUGELY SMARTER, EASILY, by just following this logic trail of the natural laws!!!

Since the distance to our destination is fixed, at 5280 ft./ mile, (6076.11549 ft./n.mi.), (1.15078 ratio), we realize that if we follow the logic trail to UNDERSTANDING DRAG, *flight path energy* --- more huge insight, knowledge, *intelligent flight rewards*, await us!!!

The simple calculation that we did to illuminate the huge efficiency problem, gave us a super easy way to find extra fuel required to climb to *any* altitude at *any* gross weight! It also gives us the insight to recognize that the game of an efficient let down, is to RECOVER THE (roughly 20)%, ALTITUDE ENERGY, THAT WASN'T LOST IN THE CLIMB!!


GET THIS
AIRPLANES FLY ON "q"
(DYNAMIC PRESSURE)
IAS $\cong$ q
CONSTANT IAS = CONSTANT q
CONSTANT DRAG!
ANY ALTITUDE!
ONE BASIC FORMULA TEACHES YOU EVERYTHING YOU HAVE TO KNOW
AERO 101 IN ONE FORMULA
$L = C_L \cdot AREA \underbrace{\left(\frac{\rho V^2}{2}\right)}_{q}$
$D = C_D\ AREA \left(\frac{\rho V^2}{2}\right)$
IT'S BASIC MAN!

CHAPTER 3

LIFT AND DRAG

Chapter 3 and 4 are the ones with the most Formulas, and Math. Don't be faked out, read on. If you do get snowed don't stop, read on, get all you can get. We'll be back, end with Pictures!

This is where we start teaching you the basics of LIFT and DRAG, so you can completely understand THE LOGIC OF FLIGHT. There is ONE simple little formula that defines them BOTH, so it's even easier to deal with, well worth looking into. You'll see that we will get a simply huge amount of information and insight out of it by twisting it around, looking at it in different ways! A few chapters ahead you'll see that the whole game is simply flying at the SMART, OPTIMUM POINT on the DRAG CURVE, which will in fact be at the OPTIMUM L/D for SPEED vs. DRAG! Just hang in and we'll take you through everything you need to understand, and we won't even strain your brain! There is even one of those scary looking Greek letters in the formula, but you'll laugh when we show you that little part of the formula just gets the pressure in front of your pitot tube*, actually equivalent to your IAS!!

* We simply use rho, ρ, the air's Mass Density, to get q, Pitot Tube Pressure

You realize, of course, that Aerodynamics can be an extremely complex subject, that can require supercomputers to get answers that are only approximate, and here we are telling you that we can keep it simple, essentially exact, for you. Well, we can, but the key, the intelligent choice that we are making for you, is to choose the special logic path, the special cases where the relationships stay simple, essentially exact, easy to understand!! It turns out that there are very valid, very fundamental performance reasons for flying an optimum constant IAS for a given gross weight, a constant optimum L/D, because, *when we do that, **drag stays constant**, all the basic relationships stay simple and essentially exact*, so that's where we are heading. Doing that, we can start right at the basic lift and drag formulas, take you right up through the whole LOGIC OF INTELLIGENT FLIGHT and never strain your brain. Once you're there you'll have such great insight, that you'll be able to see through even difficult things. SO, HERE GOES!!

The most basic formula in Aerodynamics is the ONE that defines BOTH LIFT and DRAG by simply switching a few symbols!

$$\text{Lift} = L = C_L \times S \; \overbrace{(\rho V^2 / 2)}^{(\text{"q"})} \text{ pounds} = \text{Weight}$$

$$\text{Drag} = D = C_D \times S \; (\rho V^2 / 2) \text{ pounds}$$

Do you see what we mean? Both those formulas are really the same one! We just switch C_D, the Coefficient of Drag for C_L, the Coefficient of Lift, and we convert the basic Lift formula to the basic Drag formula! We'll get back to C_L and C_D shortly. There is a lot of insight to be gained from C_L and C_D.

To jump ahead to see important things and see that a formula does not have to scare you away, the S is just WING AREA, in square feet, and that stuff in the parentheses equals "q", the ram dynamic pressure, in pounds per square foot, the pressure you feel *if you stick your hand out the window*, the *ram pressure in front of your pitot tube*. Once you see that it's that simple, you'll never forget "q" again!! **AIRPLANES FLY ON "q" !**.

Your Static Port Pressure is subtracted to get the Real q Ram Pressure!

That "Greek" term is rho, pronounced just like "row your boat". "ρ" is just the symbol for air density. V is just Velocity, speed, in fact *real* speed, TRUE AIRSPEED, TAS, (but in ft.per sec.)!

It turns out we can get a Huge amount of insight by understanding "q" better, looking at it from different aspects, and it's very basic to understanding THE LOGIC OF FLIGHT, so we'll do that now, but with just a few words to put the other items in the formulas on "relaxed hold".

Really, Static Port Pressure is subtracted to get the Real q Ram Pressure!

Obviously the wing area, S, how big it is, is pretty basic to how an airplane flies, but once the designer establishes it, it's not going to change. *How many square feet are there,* is not hard to understand. We'll discuss S further in the next Chapter, when we get more deeply into drag, because the aspect ratio, span/chord is *very* important to Induced or "drag due to lift". Aero's use *wing area* for drag, when obviously other surfaces affect drag. That needs a good discussion, intelligent answers.

BOTH C_L and C_D vary vs. speed and resulting angle of attack, (α^o). We'll discuss them shortly, C_D continuing into the next chapter on Drag. C_D has two components, "an almost" constant C_{Do} for Parasite Drag, and one that is *highly* variable C_{Di} for Induced Drag, based on $C_L{}^2$, and Aspect Ratio actually!

Induced Loss is just the Energy Cost, Loss of Throwing Air Down, to Make Lift!

It makes sense that **AIRPLANES FLY ON "q", RAM DYNAMIC PRESSURE,** that it's basic to BOTH LIFT and DRAG, each ***equally*** affected by it! What could be more basic to an airplane than **how *hard* the wind is approaching**?!!

It makes equally good sense, that "q" depends on ρ, how dense the air is, and the speed, V, in fact the V^2 you see in the basic equation. We can skip the math and Physics derivation of why it's V^2. It's this simple! Twice as fast you hit twice the air particles, each second, and the harder it is to shove them out of the way, (faster and faster), so it's a *double whammy*, V^2. It's that simple! Accept it, it's an absolutely fundamental fact.

YOU WANT A "q" SENSOR, so you can sense exactly what THE PLANE is sensing, what it is reacting to, **SO YOU CAN FLY THE PLANE BY ITS LOGIC OF FLIGHT**!!!

SURPRISE, YOU HAVE A "q" SENSOR SITTING RIGHT IN FRONT OF YOU!! IT"S a very special gauge that does an amazing mechanical and Aerodynamic trick to give you the data in a form that is more useful to you, easier to interpret for the average pilot. It's called the AIRSPEED INDICATOR, and it reads out as **IAS**. To read out in IAS it has to do the amazing mechanical trick of *extracting the square root of "q"!* (That's a pretty nifty trick mechanically!!)

In case that confuses you, don't let it. The key is real simple. **JUST RECOGNIZE THAT THE AIRSPEED INDICATOR IS SENSING THE 'q' AT THE FRONT OF THE PITOT TUBE**. That's what is important!!

Really, Static Port Pressure is subtracted to get the Real q Ram Pressure!

You don't really care if it reads Knots IAS, (or MPH in an old bird), not pounds per square foot. Pounds/ft.^{2} would not be useful to you. You probably always thought that it was bad that it didn't read out as TAS, but you see its *wonderful* that it reads IAS, drops off as the air thins, because by just sensing the ram dynamic pressure, **it ties what you're sensing to what the airplane is sensing, and flying on!!! BIG important point!!!**

YOU WANT TO FLY A CONSTANT IAS AT A GIVEN GW, BECAUSE YOUR DRAG WILL BE THE SAME AT ANY ALTITUDE , YOU WILL BE HOLDING 'q' AND L/D CONSTANT, ALL OF THE AERODYNAMIC RELATIONSHIPS WILL STAY SIMPLE AND EXACT.

You'll see when we get to drag curves in the next Chapter that we always **PLOT DRAG vs. IAS**! It stays the same at any altitude, super simple, the basis of the Simple Logic Of Flight!!!

GRASP HERE EIGHT ITEMS OF HUGE IMPORTANCE

1. **IAS IS EQUIVALENT TO "q"**, because "q" is what the Airspeed Indicator senses, ram dynamic pressure, **with static (-static)**, and **AIRPLANES FLY ON "q"**, the "wind" that **equally effects, energizes both Lift and Drag. THAT'S THE KEY!**

Really, Static Port Pressure is subtracted to get the Real q Ram Pressure!

2. **AIRPLANES FLY ON IAS** If IAS, "q" stays the same, **both lift and drag stay exactly the same**, and the **same ratio** to each other, at any given gross weight! (and that means **Constant L/D**!!) **YOU CONTROL IAS**. After direction, IAS and ALTITUDE are what you control about the airframe, (including angle of attack, α^{o}), so you need to be a lot smarter about BOTH IAS and ALTITUDE!

3. **CONSTANT IAS FLIGHT** at a given weight, and later constant L/D, constant angle of attack flight at *any* weight, is what makes THE LOGIC OF FLIGHT easy to understand and use because the relationship of all the technical factors stay **simple** and essentially **exact**!

4. As you **climb** and the **air density decreases**, your **IAS**, Indicated Airspeed, **will tend to decrease**!

5. If you put on a little more power, hold IAS CONSTANT, fly constant "q", your DRAG WILL STAY EXACTLY THE SAME, but your **TAS MUST INCREASE** to make up for the fall off in air density, rho, to hold the same "q", if $q = (\rho V^2/2)$!

6. That sets up the wonderful condition that your "friction of flight", your drag, does *not* increase, but your real speed, TAS *does* increase!! Now you'll understand better as we go along, that friction, drag, controls MPG, miles per gallon, so you don't hurt MPG, but you go faster, Voila, **FREE SPEED**!!

7. As you'll learn in the Chapter on Engines, and as we already told you on a preliminary basis, you'll actually IMPROVE MPG as you climb higher, because you'll IMPROVE ENGINE EFFICIENCY by getting it unthrottled, then leaned!! That's a double win, **FREE TAS** increase, **MUCH BETTER MPG**!!

8. In the finer print version at the end of the Chapter, we'll actually derive the equation for TAS increase with altitude, based on the fact that q stays the same at constant IAS, and find that it changes as the square root of the ratio of rho at sea level over rho at altitude. TAS = IAS $(\rho_{sl} / \rho_{alt})^{1/2}$ **We'll give you a handy table**, (p38) so grasp or skip the math, as you wish.

Now I fully understand that we can be giving you so much, so fast here, that we can get your head reeling, if you're new, get you feeling that this *is* complicated. Not to worry. The items above are "a major part of the logic", as we build you toward a total grasp. We put it all together so you can see that it all fits together. You'll see that everything will come together in a very easy, logical way, to those *extremely simple* final conclusions that you've already seen! Don't sweat!

Engineers get correct answers out of these little formulas by keeping the units consistent. That simply means that in the English system, you use foot, pounds, seconds, for *everything*, That means you don't mix up MPH, miles per hour, with feet and seconds. You calculate speed in Ft./Sec., (Ft. per Sec.) and you calculate pressure in pounds per square foot, psf, not psi.

That will seem like a big bother to non engineers, but there are two huge advantages. First, you get the right answer! Second, if you have some big complicated equation, you can check the units through and if the answer comes out with the wrong units, you know you have a mistake somewhere. It's actually a neat trick and a big help when you're slogging through complexity!

Now to show you a good example, in the equations above, naturally you want lift and drag to come out in pounds. Naturally the wing area is in square feet, ft^2, and thus you want q, the ram dynamic pressure, to be in pounds per square foot, psf. That multiplies out to pounds, just what we want!

With that, we must get into the lift and drag coefficients. They are simply dimensionless *coefficients*, multipliers, that tell you "a multiplying factor". A plane has a lot of drag, or a little, that the wing is flying slow at a high C_L, or fast, at a low C_L. The C_L is interesting in that with a little help from you, it *adjusts to whatever it has to be* to do whatever you want to do! It has to be high enough to hold up the weight, pull "G's", considering the wing area and "q" available. It forces you to pull back on the stick, retrim, make it what it needs to be to make the *lift* equation *equal the weight,* or the "G" load.

Airfoils generally stall at a C_L of 1.2 to 1.6, depending on their characteristics, roughness, and the Reynolds number (a function of density, speed and length, divided by the absolute viscosity of the air). That gives a good, max C_L and C_D advantages to big, fast planes, less so at high altitudes where the air is much less dense, . Airfoils have the interesting characteristic of increasing their C_L almost exactly .1 for every degree of angle of attack, until they approach stall and bend over, (App.C), "losing it", an interesting and easy characteristic to remember. √

The high lift devices, flaps, slats, can add a substantial increase to the max C_L capability and wing area and are one of the basic capabilities that make Jets practical. They have to lift huge loads at reasonable speeds. The Boeing 727 has the first of the modern wings. I sold the Aileron Control for it, conceived the fail safe mechanism to succeed. It sprouted multiple leading and trailing edge flaps, inboard and outboard ailerons, multiple spoilers, sequentially linked to the ailerons, based on q and control authority needed. The wing seemed to double its area in landing configuration, and looked like an aluminum porcupine hung on two naked spars at touchdown, spoilers up. Look close the next time you land in a 727, or equivalent plane.

At 200 MPH an RV C_L is ~ .125, thus at 50 mph it's ~ 2.0

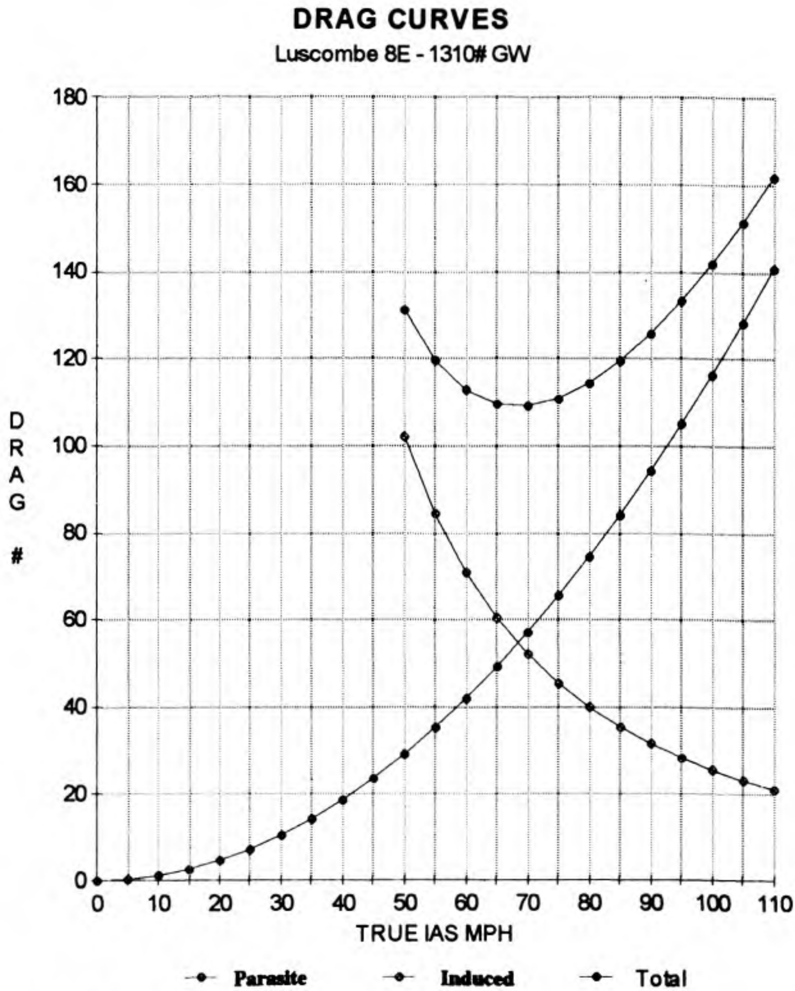
Here's the interesting insight you should grasp on the relationship of "q" and C_L. For a small homebuilt plane, like the RV6 I'm building, that can go 200 MPH and land at 50 or less, the **speed ratio of 4** produces a **"q" change** of **16** ("q" depends on V^2) so the $\mathbf{C_L}$ **must change by** a factor of **16**, to support the weight. C_L *increases* rapidly as you slow down to land.

Flaps are needed to get a factor of 16!

That's an interesting insight, but the even more interesting insight that you'll see working in the next Chapter and next page, in a real drag curve, is that the Induced or "Lift drag" coefficient $\mathbf{C_{Di}}$, **depends on $\mathbf{C_L}^2$, so it really goes up**, (256!) as you slow down! That makes practical sense because a "mushing wing" slogging through the air, logically would have a much higher drag coefficient than a fast level wing. The effect is so big, C_{Di} goes up so violently, slow, a **$1/V^4$ effect,** that it **overwhelms the V^2** in the drag formula and Induced Drag becomes a **$1/V^2$ curve**, that DECREASES rapidly as you go faster, but INCREASES rapidly as you slow down!! You'll see Induced Drag plotted on the next page. **LOOK**, at the induced drag rapidly decreasing as speed increases, and visa versa!

It all ties back to that very high angle of attack wing plowing through the air, like a high drag, "nose high", motor boat. The math and the engineering logic *are always* in tune with good "horse sense" once you "get the right grip on it". Incidentally, that same "motor boat effect" is how pilots get on the "back side of the drag curve" in extreme cases, "hanging on the prop"!

Remember - Induced Loss is the Energy Cost, Loss of Throwing Air Down, to Make Lift!



Coeficients ---- C_{Do} C_{Di} C_D

That transitioned us nicely from C_L to C_D and to the next paragraph which continues right into the fact that we have **two** Drag Curves, **two** kinds of Drag Coefficients, Parasite, C_{Do}, for all the surfaces hanging out into the airstream, that is treated as a constant, and C_{Di}, Induced, that we found is ***highly*** variable!! They add together, the **two parts** of **the total C_D**.

Most airplane people have heard that Drag (and Lift) are V^2 phenomena, that is, twice the speed, four times the drag, 3, 9, etc. You can look at the basic formula, and there it is, the V^2, just as big as life, sitting right in the middle of the "q" equation! **HOWEVER**, we've now seen there are TWO kinds of basic drag, Parasite Drag, which is a pure V^2 Drag, that **swoops up rapidly** as speed increases, with a constant C_{D_o}, and Induced Drag, the Drag due to Lift which is just exactly *opposite*, a $1/V^2$ phenomena, that **swoops down** at higher speed! (It's a FACT!)

Since one of the components is DECREASING vs. speed, total drag is **LESS** than a V^2 phenomenon, even at high speeds! When the **TWO DRAG CURVES ARE ADDED TOGETHER**, you can see they produce the **standard, leaning "LAZY J" DRAG CURVE** characteristic of ALL airplanes!! (More proportional to mid speeds!!!) You'll get very familiar with that shortly, because understanding that curve and where you want to fly on it is *the most basic objective of this book*!

Now, that just about transitions us to the next chapter where we seriously look at REAL DRAG CURVES. We must soundly close out this introduction to the basic Lift and Drag Formula. We want to get to the Drag Curves, THE PICTURE we've been talking about. Words and math confuse learners until you see it, get it, so don't sweat it. We'll finally deal with Drag in PICTURES, to *see* THE LOGIC OF INTELLIGENT FLIGHT.

For that we have gained a lot of important insight, from just dissecting the basic formula and "q" We have dealt with each of the elements of the lift and drag formula, and we hope we have kept our promise to not strain your brain!. There is much more theory here than in the rest of the book. We'll proceed to DRAG and the drag curve, a PICTURE, easier. But now, a bit of **fine print**, additional insight for those who are interested.

Earlier we told you that we'd add a "finer print version" for those who are farther along on understanding this subject, more comfortable with math and formulas, and want a deeper look on the first pass. For those who want it, we'll give you a little "bonus insight" early.

Up in item 5, some of the more perceptive readers may have thought I made a BIG mistake. I said that if you "add a little power" -- to hold IAS constant as you "rise" in altitude, (up into thinner air) ------. I know from experience that seems absolutely backwards to many people. It seems that it should take *less* power to fly in thinner air! We'll cover that a few Chapters ahead under Power, because it's so important, but for those who are ready, here is an important early insight.

Power is drag times true speed, TAS, lb. ft./sec., in Engineering units. Now you already saw that we're going to be looking into constant IAS flight, at any altitude, for a given GW, because that means drag stays *constant*, and THE LOGIC OF FLIGHT STAYS SIMPLE, and because it ties right in with optimum, constant L/D flight! Now if IAS and DRAG STAYS CONSTANT, and TAS INCREASES at altitude, POWER MUST INCREASE by *exactly* THE SAME RATIO, as IAS to TAS , and it does!!!

You'll see that's very fortuitous, because as you climb more power is required, the engine is able to put out less power as the air density decreases --- and it makes it that much *easier* to get the engine ***wide open, at as low an altitude as possible***, so it can be as efficient as possible!! Higher altitude, less air density and power capability, *hurts* engine efficiency, **but not as much as throttling it**. So the game becomes getting it **wide open, as low as possible**, at optimum IAS, (EXCEPT*) and the need for *increasing* power at altitude, *flying high,* HELPS!!

***We'll learn later, that the gain in TAS, beats the loss of Engine Efficiency!**

Before we go farther with the basic explanation, we have to deal with a housekeeping problem, for the advanced guys. Once we get a V^2 phenomenon, we have a "dynamics" problem that does an odd thing to the "consistent units" subject we explained earlier. It's not really important to the new guys (and gals), on their first pass, so we'll switch over to the finer print again, to keep the new folks concentrating on the important basics!

There is good news and bad news. The bad news is that we have a messy, esoteric little "units" problem to deal with here, that is so basic that we dare not skip it, even though I'd like to, since the objective is to keep this book on the easy way to grasp the meat of Aerodynamics. The good news is that at least we have the fine print method available to deal with it. I just hate to make this an early example, but you will quickly understand a basic about air density, ρ, that you simply must to have the whole story.

Once the Velocity is squared, and the airflow becomes a Dynamics problem, the units of V^2 becomes ft^2 / sec^2. That multiplied by an air density in pounds per cubic foot would not come out to be psf, the pounds per square foot for q, that we want, to keep the "units" correct.. It turns out that the mathematics of a dynamics problem requires that the air density be divided by the acceleration of gravity, ft./sec.^{2}, which puts the density into units that engineers call "slugs per cubic foot", (lb.sec^2/ ft.^{4}). (That looks weird even to "non Aero" Engineers.) When that is multiplied by the V^2 units above, the units do, in fact, come out to "psf" for "q"!

Recognize that although we have an odd new "unit" "slugs / ft^3", it's really just the result of using the acceleration of gravity, with everything still in normal foot, pound, second units. The math and "units" *always* work !

Sorry to have to subject you to such an esoteric engineering detail early, but it is SO BASIC to the subject of Aeronautical Engineering that it's an absolute necessity to cover it one time to be complete, for the advanced learners. ALL of the DENSITY TABLES are in these units because they *must* be!! **Standard sea level air density is .002377 slugs per cubic foot**.

For the more advanced guys who want it all on the first pass, here's the derivation of the IAS, TAS relationship. If you're going from sea level, where IAS and TAS are the same, to some altitude where rho falls off, and you want the exact TAS/ IAS relationship, recognize that q must stay the same in each case for an equivalent comparison.

For Sea Level, case 1, $(\rho_1 V_1^2 / 2) = $ Altitude, case 2, $(\rho_2 V_2^2 / 2)$

Canceling the / 2, substituting, $(\rho_{SL} \times IAS^2) = (\rho_{ALT} \times TAS^2)$

Rearranging, taking the Sq. Root $(\rho_{SL} / \rho_{ALT})^{1/2} = TAS / IAS$

$$\boxed{TAS = IAS\,(\rho_{sl} / \rho_{alt})^{1/2}}$$

That will be a cinch, for the people who are sharp on Algebra, harder for those who are rusty, and a stretch for everyone, who by now forgot whatever Algebra they had. The conclusion is as above and is written out in item 8, earlier in the chapter, for anyone who wants to understand exactly how the TAS / IAS relationship works, without going through the Algebra. Our objective, of course is to make it appropriate for any level of reader. Following is a chart showing the Standard Atmosphere, (p. 38) which includes the TAS / IAS relationship for standard altitudes. We've also put a more extensive Atmosphere Chart in Chapter 4

Notice that the TAS multiplication factor is 116.37% at a standard 10,000 ft., 126% at 15,000, 137% at 20,000, 201% at 40,000 ft. high commercial Jet altitude, and a huge 325% at 60,000 where the top fighters, U2's and SR 71's start coming into their own! Notice at 60,000 ft. you're trying to fly on 9.41% of standard air density, reaching out for those molecules!!

Before you start considering that as all "Free Speed", you must recognize that as you take reciprocating engines to very high altitudes, as we'll see later, compliments of Voyager engine tests, there is a significant drop off in efficiency, especially with high RPM friction, with the power capability dropping fast, friction an ever larger part of the total. Superchargers reinvigorate power capability, but increase back pressure, remove some work capability, and can hurt efficiency, except for special designs!

However, did you realize that for decades, the piston engine altitude record of **56,046** ft. was established October 22, **1938**! Mario Pezzi established it in a Caproni 161 biplane **unsupercharged**! Seeing that it was done at Montecelio, Italy (Sky Mountain), I thought that it may have been a wave flight. I called the NAA to check, but was told that it was real, used a very specially developed 700 HP engine and plane! I keep thinking that it was supercharged, but amazingly, the write-up in the NAA/FAI record book specifically say's, "despite the absence of a supercharger"! Nobody said it had to be efficient, reaching out for those air molecules! (I'd also bet that there's a good chance that he did find some wave lift too.)

Advanced folks may have noticed that we didn't derive, prove, the $1/V^2$ relationship of Induced Drag vs. speed, the $1/V^4$ relationship of C_{di}. We'll do that in the next chapter where we're plotting curves, making pictures of the actual drag. We'll do it in the fine print of course, but give learners help to see the **great insight, "Span Loading"**, that shows up!

A FEEL FOR "q"

Since this Chapter is very much about "q", constant IAS, constant "q" flight, it's worthwhile to get "a feel" for "q". If Airplanes fly on "q", HOW STRONG IS THAT RAM DYNAMIC PRESSURE --- HAND OUT THE WINDOW??? I once purposely, and *carefully*, put my hand out the flight engineer's vent window at 300 MPH in a B26 Invader. It did give me a good "practical feel" that I still remember, many years later. Below you can figure it was about 230 psf, 32 lbs. at 1.6 psi for a 20 in^2 hand! I also remember thinking that it was good that a 300 MPH bug didn't hit. I really would have felt that!

Back in the fine print, for the advanced guys, we established that ρ at sea level is .002377 "slugs"/ft^3. It's useful to remember that 60 MPH is 88 ft./sec., a 15/22 ratio. So 100 MPH is 100 x 22/15 = 146.6666 ft./sec. So if q = (ρ V^2/2), **q at 100 MPH IAS** equals 25.5659, **25.566, or 25.57 psf**. √

So at 100 MPH, Parasite Drag is **25.57** pounds per square foot of FPA, equivalent Flat Plate Drag Area. By just remembering that number, 25.57, and using a calculator that can "ratio" the V^2 factor, you can quickly do any IAS at any altitude!! Example: At 200 MPH "q" is **4** times as much, 102.264 psf, at 110 MPH, 1.1^2, 1.21 times as much. Get it? With a simple calculator, you can quickly ratio "q" for **any** speed, and using IAS (remember that means "q"), it works for **any** altitude! If you can't remember the 25.57, there's a great **"Patriotic Mnemonic"**, **.1776** psi x 144 in.^{2}/ft.^{2} equals **25.57 psf**.!! √√

A 1400 lb. Classic Luscombe with a 140 ft.^{2} wing , 10 psf wing loading, flies at only .07 psi. wing differential pressure, a C_L of .391at 100 MPH. At **85** IAS, q = 18.47 psf, C_L.541, **100 TAS** at altitude, economy range is **800 miles** at only **3.75 GPH!!!!** √

CHAPTER 3, THE LIFT AND DRAG FORMULA

It is absolutely amazing how much insight can be gained on how one flies an airplane logically, intelligently, efficiently, from the **one basic formula** that describes **both lift and drag**! From a pilot's standpoint, it is *almost a total education in one package.* If one mentally walks around it, prods it, exposes **all** the many hidden secrets and incisive concepts, it offers up **huge insight!!**

We are by no means done with it because it's logic will underlie this entire book, and we will find that it quickly yields the insight to understand the effect on drag and necessary speed as weight changes in Chapter 6, an absolute fundamental in the LOGIC OF FLIGHT. **Really grasp, that basic formula!!!**

> The **central fundamental that we wish you to grasp in the, formula, is the CONCEPT OF CONSTANT OPTIMUM "q", CONSTANT OPTIMUM IAS FLIGHT, at a given gross weight. That leads directly to the CONCEPT OF CONSTANT OPTIMUM L/D, CONSTANT OPTIMUM ANGLE OF ATTACK FLIGHT, AT ANY WEIGHT!** Both concepts make the logic so easy and exact. By starting you on constant IAS, constant "q" , teaching you **where** you want to fly on a **Drag Curve**, bringing in **weight effect** on **drag** and **speed**, you'll **"get it all"**, laugh, in hindsight, at how easy it all is. It's ridiculous, really, that there was never anyone to teach it.

There is so much basic insight in this fundamental Chapter, that, rather than try summarizing it for you here in insufficient space, might we suggest that you go back and skim the "highlighted" items in the text, the Review, in **SQ3R**, (p5)! For sure, **GRASP** that **TAS is free, does not cost fuel, hurt MPG, BECAUSE Drag does not increase, if you "nail" an optimum Lift vs. Drag, by simply holding "q", IAS --- for a given weight!**

ICAO INTERNATIONAL STANDARD ATMOSPHERE

Alt.	TEMP.	PRESSURE		DENSITY		TAS/IAS
	(-3.56Δ°/k)		RATIO		RATIO	RATIO
h	t°	p	p/p_o	$\rho\ 10^4$	ρ/ρ_o	$(\rho_o/\rho)^{1/2}$
ft.	F°	Hg"	δ	slugs/ft^3	σ	$1/\sigma^{1/2}$
0	59.00	29.92	1.0000	23.77	1.0000	1.00000
1000	55.43	28.86	.9644	23.08	.9711	1.01482
2000	51.87	27.82	.9298	22.41	.9428	1.02986
3000	48.30	26.82	.8962	21.75	.9151	1.04537
4000	44.74	25.84	.8637	21.11	.8881	1.06112
5000	41.17	24.90	.8320	20.48	.8617	1.07735
6000	37.61	23.98	.8014	19.87	.8359	1.09385
7000	34.05	23.09	.7716	19.27	.8106	1.11074
8000	30.48 ✓	22.22	.7428 ✓	18.68	.7860	1.12790 ✓
9000	26.92	21.39	.7148	18.11	.7620	1.14561
10K	23.36	20.58	.6877	17.55	.7385	1.16374
11	19.79	19.79	.6614	17.01	.7155	1.18217
12	16.23	19.03	.6360	16.48	.6932	1.20106 ✓
13	12.67	18.29	.6113	15.96	.6713	1.22055
14	9.11	17.58	.5875	15.45	.6500	1.24023
15	5.55	16.89	.5643	14.96	.6292	1.26056
16	1.99	16.22	.5420	14.47	.6090	1.28156
17	-1.58	15.57	.5203	14.01	.5892	1.30276
18	-5.14	14.94	.4994 ✓	13.55	.5699	1.32468
19	-8.70	14.34	.4791	13.10	.5511	1.34698
20K	-12.26	13.75	.4595	12.66	.5328	1.37005
25	-30.2	11.10	.3711	10.65	.4481	1.49387 ✓
30	-48.0	8.885	.2970	8.893	.3741	1.63479
35	-65.77 ✓	7.041	.2353	7.365	.3099	1.79630
40	"	5.538	.1851	5.851	.2462 ✓	2.01532 ✓
50	"	3.425	.1145	3.618	.1522	2.56279
60K	"	2.118	.0708	2.238	.0941	3.25945

CHAPTER 4

DRAG CURVES

This is where we will start constructing Real Drag Curves, "drag in picture form", so you folks who had trouble with the math in the last Chapter will find that, true to our promises, like Sylda Smith, my old Algebra teacher, "we won't let you fail". We will still have math, theory, in this Chapter, but since we'll end up with pictures, that will make very good sense, and fit with the final conclusions that you already have a pretty good feel for, you can't possibly get snowed or lost. All the math will show is that the Parasite Drag Curve "swoops up" as you go faster, and the Induced Drag Curve, due to the Lift that is generated, "swoops down" as you go faster. There's nothing scary about that! We'll add those two curves together to form the classic, leaning, "lazy J", composite drag curve, that all airplanes have as a Basic Drag Characteristic --- You'll end up seeing soon, that there are "three optimum places" to fly on a drag curve, but only one where a "Thinking Man Buys Speed Wisely, Frugally"! You'll see that it's so easy to grasp where speed is available "cheaply" for little drag, fuel and cost, that it's a real "laugher", that you'll never forget!

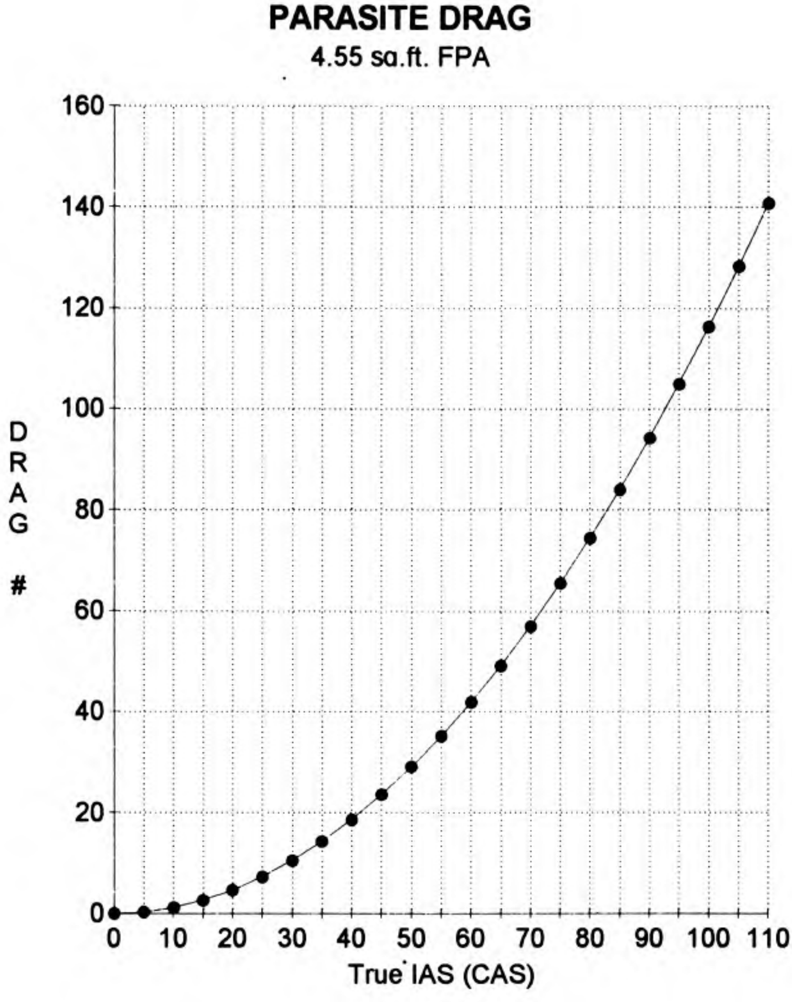
Remember, the conclusions to the whole LOGIC OF INTELLIGENT FLIGHT, are so easy that we started to show them to you in the first Chapter. We're taking you through the core of the Aerodynamics of Flight to show you that you can "grasp the whole subject" so if you're new to all this and not strong in math, don't worry, because if one part "snows you" we'll keep on coming back to things you can see, so there is no way that we'll let you get lost. We intend that this be fun, and that you end up proud of yourself, confident in your new knowledge, and that you remember and use what you learn here for the rest of your life, in SMARTER FLIGHT!!!

We'll cover the Parasite Drag Curve first, because it's simple, has a constant Drag Coefficient, $\mathbf{C_{Do}}$, and is a simple V^2 Curve that simply "**swoops up**" as you go faster, twice as fast, four times the drag, three times as fast, nine times the drag! Get it? Look at the Parasite curve on the facing page. **That's what a simple V^2 curve looks like**. Remember, like in the last Chapter

$$\text{Parasite Drag,} \qquad \mathbf{D_o} = \mathbf{C_{Do}}\ S\ \overbrace{(\rho\ V^2/2)}^{\text{"q"}}, \text{ pounds}$$

A real number for a C_{Do} for a classic Luscombe is .0325 from ✓ **Z**ero **T**hrust **G**lide **T**esting, the first time in history that a real drag coefficient was obtained from a flyable propeller driven airplane! In 1952 August Raspet got .033, free gliding a propellerless Cessna 120, with the cooling ducts open, a good comparison of these two classic planes, which are very evenly matched.. In actual fact our Luscombe tests probably gave it a small advantage, because we found essentially perfect test conditions three miles out to sea, at dawn, in perfect dead air, a condition not normally attainable, the real advantage of ZTGT!

That .0325 **Parasite Drag Coefficient**, is also known as the **Zero Lift Drag Coefficient**, a logical name and concept to grasp! If that .0325 coefficient is multiplied by the Luscombe wing area, 140 ft.^{2}, we get $\boxed{4.55\ \text{ft.}^2}$ another concept, ✓ **Equivalent Flat Plate Drag Area**, that is a particularly good, ✓ undistorted, way to describe Parasite Drag, as you'll now see.



It is the convention, in Aeronautical Engineering to use S, the wing area in both the Lift and Drag Formula. It provides a convenient and consistent basis, which however is not completely logical, if one looks close, and it never seems to be specifically explained in the basic texts. So, we'll give it a good airing here to eliminate any possible confusion for you.

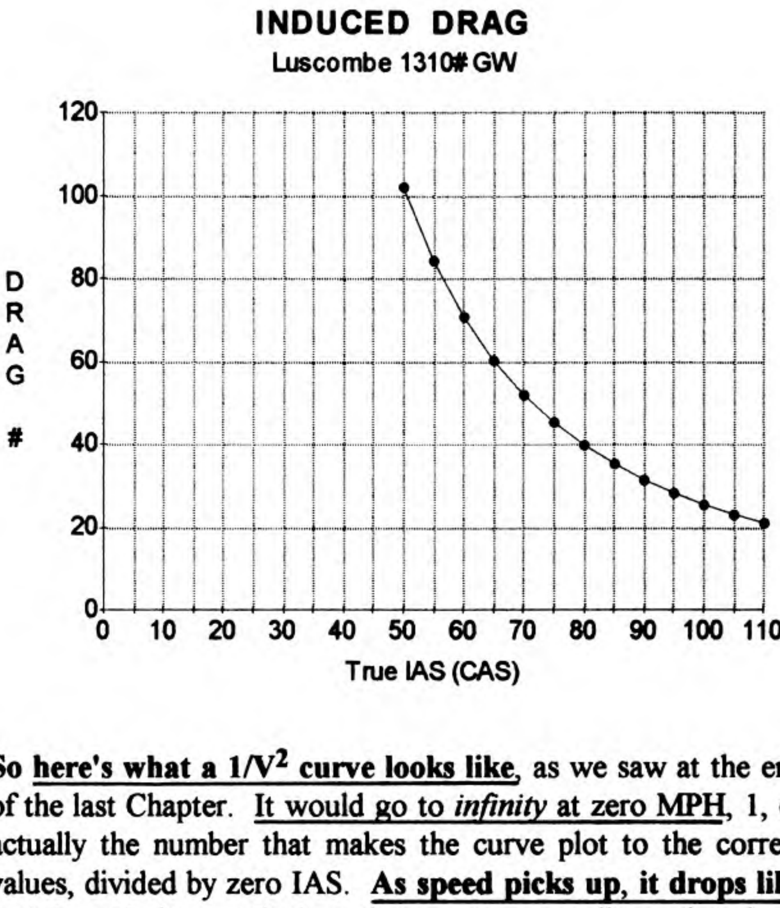
If one looks into the basic texts on drag for parts of planes, like wheel pants, struts, etc., they immediately start talking about "cross section area" and related drag coefficients. -- They would clearly be *different* than a coefficient related to a wing area!! In fact, experiences teaches that parasite drag is most closely related to "total wetted surface area", with due allowance for some "pressure drag", if there is some "separation" occurring!

Clearly then the use of wing area is consistent, and convenient, but a tad less than precise, especially when one recognizes that two planes with abnormally big and small wings would have somewhat distorted "drag coefficients" that should **not** be directly compared!!! Recognize *the **flat plate area** concept nicely steps around this distortion, eliminates wing area, and **permits accurate, undistorted comparisons between planes***!! Parasite Drag is simply, FPA x q, pounds, at any given CAS.

The FPA concept seems to imply a drag coefficient of "1", which is a tad low for a true flat plate (vs. cross section), unless it's two in tandem. Ignore that, just use FPA x q, pounds!

The good news, however, is that S, wing area is used consistently in both the Drag and Lift calculations, and in calculating C_L and both C_{Do} and C_{Di}, so all calculations remain simple and consistent, valid justification. Even when the wing area is greatly expanded with leading and trailing edge flaps, the basic wing area, S, is still used. A normal Flap C_L of 2, 2.5, can act bigger, maybe even 3, or more on Complex Jet Wings.

We'll cover the Induced, or "Lift Drag" Curve next. Remember it has that trickier, "highly variable" C_{Di} that increases as $C_L{}^2$, so that C_{Di} violently increases as you "slow down", overwhelms the V^2 effect by producing a $1/V^4$ C_{Di} effect, a **$1/V^2$ Induced drag curve** --- that **"swoops down" as you go faster!** ***Tricky!***



So **here's what a $1/V^2$ curve looks like**, as we saw at the end of the last Chapter. It would go to *infinity* at zero MPH, 1, or actually the number that makes the curve plot to the correct values, divided by zero IAS. **As speed picks up, it drops like a sinker**. To be practical, we just start D_i at stall speed, to keep it in a realistic range. Recognize though, it **never goes to zero!**

NOVICES: Do Not Try the next serious Algebra - for advanced guys! C_{Di} depends on $1/q^2$, $1/V^4$ -- thus D_i depends on $1/q$, $1/V^2$, but we'll learn, of great fundamental importance, **Induced Drag depends on SPAN LOADING²**, a simply marvelous insight to grasp!! It also includes the classic Prandtl/ Oswald formula $C_{Di} = C_L^2 / \pi A_R e$, that shows that the induced drag coefficient depends on C_L^2, the aspect ratio, and is "fudged up" to a correct value by the Oswald factor, e, "basic stuff" in Aero! That sounds terribly complex --- but it's just a curve that swoops down.

Dividing by, say .8 Oswald, adds 1.25 Induced - for Tip Vortex Loss!!!

DERIVATION OF THE BASIC DRAG FORMULA

Novices - Skip the Math - See the Bottom Line Answer in the Box!

PER THE BASIC LIFT FORMULA, IN LEVEL FLIGHT

Lift = Weight = Lift Coef. C_L x Wing Area S x q

$W = C_L \times S \times q$ Solve for C_L $C_L = \left(\frac{W}{Sq}\right)$

INDUCED DRAG COEFFICIENT, PER PRANDTL AND OSWALD

$$C_{Di} = \frac{(C_L)^2}{\pi e A_R}$$ (Below, we'll substitute formula for C_L above)

Where Aspect Ratio A_R is $\frac{\text{Span}}{\text{Chord}}$ or $\frac{\text{Span}^2}{\text{Area}}$ or $\frac{b^2}{S}$

Where e is the Oswald Span Efficiency Factor

$$C_{Di} = \left(\frac{W}{Sq}\right)^2 \frac{S}{\pi e b^2}$$ Substituting for C_L A_R Now rearrange

$$C_{DI} = \left(\frac{W}{b}\right)^2 \frac{1}{S\pi e q^2}$$ Notice $\frac{W}{b}$ is Span Loading

INDUCED DRAG, PER THE BASIC DRAG FORMULA

$D_i = (C_{Di})\ S\ q$ Now Substitute for C_{Di} from above

$$D_i = \left[\left(\frac{W}{b}\right)^2 \cdot \frac{1}{S\pi e q^2}\right] \cdot S \cdot q$$ Next, simplify

$$D_i = \left(\frac{W}{b}\right)^2 \cdot \frac{1}{\pi e q}$$ Recognize, $\frac{W}{b}$, is SPAN LOADING

$$D_i = \frac{(\text{SPAN} - \text{LOADING})^2}{\pi e q}$$

THUS, THE COMPOSITE DRAG CURVE FORMULA IS:

$$\boxed{\begin{aligned} D &= D_o + D_i \\ D &= (\text{FPA} \times q) + \frac{\text{SPAN\_LOADING}^2}{\pi e q} \end{aligned}}$$

Where $q = \frac{\rho V^2}{2}$

A Little Insight on How Science Develops Smarts!

Ok now, this is a good time for *all* of us to **have a good laugh *together*!** To any normal non engineer, **that page over there looks ridiculous, funny!** Most regular folks would run for the trees, either laughing, or muttering about ridiculous engineers.

In fact, however, some individuals are quite Smart, Good at Math, love it, **can develop nifty New Scientific Insights** on how Nature, Science, Physics works. **This is a Good Example!**

Here we find Induced Loss, the **Energy Loss of Throwing Air** Down, to make Lift, **depends on Span Loading,** Less Loss if Span is Big. Loading Goes Down, we Don't Have To Throw the Air as Hard, to Make Enough Lift, and We Get Completely New Insight. **This is a Good Insight on Math Creativity.**

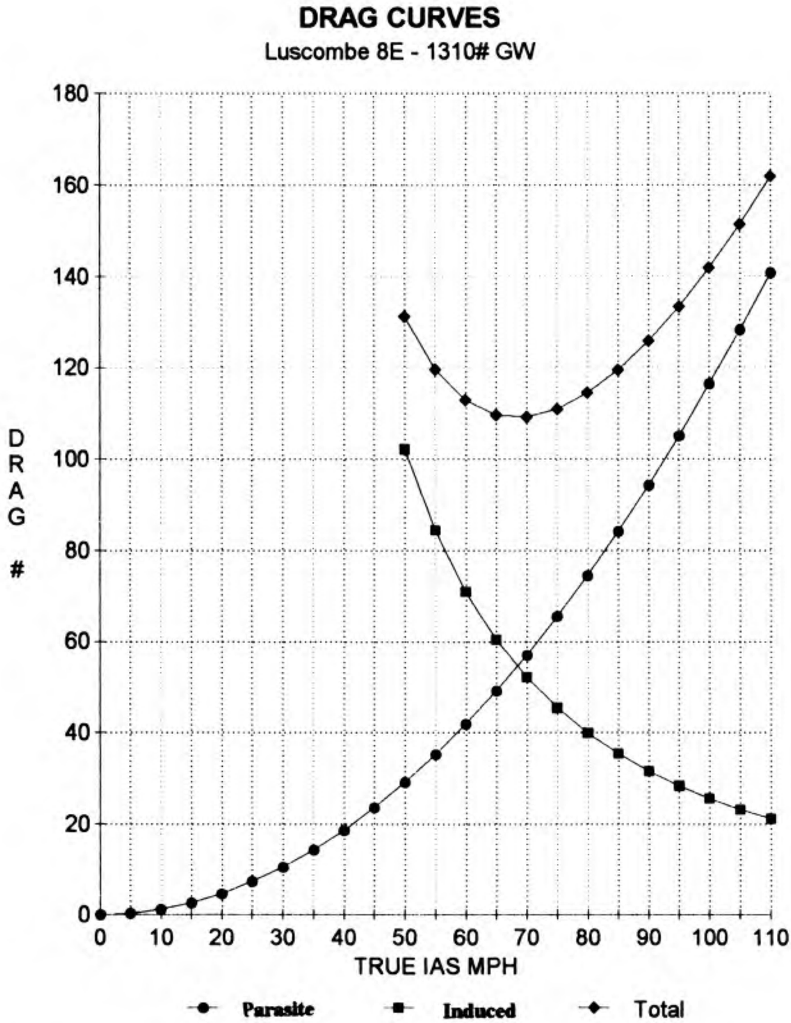
Would you believe that way back in **1918, Prandtl,** in Germany figured out that the Induced Drag Coefficient, was just $\mathbf{C_L^2}$ **divided by π and the "aspect ratio"**, which is, span/average chord, or span^2/area. It's an amazing fact in engineering, that there is always a smart guy somewhere, that has the basic theory worked out, while everyone else is still "hacking", in the dark. **Oswald** came along a decade later and **added his "fudge factor", (e), .8* ± , to account for Tip Vortex Loss,** to boost the **calculation of Induced Loss up to its actual value. Voila!**

Dividing by nominally .8 increases the induced loss by 1.25, for Tip Vortex Loss!

So we get a BIG SURPRISE INSIGHT. **SPAN LOADING^2**, controls the Induced Loss! q is on the bottom, so as we've seen, the **Induced Loss** decreases fast, as you go faster, but **goes through the roof if you slow down, mushing!!!!**

*** On Long Span Wings, Less Tip Vortex Loss, Oswald's e is Bigger!**

That Math is a lot more complicated than I intended to put in this book, but it covers an important basic subject on how Induced Loss Works, can be understood. The book would have a hole without it, **so we just put it in for the Advanced Folks.**



C_{Do} C_{Di} C_D

Now, if we just plug that Drag Coefficient into the Basic Drag Formula, (and that means we just multiply it by S q), we get a pretty simple conclusion and expression.--- **INDUCED DRAG equals SPAN LOADING^2 /π e q.** Not only does that give an airplane designer, *and* pilot, an easy way to understand "LIFT DRAG", there is the second great insight. The q^2 in the bottom of the drag coefficient formula, overwhelmed the q in the top of the drag formula, we end up with q on the bottom , **Induced, (Lift Drag) works exactly opposite to Parasite Drag, Induced swoops down vs. speed** (q on the bottom)**, while Parasite swoops up,** a $1/V^2$ curve <u>and</u> a simple V^2 curve!!!!

Now Look, of course that page can look scary, if you're new, but **hell, anybody can understand** that there are **two drag curves**, **one** that **swoops up**, and **one** that **swoops down**. **IF YOU GOT THAT, YOU GOT THE CONCEPT, THE GRASP YOU NEED , AND THE WHOLE REST OF THE GAME, THE BOOK, IS GOING TO BE A CINCH!!!**

SO HERE IS WHERE WE START GETTING REALLY SMART! LOOK AT HOW SIMPLE THE TWO PARTS OF THAT COMPOSITE DRAG CURVE ARE. <u>PARASITE Is Simply</u> <u>FPA x q,</u> <u>it swoops up!</u> <u>INDUCED Is Simply</u> <u>SPAN LOADING^2 / πeq</u> it <u>swoops down vs. speed</u>. $q = (\rho V^2/2)$ **(Learn as deep as <u>you choose</u>.)**

YOU CAN PLOT EACH OF THOSE SEPARATELY AND GET THE TWO, AS WE JUST DID, --- AND/OR --- YOU CAN <u>ADD THEM TOGETHER</u> AND <u>GET THE STANDARD COMPOSITE LEANING</u> "<u>LAZY J" DRAG CURVE</u> --- ON THE FACING PAGE.

NOW <u>THE WHOLE GAME IS UNDERSTANDING</u> where <u>THE THINKING MAN FLIES ON THAT CURVE</u>. Look.

Having (conquered??) the theory, the math, and converted it to <u>PICTURE FORM</u> that <u>EVERYBODY CAN UNDERSTAND</u> for sure, we'll jump to the next Chapter to grasp the <u>three optimum places to fly</u>, <u>in picture form</u>. We'll see there are <u>SMART places to fly</u>, <u>where we **BUY SPEED FRUGALLY**</u>, and places where you get **BIG DRAG**, a poor speed payoff!

CHAPTER 4, THE BASIC LIFT AND DRAG CURVES

Anyone can grasp the simple final logic of intelligently flying an airplane. Our objective in this book is to help any Pilot, anyone interested in THE LOGIC OF INTELLIGENT FLIGHT, to "actually grasp the central foundation of Aerodynamics", to see what the airplane senses, what it's logic is, and **why**!

Of course you'll recognize that we face the very real problems of helping the full spectrum of people: the guy who's never been good with math or science, who's afraid of this, even if he doesn't need to be, who needs lots of encouragement and help, to soon realize that with help, he CAN get it,-- the funnier case of the fiercely free spirit pilot who'll actively fight learning, unless we bowl him over with "insight", the high IQ critic who'll want to be critical that we adopted a "super emphasis" writing style that aims at making it impossible to finally fail!

These were the two toughest Chapters, where we dove right into the basic formulas, the math, the curves. Ahhh, the curves; now it's in "picture form" that will make it impossible to misunderstand, impossible to not get it. **My gamble, my bet, is that almost everyone will see that there is so much to be learned here, that they'll get themselves through it, which ever way works for them, get it, and we'll go from thousands of pilots who don't have a clue, to a bright well informed throng. Help me, help yourself win on that bet!!!** √

Now that we have the drag curves in picture form, it will be fun and easy to see, fully understand, "the three optimum ways to fly", the concept of "MAX SPEED/$", the logic of maximizing speed vs. drag, fuel burn, cost; the way the thinking man does **not** go for speed on the drag curve, but gets it free at altitude, with the engine far more efficient. **Be amazed at your insight!** √

CHAPTER 5

THREE OPTIMUM FLIGHT MODES

The objective of the whole game is MAXIMIZING SPEED, MINIMIZING DRAG, and this is the Chapter where we show you the first and most fundamental step, WHERE A THINKING MAN FLIES ON A DRAG CURVE!! Earlier in introducing you to the logic of flight, we showed you HOW to HOLD an optimum point for a given weight, by holding IAS at any altitude. But this is the crucial missing information, where that optimum point, optimum IAS is on a drag curve! We purposely are not taking you first to the most simple, constant optimum L/D, constant optimum angle of attack method, --- because, you really need to understand this most important fundamental first, then understand the effect of weight, on drag and speed, IAS required, (next chapter) and then later, headwind or tailwind, all of which are best seen on a drag curve!!!

Now, we will show you the THREE optimum flight conditions, and why the third, the Thinking Man's Way, that *maximizes speed vs. drag*, is clearly the way to go!!! We will use the composite drag curves, that we just developed, but we will also "borrow the power curve", that we develop a few chapters hence, -- along with a bonus "L/D Curve", so you can see how it fits in, and the "magic tangent line", That Makes The Logic Of Flight CLEAR!

The Minimum Drag Point -- The Voyager Flight

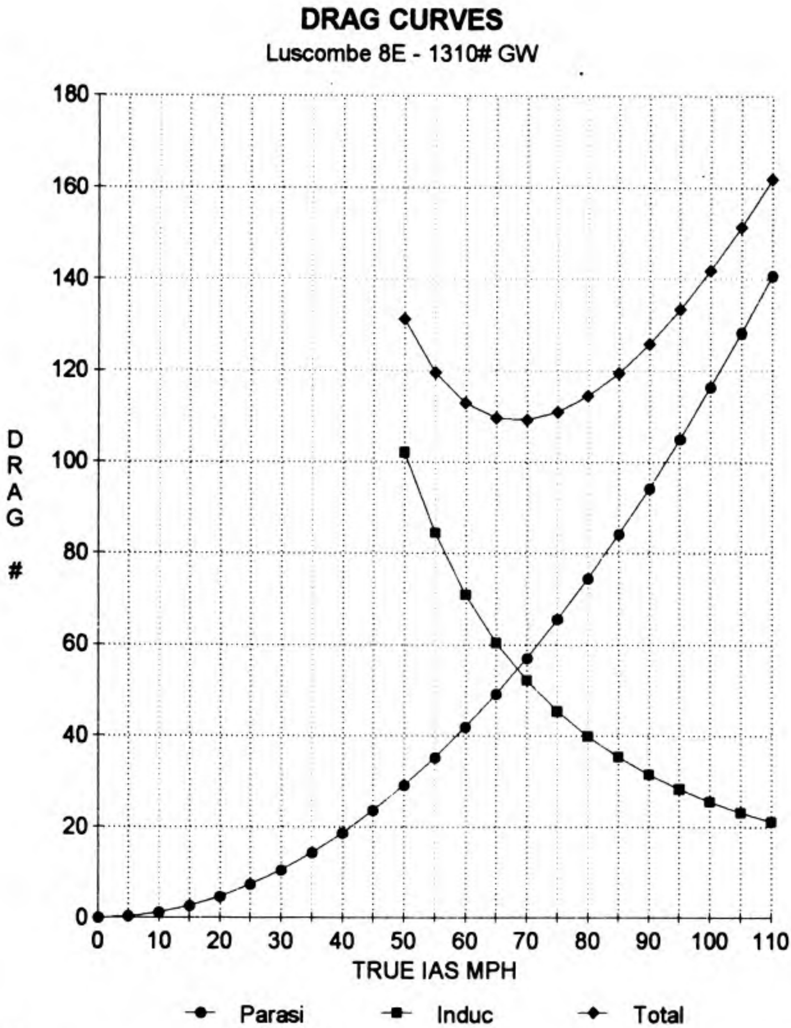
The **classic, optimum flight mode** taught in all the basic text's, is the **minimum drag, max L/D** point, (IAS). It nominally occurs at the IAS where the Parasite and Induced Drag Curves cross and are equal. LOOK. Quite logically this is the point where the least energy is consumed for any given flight range, the least fuel is required. **Range will be maximized**, along with **MPG**, miles per gallon of fuel. Look, it's at 68 MPH IAS.

Recognize it's equally logical that this minimum drag point is also the max L/D point, since in level flight, lift *exactly* equals the unchanging weight, that the drag curve was drawn for. You'll see L/D plotted on the *next* curve, so the one on the facing page won't be cluttered. L/D is like a *mirror image of drag*, but do notice the scale change, because it's a ratio ≅ 12:1.

Obviously the minimum drag point is one optimum, it's cheapest, MAX L/D, max range, but UGH, look at the speed, less than 70! You can go a long, long way, but you may die of boredom first. No THINKING MAN is going to fly there --- unless you're trying to **double** the distance record, **fly all the way around the world, unrefueled**, get every foot of range out of every drop of fuel. That's why the world flight took **nine, 9 DAYS**, 3 minutes, and 44 seconds. It flew 26,358.6 miles! I was the Technical Director, Mission Control on the **Voyager**. There are a few books left, all the facts, if you're interested..

Wildly, we predicted the Tail Wind to .007 MPH, and it was Science, genuine!!!

Jets start getting some compressibility wave drag as they approach Mach 1, which causes the drag curve to go even more vertical, faster, but the fact of HUGE SIGNIFICANCE is that other than that, and some favorable, ***drag dropping rotation*** that we'll show you, all drag curves have the **same characteristic shape.** So what you're going to learn in this Chapter, works for **any** airplane and is **the most important thing you'll ever learn about airplanes,** Cub, Classic, Bonanza, Homebuilt, 777!



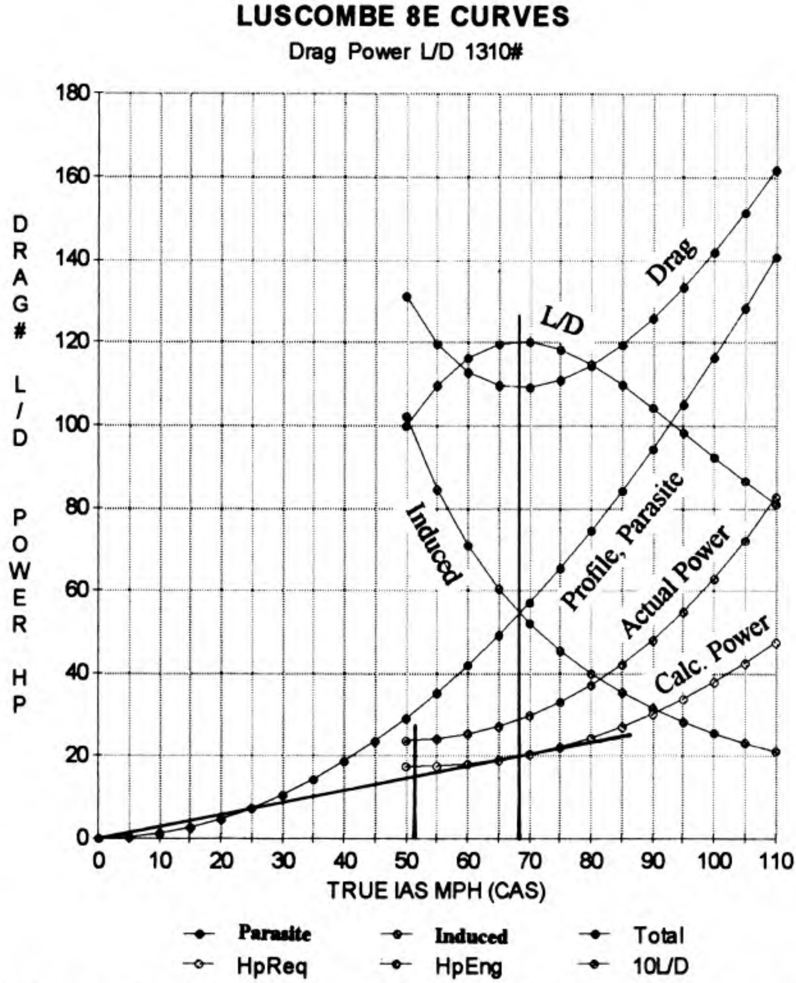
We're going to look at **Minimum Power, Max Endurance, the 2d Optimum** next, but first the thing to start noticing above is **how flat the bottom of the drag curve is**---but how quick it starts to go vertical! That's where the smart insight is going to come from! At first, **as you leave the min. drag IAS**, going faster, **extra speed** is **almost free, almost no extra drag!** √√
THERE'S AN OPTIMUM POINT to fly, before "drag goes near vertical"!!!! First, let's dispatch that Min. Power Optimum.

Once you have a drag curve for an airplane, it's a straightforward job to construct a **"POWER REQUIRED Curve"**. Remember, Power is simply Drag, lbs. x true speed, TAS, ft./sec, therefore, ft. lbs./sec. It's **rate of use of energy!!!** You divide by 550 ft.. lb./sec (per HP) to get the answer in HP. That's the lower curve, on the facing page.

Recognize the Drag Curve (vs. IAS) is valid at any altitude, **but power depends on TAS, which increases with altitude, so that Power Curve is only valid at Sea Level where IAS equals TAS**. There's a "family of curves" as altitude increases!

As you'll see in the Chapter on Power shortly, you get the "**ACTUAL ENGINE POWER CURVE**" by running a low level "SPEED POWER TEST", correcting for any pressure, altitude, temperature, power loss. Comparing the two tests, actual/calculated, yields **real overall propulsion efficiency, η_p**. What you can find on a Classic, like the Luscombe, is markedly **decreasing** η_p as more engine power is applied, even a rough curve indicating poor flow, separation, which we've smoothed here a bit to keep the picture simple for you. LOOK, you can still clearly see the "actual HP heading skyward" as η_p degrades --- you'll see that's **another powerful argument for not trying to brute force a plane faster than it was designed to go!!!**

Ah, but the **central point we want you to learn here is the POWER KEEPS DECREASING, BELOW THE MAX L/D IAS!!!** The simple thing that's happening is that the speed is decreasing more than the Drag is increasing, so the product decreases. Theoretically, mathematically, the min. power speed is .7598 x the Min. Drag IAS. Actually, LOOK, the curve is so flat, you can hardly discern the low point, it's *pointless*!!! Also, the min. power is barely lower than at the min. drag IAS!



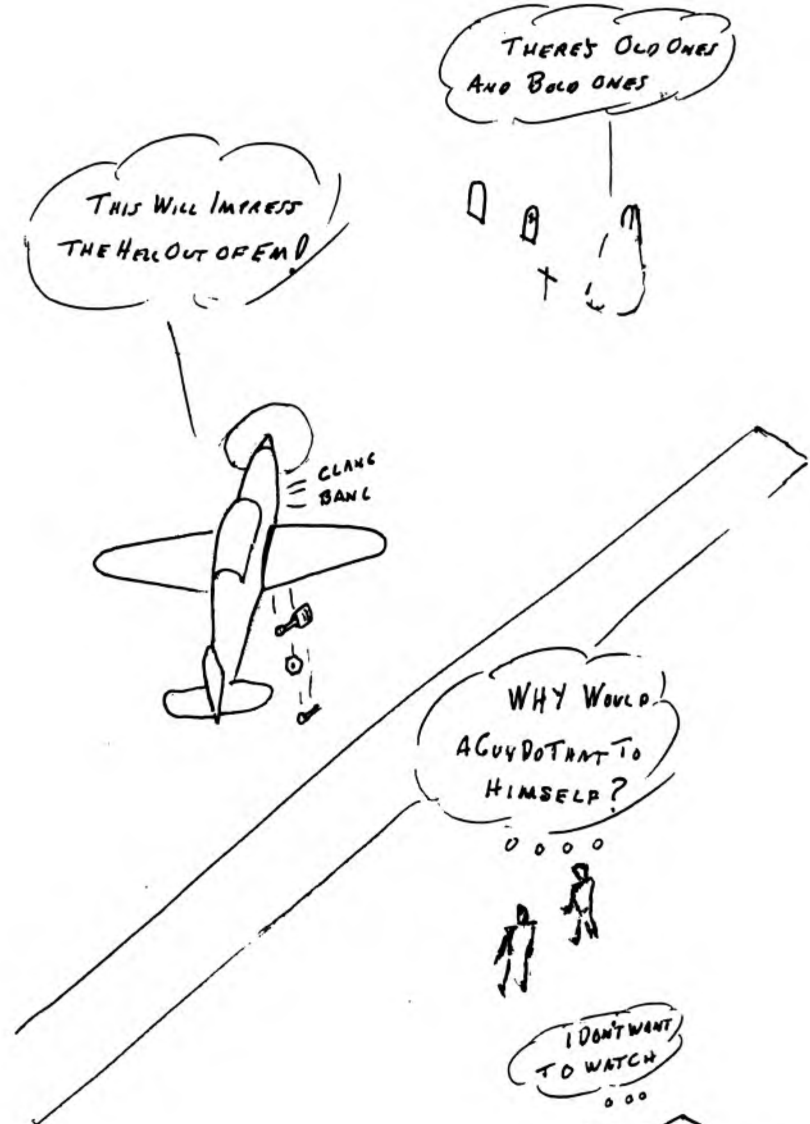
What practical use is this optimum? Well, if you're trying to win a (duration) model airplane contest, it's the "**max duration glide**". Ditto if everyone is scrambling to get life jackets on before you "ditch". If you want to go for a "duration record" (at a tad below 52 MPH in a Luscombe) maybe dangerously close to a stall, heavily throttled, you might consider it. The MAIN POINT TO RECOGNIZE is, **slow, at min. power, the most power is available for climbing, to hoist your GW skyward, so you get theoretical MAX CLIMB ANGLE**, for

The Fourth Root of 3 is $\sqrt[4]{3} = 1.31607$, Inverted, .7598 clearing trees. The **max climb rate, is at Min Drag IAS, if** you have a controllable prop for max H.P. RPM. **Fixed pitch, faster gets more RPM, more HP**, so the **real max climb rate IAS, by test is really some MPH faster**, especially recognizing the curve is very flat, **BUT** if you're really going **for max angle** to clear the trees, going faster is **not** the right theoretical move. Soaring at "min. power", which is also "**minimum sink rate**", you'll climb the fastest, **the most**, "crossing" a lift area, "**slow**"!

Frankly, I think that's pretty incisive insight, where you hardly ever get good answers on subjects like that, so for the folks who are ready for that level of X-Ray vision, I think we're coming through on our promises to get you a quality education.

The really important point, the really incisive lesson here however, is that there is **a BIG FAT SAFETY ITEM HERE!!** Two local guys were recently killed, doing a max performance climb out, when they really didn't have to, **nose way up, weight partially supported by thrust — the engine died, instant stall, it's more than a matter of getting the nose down.** They just fell like a brick, died in an ugly fire. Terrible, worse because it was pointless. The airplane always does *exactly and unemotionally*, what the Physics book decrees. It was not guilty. Nice guys, good pilots, I'm told, not technical, their sin was probably no bigger than not having a clue of the death corner they unnecessarily put themselves in. Simply, I have no critic in me for such tragedies. I'd rather take the time to be **sure you do understand.** If you "gotta flat hat", don't do it in a "coffin corner"! **THAT INSTANT STALL IS REAL, specifically because in a powerful plane, nose way up, that engine is supporting weight, and if it dies, you will, if low!!!**

Compliments of Zero Thrust Glide Testing, and the EAA sponsored CAFE Organization test programs we did, that we'll tell you about later, we have some really incisive, never before


THERE'S OLD ONES AND BOLD ONES
THIS WILL IMPRESS THE HELL OUT OF EM!
CLANG
BANG
WHY WOULD A GUY DO THAT TO HIMSELF?
I DON'T WANT TO WATCH

available, *specific numbers.* The RV series of homebuilts, designed by Dick Van Grunsven, are marvelous airplanes, one of a new leading edge of flight actually. They "go fast", "land slow, thus safe", "are strong as a bridge", aerobatic, agile, light to the touch, "a joy to fly". Clean, efficient, they step out to higher speeds readily, 170 to over 200, at impressive MPG, flown intelligently. At just over gross, an RV6 has a min. drag, max L/D speed of 106 MPH. That calculates to 80.5 MPH, min power, max climb angle. That's a fat margin above the nominal 50 MPH ballpark stall speed, with flaps, depending on GW.

The "lead sled" max performance, planes that do not have that "speed ratio of four", will not survive a slow, nose up, engine failure. How do I know that? Because the guys that were killed had it happen to them in an RV4, with all that generous margin, great aileron control and a gentle normal stall, because of wide wingtips, that results in low required C_L tips, that "hang on well". A designer just can't do more for you than that.

The pertinent hidden detail to know here, is that the RV also has an exceptional airfoil, the 23013.5, the same class as the DC-3, the Bonanza, many other famous and excellent planes. That airfoil "hangs on" so well, that when it lets go, it's all done and stalls totally. So what you can read into that accident, is that in all probability, the nose was way up, they could have been even slower than "min. power speed", they didn't get the nose down, possibly going for the fuel valve, which some people thought they bumped, and the "Physics book got them"

I had no intention of covering that subject here, but as I started to think it through, to nail it completely for you, it became clear just how dangerous that "slow, nose up" case can be, even in a plane that gives you more "margin" than most designs would. If you're going to fly high performance planes, you better understand where the coffin corners are, be properly careful.

The Rocketdyne P.A. on my Gemini Controls, Dom Novelli who became a valued friend, after I saw him solve some serious internal mistakes, like a real pro, was killed years ago, when that American DC 10 crashed at Chicago. An engine blew, took out the left wing leading edge flaps hydraulics, but not the right. The pilot was "good", but couldn't see the wing condition, knew the book, "slowed" to best 2 engine climb speed, *and lost it,* stalled, no longer had enough q and control authority to maintain the asymmetrical flaps, he had been handling!. There's a terrible photo of a **low** DC 10, **wings vertical**. My conclusion, I'll just forget, the max climb case, just not get myself into cases where I need max climb angle!! The ***only*** time to be low and slow, high α^o, is flaring for touchdown.

Now, before we go after the "third optimum" MAX SPEED/$, the real objective of this whole book, let's go back and finish completely understanding the relationship of the "Power Curve" and the "min. drag, Max L/D" case. Notice that we've drawn a line from the 0,0 origin, "tangent" to the airframe power required curve. Notice that it's tangent, (just touches), right at the min. drag, max L/D IAS! That's no accident. In this mathematical, natural law lash up, everything relates to everything else in such an orderly way that it's quite extraordinary really, and it's why we can show you a LOGIC OF FLIGHT that is so orderly, simple and exact. Science is so vastly more extensive, so all encompassing, that if you grasp its wonderous extent, you finally decide that the first Chief Engineer was so vastly smarter than the best of us, that we're a real pack of neophyte hackers! Science's logic is everywhere!

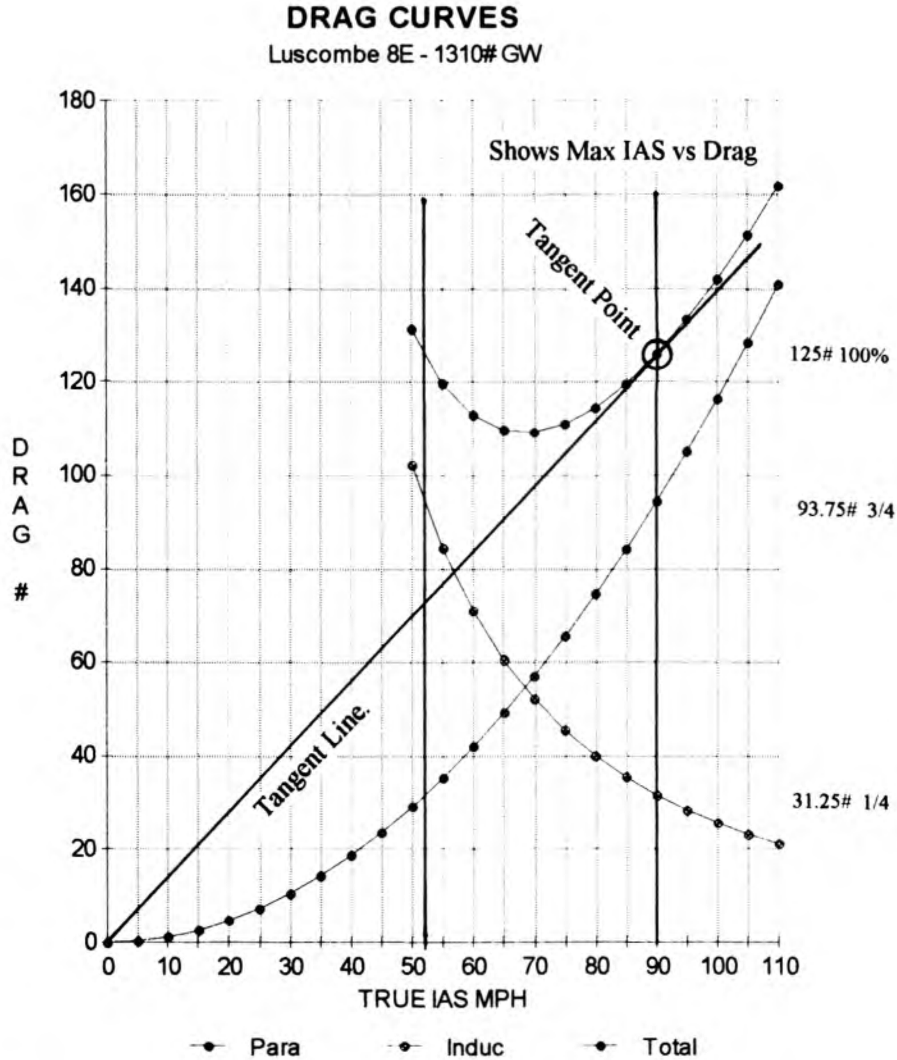
The main thing we want you to notice is that **everything lines up at the same IAS: min. drag, max L/D, tangent to the power curve, the two drag curves cross, equal, for this classic optimum case. The case has everything going for it, except it's just too slow to be used, except for max economy!**

Mathematically, the Power Curve has a tangent at min. drag IAS because: 1. "the rate of change of the drag curve is max at its bottom minimum", 2. the power curve was calculated from the drag curve, so it just "kisses" the tangent -- The reason for that will seem obscure, -- but recognize the tangent line can be thought of as a slope line *that relates power to IAS,* -- now notice that *every point on the power curve lies above the tangent line, except the tangent point, the min. drag point*-- because the "upsloping" drag curve calculated the power curve!

Now that's far more subtle and obscure than we'd normally want to deal with *except*: 1. that nicely and totally puts both the "min. drag" and also the "min. power" cases to bed and behind us and, 2. **the most important point in the whole book is just about to show up with a more simple version of a tangent line!**

LOOK, on the facing page, we've brought back our simple three basic drag curves and added a tangent line from the origin. **THE TANGENT POINT ON THE COMPOSITE DRAG CURVE IS THE POINT WITH THE MOST SPEED IN PROPORTION TO DRAG ---- ON EVERY AIRPLANE!!!**

This point is simple, not subtle and obscure. **NOTICE HOW EVERY OTHER POINT ON THE DRAG CURVE IS ABOVE THAT TANGENT LINE! THAT MEANS EVERY OTHER POINT HAS MORE DRAG IN PROPORTION TO SPEED -- THE TANGENT POINT HAS THE MOST SPEED IN PROPORTION TO DRAG!!** Did you get that for sure? Again, all points on the tangent line have the same proportion of drag vs. IAS. All other points on the drag curve are above it (extra drag). So the one point of tangency is the **optimum speed vs. drag, traveling IAS**, to fly **on every reciprocating plane in the world**, (and many Jets.)



Now if Drag, Fuel Used, and $ Cost are all equivalent, you can see that tangent point is MAX SPEED PER $ --- except that we're going to go much faster by climbing high, (TAS), then we're going to maximize engine efficiency, minimize fuel burn, spend much less on fuel, high, by getting the engine wide open and leaned. SPEED / $ IS MAX HIGH!

Notice Drag is 3/4 Profile, 1/4 Induced, at Max. IAS / $ -- or Visa Versa at Min Power IAS,

Now do you see how wildly easy it is to be a really sophisticated pilot. There's just no reason to be afraid, it's so easy! You just go for that smart IAS on the drag curve, climb up until you're "wide open", and leaned!!!! We'll show you Jets just do their own version of the same game!

That just has be the biggest and best hidden joke in all of flight. There are hundreds of thousands of pilots, and almost no one knows that there is such a SIMPLE LOGIC TO FLIGHT, TO HOW AIRPLANES "WANT" TO BE FLOWN. Many would actively fight learning it, scarred stiff that it's some big technical drill that they could not possibly cope with, when it's something you can explain to anyone, once you grasp it. **Remember the PICTURE, the drag curve, where you want to be on it, fly at that IAS, go high, wide open, and lean. RECOGNIZE WE'RE MAKING IT MUCH MORE COMPLEX, BY USING IT AS A TEACHING MECHANISM, TAKING YOU THROUGH ALL THE STEPS, TEACHING YOU A GOOD BIT OF BASIC AERO ENGINEERING!!**

That term MAX SPEED per $ tends to jar people at first, they're not quite sure what it means. That's almost justification for the term, because it forces people to stop, and question, and think. You can see now, that we ***maximize speed vs. drag, fuel, cost***. That boiled down is where you **buy speed most frugally!!! Now recognize that it is NOT some wimpy, slow, time wasting, too frugal speed ---- because the ENGINE IS WIDE OPEN, the plane is at V MAX, only where it is ALSO at its MAX POSSIBLE EFFICIENCY!!!** The plane can go faster at sea level, but down there it's like flying through JELLO! **The atmosphere is only 2/3 as dense at just over 13,000 ft. --- and that means it's 1 1/2 times as dense, down there vs. 13,000!!! Recognize to a Jet at 40k, where the density ratio is .2462, the air down there is FOUR HUNDRED PERCENT THICKER!!** Ref. your ICAO Table.

The ANSWER is on the BOOK COVER

It's this EASY!!!

Fly 1.316 Times the Handbook *Min. Drag, Max. Climb IAS*! ✓

Just Climb up until the plane quits climbing, finally, fully leaned! ✓

(Now, look at the ICAO Atmosphere Table p. 38, 152, marked up for you!)

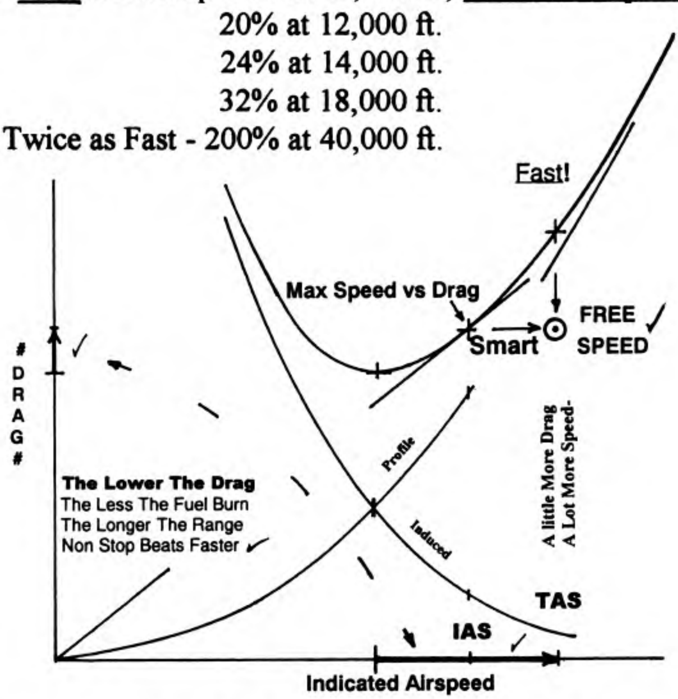
Your TAS will be up 16% at 10,000 ft., above IAS Speed!

20% at 12,000 ft.

24% at 14,000 ft.

32% at 18,000 ft.

Jets Twice as Fast - 200% at 40,000 ft.



The IAS Drag Curve -- vs. Altitude TAS Speed
The Basis of Intelligent Flight!

It's all in Picture Form on the Book Cover!

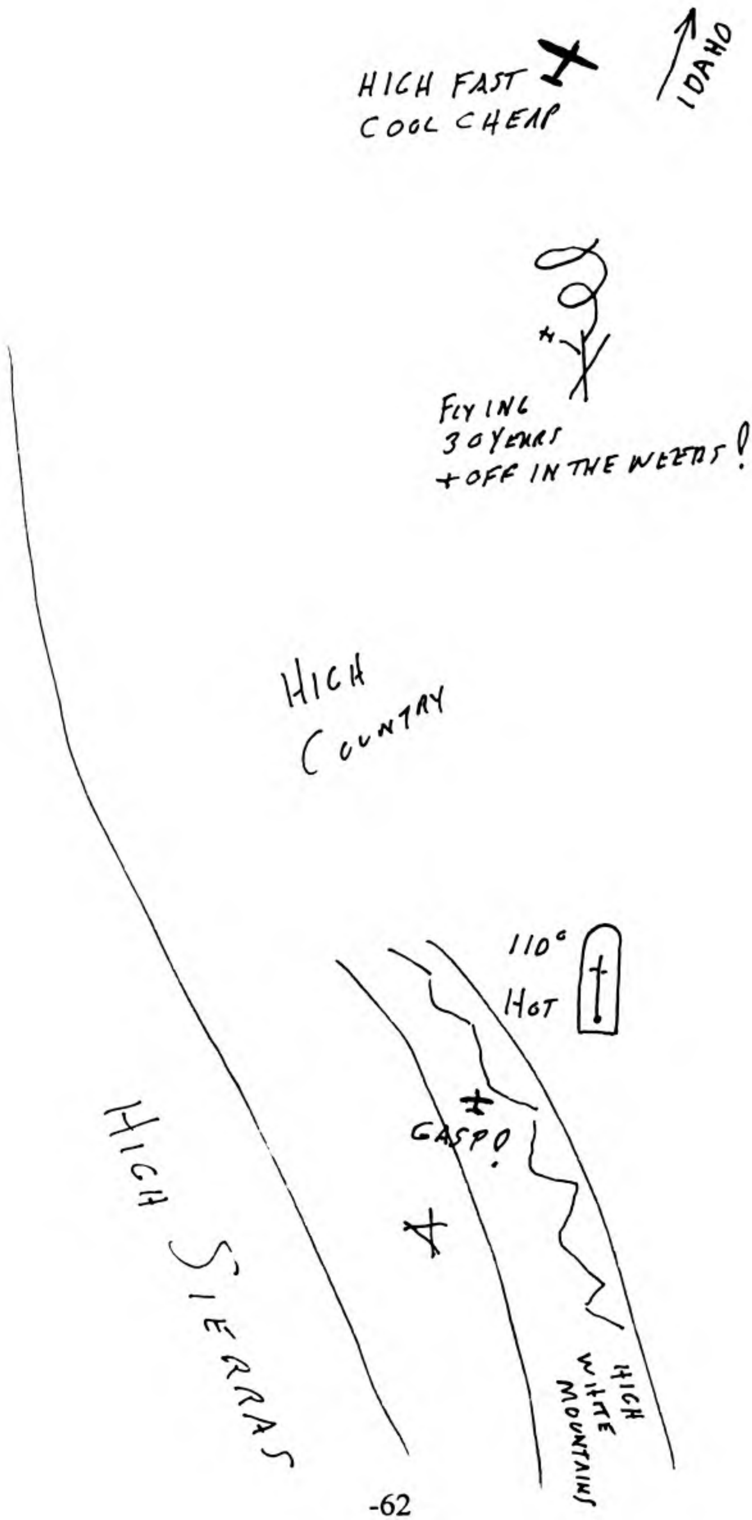
The Max IAS vs. Drag is 1.316 times Min Drag, Max. Climb V!

(The drag is up only 15%, 1.15, a bargain over the absolute minimum!)

The TAS / IAS Speed is up a lot, as above, and that's FREE!

1.2 x 1.316 at 12,000, is 1.58, 158% for 15% - a Great Bargain!

1.316 is $\sqrt[4]{3}$, the fourth root of 3, $\sqrt{3} = 1.732$, $\sqrt{1.732} = 1.316$ ref p.68.


HIGH FAST
COOL CHEAP
IDAHO
FLYING
30 YEARS
+ OFF IN THE WEEDS!
HIGH
COUNTRY
110°
HOT
GASPO!
HIGH SIERRAS
HIGH
WHITE
MOUNTAINS

Do you suppose you'd get those bargain tickets if the Jets had to fly through that? Now remember you're burning something like **4 to 6** times more fuel, than the basic energy requirement, so you better be able to "do something at least half way smart"!!

Now **at this point you have the book licked**. The hard part with the basic theory is behind you. You just got the most basic and important part of the whole book, **where** you really want to fly on your drag curve. There is a huge amount of valuable insight, yet to come, that we can pass on, but it's all going to be easier and interesting, not subjects you'll have to sweat over. √

Now in conformance with our policy of always keeping you clear on where we are, -- and where we're going:

1. We just learned **where** to fly "an optimum" on a drag curve.
2. Earlier, we learned **how** to **hold IAS**, **to hold an optimum.**
3. Next, we'll learn the **effect of weight, on drag, and IAS.**
4. Then we'll learn **constant L/D, optimum α^{o} flying.**
5. Then we'll be ready to get into Power, the Engine, Leaning, the Propeller, the rest of the book. There is a lot of good insight that can be passed on, but it won't be a sweat.

Let's take a paragraph detour, and I'll give you a snapshot insight into what understanding this fundamental logic can do for you: In June 1994, a gang of us took off, "for a fun break", for "a Classic fly in" in the mountains of Idaho, 804 miles from Camarillo, California, most of the United States, S. to N. I left two hours after the other guys, got there an hour before them, went non stop, burned 70% of their fuel, had **half** their cost using auto gas, listened to them struggle over high ridges out of Bishop in *110F° sea level air*, avoided the wild dust devils at God forsaken Winnamucca, that ran one of them off the runway into the weeds.. They wondered how I could do that. **It was easy, cool, comfortable, fun.** I had a No Numb Buns Seat!!! They landed TWICE, lost time, $, sweat a lot; had *worries*!!!

Now, before we go on to wind up this Chapter with some valuable additional insights let's answer some obvious questions.

IF UNDERSTANDING THE DRAG CURVE IS THE GAME, CAN I GET ONE FOR MY PLANE? --- At this writing using Zero Thrust Glide Testing, we have the breakthrough complete Aerodynamic data on my Luscombe 8E*, published in the July-August 1993 AIAA "Journal of Aircraft", including the real drag curves, the calculated theoretical, and actual power curves, and **thus the real propulsive efficiency at various Indicated Air Speeds**. We also have **CAFE ZTGT** tests on an **RV6*** and a **Whitman Tailwind**, and base line testing of a **Cessna 152**. As time permits, we hope to do power testing on an RV 6, so we can see its Theoretical Power based on the Drag, and the Actual Power, and thus the Actual Propulsive Efficiency Curve, which we know will be much better than the low Luscombe η_P. Unfortunately, the new Lycoming engines on the additional planes that we wanted to test consistently had inadequate end play in their main bearings to permit easy, good ZTGT Tests.

***EAA Sport Aviation, Mar., Apr., 95, Lusc, RV 6. Sep. 93 CAFE RV 6.**

The simple enough answer for you is that the **Max. L/D IAS** for your plane is usually published, and available, or reported as the **Best Climb Speed**. That IAS times the Fourth root of 3, $\sqrt[4]{3}$, **1.316, is the Max.IAS vs. Drag Speed**, and as you've learned, its reciprocal, **.7598** is the Min. Power, Max Angle of Climb IAS Speed, so there is a way for you to find your needed IAS Speeds.

ISN'T IT KIND OF RIDICULOUS TO USE A LUSCOMBE TO EXPLAIN FLIGHT IN THE SPACE AGE, TO JET PILOTS? --- No, it's entirely appropriate for several reasons. **First**. It's the classic basic that every pilot can understand, from the student, to the 30,000 hour Captain who first learned in a Cub, T-craft, Cessna, or "the first modern all metal production plane, the Luscombe", "*no sticks, no nails, no glue*"! The guys who figured out how to do that in 1938, in the Depression, when not everyone was eating, deserve to be remembered!

Second. Somewhere in the explanation, everyone will realize the fact that I really mean it, **all** planes really do work the same, only the speeds change, so the simple basic Classic becomes an ideal teaching tool and a basis for comparison, which leads to:

Three. On p.182, the Appendix, we superimposed a Luscombe and an RV6 drag curve. It's clear that the RV 6 "J curve **rotates**", much lower Parasite Drag vs IAS! It's a much lower slope vs IAS. A modern design can "squirt" out to a much higher speed at no increase in Drag!!! The "short wing" RV6 has an induced drag curve **twice** as high, but a parasite curve that is **only half** the Luscombe's, so you cruise at 170 TAS MPH, *smart*, *fast*, not 100, at the same or better MPG, with low drag, better propulsive efficiency. Amazingly, you have almost the same low induced drag, despite the 2x curve, because you're going FAST, where induced drops like a sinker, the reason you see a 20,000#+ F104 with a, maybe, 8 foot, 10 inch half wing stub!!!

At 1600# G.W., more Induced, RV's can Fly at 140 IAS, 170 TAS, 12,500', 27MPG!

Space Age. At the crucial all up Apollo 5 unmanned test launch, Astronaut Gordon Cooper was enthusiastically telling me all about his wife Trudy learning to fly in a Luscombe in Hawaii. Over 2000 are still flying, plenty with senior Captains having **carefree fun**. A break from designing, manufacturing spacecraft controls, twice, coming back from skiing at Mammoth, I had mine in the Sierra wave at 18,500, at idle, Mt. Whitney and the whole Sierras on a fast down elevator. (To do it safely, you go in and out under the *forward* ends of the cap cloud.) It's **spectacular**, no kid stuff, all the fun a guy needs!

OK, back to work. The great thing about the orderliness of the LOGIC OF FLIGHT is that while it is all very precise and mathematically definable, you can see it just as well, maybe even better, with just plain old **horse sense**, really understanding the drag curve, **the picture.** You'll also see soon, and in Chapter 6 that there is a lot of room for **judgment**, using grasp to suit the occasion. My job is to be sure you **see the horse sense of it all!**

Way back on page 51 I showed you that **the bottom of the drag curve is very flat**. It would be **actually dumb, to fly at the classic min. drag IAS, because it costs almost no drag to go significantly faster!** Pretty soon, however, the curve is heading up fast and you're buying speed at a greater and greater drag penalty!! The math optimum is at the **90** MPH IAS tangent point. There is a *trap there however, and I want to be very sure you see it, understand it!!!* It LOOKS like the drag curve is very parallel to and close to the tangent line over a broad speed range, nearly the same ratio of drag to speed --- and that's **true, BUT that ratio is not the real bargain. The BARGAIN IS TO GET THE ALMOST FREE IAS BETWEEN 68 AND 80, GO 85 — THEN GET TO 100+ TAS REALLY FREE, BY CLIMBING HIGH!!! LOOK, THE GAME IS TO GET THE BARGAIN IAS,** ***STAY LOW ON THE DRAG CURVE***
If you go up on the drag curve, your MPG goes DOWN – ***grasp that.***

Up your drag from 113# to 140#, at 100 IAS, drag is **up 23.8%** and your **MPG is DOWN to 80.7%**. **Much smarter to grab the bargain and get your speed FREE by climbing HIGH.** In the next Chapter that varies weight, I'll show you how I fly 85 IAS at all gross weights, go normal Luscombe speed of 100+ high, and get super range and economy. **DO YOU SEE THE JUDGMENT, FLEXIBILITY, HORSE SENSE — ROOM FOR REALLY UNDERSTANDING WHAT YOU'RE DOING HERE. You can tailor what you do to fit the flight you** ***want*** **to do,** ***BUT*** **IT'S HOW HIGH YOU FLY ON THE IAS DRAG CURVE THAT CONTROLS REAL MPG!! I simply fly 85 IAS. at 113# Drag Light, for less drag, better MPG..** I burn only 3 3/4 GPH at 100+ MPH, 800 mile range!

In the next Chapter, 6, you'll see clearly that ***weight costs you drag!!!*** **There you can see that** ***with judgment, really understanding*** **all the overall facts, you can be even more sophisticated than the mathematical optimum. You'll see that by flying a thoughtfully selected CONSTANT IAS**

rather than Max IAS/Drag. **I fly a lower part of the drag curve especially "at high gross weight, heavy with fuel", stay at a lower IAS, for better range — that allows me to go farther non stop, — beat the socks off the guys who are trying to go fast, but are always down there on the hot desert floor buying $$ gas, tortoise vs. hare!** (This is all an early look at the advanced meat of Ch. 6). Realize, you won't be doing it at a wimpy speed --- **You'll be *wide open*, flying where the plane and the engine are at, or right up tight against their max efficiency, depending on your insightful choice!!!** ---- Are we having fun , are we getting smarter, painlessly???

Don't get misled by those slow sounding Luscombe speeds. Remember we're teaching principles here with the basic plane. We have the numbers on the Luscombe and the RV family. An RV6 at 140 IAS, is actually going 170, or more at 12,500'. Rather than burning 8 or 9+ GPH you can burn 6.1 GPH. That will give you over 1000 mile range on 37.5 gallons, LA to Seattle non stop, in 6 hours. With oxygen, a high H.P. RV does 185 SMART. The planes designed for speed alone do it proportionally faster. Jets do their own twice faster TAS/IAS.

Of course on days where you want more Speed, you just up the IAS to what you choose.

We're teaching SMART here, not slow, but slow on the drag curve, high, is how it's done. **We're teaching the Thinking Man's way to Fly, the Simple Logic Of Intelligent, Efficient Flight. More than that, we're teaching you how to really understand what you've done and loved all your life, or will do, if you're one of the young ones getting smart early.**

OK, hopefully we've shown that this is **not** about being a "Techie", but rather the joy and advantage of really understanding what you're doing, actually deserving to be seen as a real Thinking Man, with real *insight, able to make incisive judgments* on how you fly "this one". But let's switch back and see more of the incisive insight that an inside look can show us.

$\sqrt[4]{3}$, a good laugh. I'll bet in your wildest dream you never thought you'd be interested in, "the fourth root of three, 1.316". I'm sitting here laughing at this dumb computer, thinking of my great 33,000 hour QB friends, who have been known to hoist a few, saying "what the hell was that you just said there Jack" I'm particularly thinking of Starr Thompson, who's going to take a crack at drawing better cartoons for me, to help make it clear that we can have some fun here getting smarter. He has this wonderful, perfectly facile face, for a natural cartoonist, that would "instantly screw up to the perfect quizzical expression", upon hearing that one! He'd say something like "what could that possibly have to do with anything", and his face would match!

Pick up your home calculator, that probably does square roots, and take the square root of 3. That's 1.732, a number that shows up all over science. Then take the square root of that, and you get **1.316,** a number that shows up absolutely nowhere, except that a Math drill can prove that it and **its reciprocal .7598**, .76, relates the **MIN. DRAG**, max. L/D speed to **MAX IAS/$ speed**, and the **MIN. POWER speed**, helpful, key insight. √

With Starr's talented help, we've made a joke of **"the funny fourth root of three"**, but of course we're sneaky, and I'll bet you remember that silly number, *or* **how to get it instantly** on almost any calculator. You see, if I tell you that the max L/D speed on an RV6 is 106 MPH at 1650# GW, in a flash, **you can instantly know the SMART IAS, 139.5, and the min. power IAS is 80.5!!!** As soon as you tumble to the fact, that, **that little trick also works on a 787, or any plane in the world, I'LL BET YOU DO REMEMBER THAT FUNNY NUMBER, "1.316", OR, HOW TO GET IT quick!!!** !

3/4 Profile, 1/4 Induced, at Max IAS/$, or Visa Versa at Min Power IAS, because--- $\sqrt[4]{3}$ multiplies V, but V is a V^2 function, so effect is $\sqrt{3}$, 1.732., and 1/1.732 = .57735, 1.732 exactly 3 times bigger,so induced is 1/4 of loss, profile 3/4 at Max IAS/# Drag, or Visa Versa at Min Power!

There are more orderly things about these three optimums, and their logic, that everyone can see and appreciate. At the **Min. Power IAS**, the **Induced Drag is 3/4 of the Total Drag, and the Parasite is 1/4**. **At the Max. Speed/Drag, or $,IAS, that exactly reverses, Parasite Drag is 3/4 of Total Drag, Induced has fallen to 1/4.** Of course, at min. drag they're *equal*

Now, that looks nice and neat and simple, but there are always additional subtle insights that can be seen once you walk around them a bit. On the modern, **low Parasite**, low flat plate area designs, that relegates the Induced Drag to 1/4 of a **smaller** number as well!!! As explained above that makes Aspect ratio much less important. Physically you scoot out to higher speeds, end up with **"low lift drag", even with a short wing**, high span loading, like the RV6 and the fighters. The old, graceful, long wing, high Aspect Ratio Luscombes, cruised well on little power. Surprise, the **low Parasite homebuilts** scoot out, go fast, get **great MPG** ***fast***, use the Physics book much smarter!

Of course there are always little subtleties that mess up the simple, precise, order of things, all pro's know that. The more important thing, however, is to not let the minutiae obscure the central facts and logic. Pilots never had a chance to see easy conclusions here, because the important central story never got out to them in an intelligible way, and that's bad and wrong.

So let's illuminate, but then ignore some of the minutiae, as we go. A good part of parasite drag is the wing profile drag, and a part of that is α sensitive. That can be used, ignored, or lumped with induced. We were able to get near perfect air in our Zero Thrust Glide Tests, at dawn miles out to sea, with our engine available for safety, so we were able to separate it out, have a 3 part C_d, below. It acts like extra induced and that steepens the apparent Induced curve -- which 1: causes a slightly faster min. drag speed, 2: causes the Parasite and Induced curve to not cross exactly under the min. drag IAS, with the α sensitive profile plotted separately. Our simplified curves are generated using the proper flat plate area, and the proper span loading. We used a poorer Oswald factor, .7, not a correct .74, kicked up the slow end of the drag curve, simulated the α sensitive profile.

$$\begin{array}{ccccccc} & & \text{Parasite} + & \alpha \text{ sensitive Profile} & + & \text{Induced} & \\ C_d & = & .0325 & +.009444(C_L - .4)^2 & + & C_L^2/(\pi A_R e) & e=.74 \end{array}$$

Also, modern laminar flow airfoils used on leading edge homebuilts can have a drag bucket, lower drag in a "sweet spot" lift coefficient range, but that can readily be seen and accounted for if you have an actual drag curve. The key, really, is to ignore the minutia, learn the basic big picture, and then account for the refined cases, which is easily done once you understand. Recognize with laminar Drag Buckets, the designer needs to be sure to pick an airfoil with a drag bucket, where you really want to fly!!

Summing up MAX IAS/ DRAG vs. Min. Drag, Max L/D

- **We go 31.6% faster, that's .7598 time, save 24% on time.**
- **Drag, by calculation is up to 1.155, +15.5%** , costs MPG.
- **MPG,** (the reciprocal of drag), **drops to .866, loses 13.4%**
- **Power required, Drag x Speed goes up to 1.52, + 52%**

Demanding more Power is Good, Gets the Engine Wide Open at a Lower, More Efficient Altitude! ✓

The meat of this Chapter is the most important insight that you will ever learn about airplanes, Classics through Jets!

The Min. Power IAS, is max endurance, max climb angle,
Min Sink, Longest Duration Gliding - but dangerous, if near Stall!!!
The Min. Drag, Max L/D, classic optimum flight mode, is max range, best economy, best MPG, but really too slow. (max climb rate, if a controllable prop), Fixed Pitch, More IAS is Best!

The true optimum flight mode is the IAS (vs. GW) that maximizes IAS vs. DRAG, Fuel or $Cost, especially when it is flown at high altitude, for FREE TAS, with a properly leaned, wide open engine, maximizing engine efficiency, for this Plane, the TRUE MAX SPEED/DRAG, Fuel or $ Cost!

The fourth root of 3, (1.316, and its reciprocal .7598), relate all of the speed and time ratios of the 3 optimum modes!

Thus, flying max IAS/Drag flies you 1.316 times min. drag IAS, takes .7598 as long, saves you 24% on time. A drag calculation shows that drag is increased 1.155, which reduces MPG to .866, the reciprocal, costs 13.4% more fuel. Since Power is Drag x Speed, required Power goes up 52%.

That last point proves to be the clinching advantage, because, as you will learn in Chapter 9, your engine must be "too big for optimum efficiency", since it must be sized for a good climb rate at sea level, *which forces throttling, thus lowered efficiency, by turning the engine into an air pump*! THE WHOLE GAME BECOMES FLYING THE PLANE AT THE IAS AND/OR ANGLE OF ATTACK WHERE the IAS / DRAG IS MAXIMIZED, WITH THE ENGINE WIDE OPEN, LEANED, AT *MIN*. ALTITUDE!! Recognize I said *MIN*. Altitude, because you want your wide open altitude to come out as low as possible, because the higher it is, the less your max potential efficiency. (Ch.10)
BUT — We'll Learn Later, in CH 10, the TAS/IAS gain beats the Efficiency Loss!


"JOE GROSS"
WOULD YOU SIT ON THE CEMENT? THE KIDS WILL FIT IN THE "BARROW."
GOOD GRIEF
SHOULD HAVE JOINED THE TEAMSTERS

CHAPTER 6

WEIGHT EFFECT ON DRAG, SPEED

We tend to think that weight costs us climb performance, without thinking further to its effect on drag, speed required, and fuel consumption. However, now that we're pursuing an orderly, logical approach to our flying we'll quickly see that the effect is substantial, but happily, easy to see and understand, because it's quite proportional!

It's easy enough to see and understand, that this Chapter can be short, (so we'll practice a few calcs). To make it easy, however, we'll think ahead to our next Chapter where we'll address constant L/D, constant angle of attack flight. We'll still focus on our "ideal IAS method", to see weight's effect on the ideal IAS, and Drag, and the Drag Curves. You'll find that you'll quickly "tumble" to what's really going on, start to grasp the whole big picture, if you haven't already.

Right from the very start, we made it clear that, although we'd pursue an Ideal IAS method, and go through all the steps to really teach you the "WHOLE LOGIC", we'd really be working on an "integrated concept", where ideal, constant L/D, and angle of attack, also worked, with both methods yielding the same optimum final result. Well, right here is where it all comes together, in an amazingly easy concept, you probably didn't see!

Amazingly, it's this simple: If you're really heading toward flying **constant, optimum, L/D**, if you **double your Weight**, thus your Lift, you **have to double your Drag.** ***SIMPLE!!!*** There's a good chance that you never thought of that before, even though it's dead simple. People seem to not tumble to that. So, if you did see it before, give yourself "special good marks".

The corollary is just as simple and true, and not obvious also. Double your weight and **drag** and you **double your fuel consumption, cut your MPG in half!!!** WOW --- but wait, that seems severe, what's really going on here? This is a point where your insight can go way up!!! The hooker is, if you're really trying to fly constant L/D, constant angle of attack, **you must speed up**, to "hold" that same angle of attack, not "mush out" to a steeper angle, under load. You don't have to be an Aerodynamicist to grasp that, your Pilots horse sense will tell you that's true. Sure, I realize that still probably seems "a little severe, unfair", but you see, if you don't do it that way you're not comparing "apples to apples", it's the only way that is fair!!!

We'll see real clearly, shortly, what's really happening, by plotting a **family of curves** for **three gross weights**. We can even accurately **see** what **relief** we get if we **purposely do not speed up**. We now have a wonderful capability to get **specific answers**, either by number calculation, or **just looking** at our drag picture, the Drag Curves, with our now very orderly way of flying, and **looking at specifics**. (You're becoming a pro!)

Before we plot curves however, we should first understand **what increasing weight does to** our **required speed, IAS**. We're going to quickly find that IAS is also proportional, but in this case, **proportional to the square root of the gross weight ratio**! That sounds like a mouthful, is apt to strike fear in the heart of the non math folks, but don't panic we'll lay it out, **so you can see "as much as you wish"**. **It's valuable**, because

!

making "Drag and IAS corrections for gross weight" is basic in flight testing, isn't hard at all with "calculators", once you see it. If you're not a "calculator person", have courage, "dive in" here, we'll help you with examples, *You'll see it's quite easy! We'll risk making it look hard, with a derivation of the method, then calculations, to help you, learn what you wish!*

Now, what we're going to do here is just write our basic lift formula twice, for two gross weights, drop out everything that doesn't change, make a simple proportional statement that we will take the square root of, to find a new "heavy speed", V_2 ratio.

$$\frac{\text{Lift} = \text{Weight} = 1400\# = \cancel{C_L} \times \cancel{S} \times (\cancel{\rho}\, V_2^2/\cancel{2})}{\text{Lift} = \text{Weight} = 1310\# = \cancel{C_L} \times \cancel{S} \times (\cancel{\rho}\, V_1^2/\cancel{2})}$$

Recognize we want to see how much our V, our IAS changes, if we change our GW from 1310#, half fuel, up to MAX GW, 1400#, full fuel. We don't want anything else to change, not altitude, ρ, certainly not S, wing area, certainly not C_L since we want the L/D to stay the same. Now, since those things don't change, trust me, if you're new, it's mathematically legitimate to just drop them out, and create a "proportional statement" as follows, by just treating what remains of the formulas, as a big "ratio" --- to find the new "unknown" V_2, its "ratio" to V_1.

$$\sqrt{} \qquad \frac{1400\#}{1310\#} = \frac{V_2^2}{V_1^2}$$

Now, do you see that if we take the square root of the "weight ratio" we get the "speed ratio". (permit me to not use the square root sign, but its equivalent, a 1/2 power, since I'd have to switch to another computer program to create a sq. root sign.)

Be Consistant, stay with IAS, 1 and 2, or TAS, 1 an 2. Either OK, if Consistant!

$$(1400\# / 1310\#)^{1/2} = V_2 / V_1 \quad \text{or, rearranging}$$

$$V_2 = V_1 (1400/1310)^{1/2}$$

(Ignore the derivation, if it confused you, just use the result.)

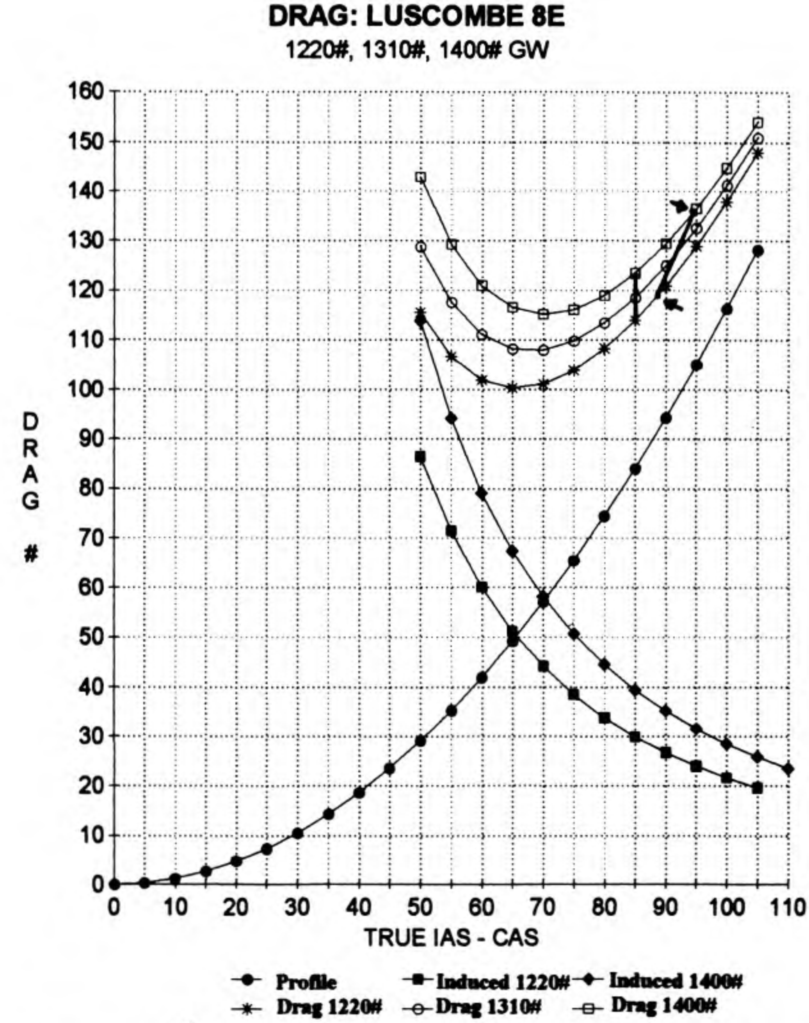
So, go ahead, be brave, if you're new, punch in 1400/1310 in the calculator. You get 1.0687022, the weight (or Drag) ratio, then just hit the square root key and you get 1.0337805, which is the speed ratio! (If you can navigate an airplane, that won't strain your brain, so relax, if you're new, decide you CAN do it. (Would you believe that I just did that on a calculator that I bought at the local drug store check out counter, for $1.00. This modern life is truly amazing, if you stop to appreciate it!)

Now, do you really appreciate and realize what you've just done? You've calculated BOTH the DRAG and SPEED, ratio, going from 1310# to 1400#, specifically 1.0687, and 1.0338!!! **Exact and easy!!!** (We were working and thinking in IAS, and we left C_L and ρ unchanged, so our answer is in IAS, but if we had been working in TAS, the ratio would work for that also.)

(The inverse, or reciprocal of those two numbers .9357143, and .9673233, shows you how much you would decrease your drag and speed too, if you decrease your weight from 1400# to 1310# burning off half of a Deluxe Luscombe 8E's fuel, 180# total, 30 gallons. Don't be confused, the math works either way!)

Now we've got the subject "nailed" (!?) so on the opposite page I've plotted three curves, Full Fuel, 1400#, at Max GW, Half Fuel, 1310#, Zero Fuel, 1220#, so we can see what happens when we burn off a full load of fuel starting at 1400#, max GW! Now we can **see** the **effect**, the **picture**, it's **significant drag!!**

The three key Max IAS/ Drag, IAS MPH speeds are **94.877**, **91.777**, and **88.568**, all calculated as above, (from the original



ZTGT test data, Min. Drag IAS of **68.12** MPH at **1250#** GW. I multiplied 68.12 by $3^{1/4}$, as we learned in the last Chapter to get the 1250# Max IAS/Drag point, of **89.65096** MPH). Practice on one or more, to prove to yourself that you can do it, **and you can forevermore handle GW speed changes, just using the square root of the weight ratio!!!** As above, you get the **drag even easier**, since it's a **simple GW ratio**, starting from **136.34#**, at **1400#** GW, 127.57# and 118.81#. Go ahead, do that, see that you can!!

Of course I hate to "complicate" my nice clean pages, with busy work calculations, and there's risk in having "too much", but recognize "new guys" need encouragement, help, practice!

The big picture thing to see is that weight costs. Look, we're **well above the min. drag, light, of 101#,** or114 to123# at 85 IAS. ***Don't treat your plane like a truck!*** **The designers *"get livid"* when you pile on weight!** Before we go on, let's *think*.

Recognize, the calcs work out easy, because you've simply looked at **the same point on the drag curve, as you change GW,** straddle 3 Drag Curves for the 3 GW's. In this case we're looking at the *optimum tangent point*, so it works. The method works for any other point like the Min. Drag point, actually **any other point you choose, but it must be the same, point --- where the α^o, C_L, L/D, all stay the same, get it?!!**

(You can **not** use, say, the Min. Drag of 103.5#, at 68.12 MPH, at the test 1250# GW, to "ratio" to a "tangent point" drag. You would come out wrong, all confused, **because it's a completely different point. When you move around the curved curve, you can't use the simple ratio method** --- you've completely changed the α^o, the whole game!!! You need to use the $3^{1/4}$ trick, or calculate and plot new curves as I did -- as follows.)

We'll tell the advanced guy's (and gal's), that I generated the three curves simply using the basic formulas we developed back on page 44, using a flat plate area of 4.55 ft.^{2} for Parasite, and the (Span Loading)^2, using the three gross weights, a span of 35 ft. and an e of .7 to generate the Induced. Remember: Drag = Parasite + Induced = FPA x q + $(GW/Span)^2/\pi eq$

Incidentally, EVERYBODY RECOGNIZE that generating the three curves **only required the one Parasite Curve**, but then **three induced curves for three Gross Weights!** Notice that the middle induced curve is missing -- only because "Works for

Windows" only copes with 6 printed curves. I could and did calculate all seven, but six seems to be the print limit. It's easy to eyeball where that middle curve would be, so, not a problem.

Now, let's look at the great insight that we get **easily**, from the ratios that we've done. **Starting at 1400 GW, burning 180# of fuel off, we slow from 94.877 MPH IAS to 88.568, 6.31 MPH IAS, drop our Drag from 136.34# down to only 118.81#, a significant 17.5# difference, to 87.14%, (Invert, MPG is 1.1475, +14.75%). That top Drag is a lot higher than 118.8#, in fact it's 14.75% higher, MPG to 87.14%!**

THE CLEAR MESSAGE IS THAT LOADING UP YOUR PLANE DOES COST YOU FUEL AND $$$!!! ---- BUT ----

Now here is a very significant insight, where you really start learning what's going on. Look at the picture, the curve. If you just fly the 88.5 IAS, your drag only goes up ABOUT HALF AS MUCH, about 9 pounds — and you're automatically flying A LOWER SEGMENT OF THE HEAVY CURVE!!! — At 85 IAS, drag is even less, ~123#!

Per the Cartoon at the beginning of the Chapter, Cessna 182 Pilots going out of the country, to build their "vacation cabins" long ago learned that "great truck" hauls whatever you can fit in (within some reasonable limits of course). Literally, cement, wheel barrows, wood, literally the "kitchen sink" in addition to the wife and kids, fly regularly. BIG LOADS COST FUEL --- BUT HOLDING, OR LOWERING THE IAS IS THE WAY TO FLY HEAVY ECONOMICALLY, OR FARTHER - BUT, THAT COSTS SPEED. **Understand, pick your choice!**

That Drag Curve shows that when I need a long range to go non stop, I just fly a constant 85 IAS, go high, 10,500', lean, 100 TAS, beat the socks off the guys trying fast, - who have to stop! !

CHAPTER 6, WEIGHT EFFECT ON DRAG, IAS

In this Chapter we risked making an easy subject look harder than it is, by encouraging those who aren't yet comfortable with calculations to do them, square roots and all. We showed the actual numerical calculation results,. Since this is a teaching book, for pilots at all levels -- a little risk, trying math, is OK -- especially if, by now everyone has caught on to the fact that: *you really can't get lost in this book because we always come back to the same theme, the same simple conclusions. HERE, WE'RE SIMPLY TEACHING HOW MUCH DRAG AND OPTIMUM IAS CHANGE, ---- IF YOU* ***CHANGE WEIGHT!!***

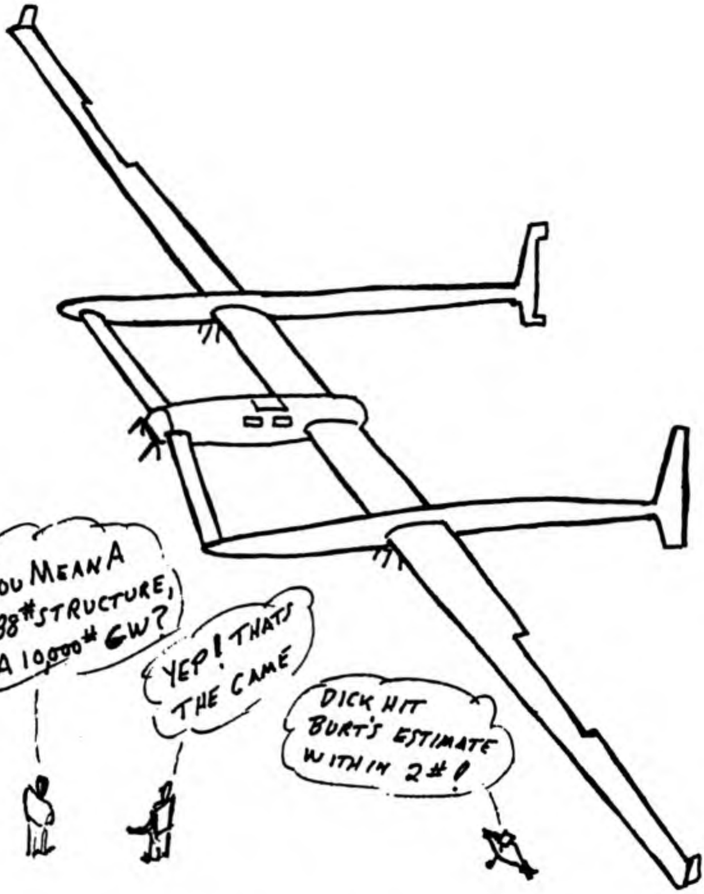
1. **Flying our optimum IAS, optimum angle of attack system, if your weight goes up some percentage, say 21%, to 1.21, your drag goes up 1.21, 21% -- dead simple, but $$**

2. **Ditto, if your weight goes up 21%, to 1.21 times the original weight, your IAS has to go up, the square root of 1.21 , to hold the same angle of attack, the same flight condition, --- which is 1.1, on a simple calculator --- +10%.**

For those of you who are afraid of math, please don't let yourself get faked out by any of this. You can skip it! Our objective is to give you help, not let you get lost, snowed or confused. Sure it may seem hard at first, but hang in. Practice, you'll see you can , you'll be proud.

ANY PART OF THIS BOOK CAN BE READ, IN A FEW MINUTES, A FEW HOURS. WE EXPECT PILOTS AT ALL LEVELS WILL READ, AND REREAD, GETTING SMARTER AND SMARTER AS THEY GO! We'll both succeed.

The central message in this Chapter is that treating your plane like a truck is not free. Don't build it, fly it too heavy!



The basic design requirement on the Voyager, was to make a fantastically light *yet* strong structure, so it could take off FOUR times heavier than it lands, *75% FUEL*, the heaviest/lightest plane, by far, in 1986, a weight ratio of 4, a speed ratio of 2, efficient at every weight!!! Actual numbers, 9694.5# T.O., 7011.5# fuel, 6796.4# used, 26,358.6 statute miles, equator 24,903.1+ 1455.5! If you're interested, there are still a few copies of the Voyager Official Log, Flight Analysis, and Narrative Explanation, identical to what we put in all the National Archives, a collectors jewel! 818 360 1105

Weight Effect, The Last Chapter, 6, A Little Extra Insight

Unlike a ground vehicle, a "flying machine" has to "hold itself up in the air". THAT'S NOT FREE! It's no big surprise, then, that the more a vehicle weighs, the higher it's drag, the more energy it consumes "levitating itself", flying, all in nice neat proportion. Just plain old horse sense says we should find that sort of relationship in the basic Physics of the situation, and of course , we do!

Worthy of notice, "we can slide down the induced drag curve", decrease "the drag due to lift", but we must do it "by sliding right up the Parasite curve", going faster, so there is no escaping either the Physics or the "horse sense" of it all!!! All of Science is like that. It's thoroughly logical, the math follows right along, because it was there all along. We just aren't smart enough to see it unless, or until, we work at getting our act together as we have been here. You are to be complimented, if you're "hanging in", learning how your world works, one of the small percentage of humans, using your intellect to "really understand".

Most good planes can fly at an L/D of 12, or 13 to 1, but drop to something like 10:1 at Max IAS/$, *equivalent to a coefficient of friction of .1, 10%,* just like sliding a block across a table, in high school Physics class, at .1 to .25. It's not super low, like the rolling steel wheel of a train, .004, but it's pretty good for a "self levitating" *speed vehicle* !!

The corrections you learned in this chapter, are a real basic in Aero Engineering, because you can use them for correcting all test flight data points to the same GW, in addition to getting the feel and understanding, you just did. Get as smart as you wish, skip, or practice the math. ✓

Chapter 7

Optimum L/D, α^o

(and insight on airfoils too)

Since we've been talking about constant α^o, optimum, L/D flight from the beginning, it will almost be an anti-climax to finally get to it, but there are many things to learn about it, and airfoils. It's an amazingly simple concept, but you'll be surprised to see how sensitive it is, how small the angle differences are at higher IAS, CAS speeds You'll see, almost with x-ray insight when we finish, that the basic "flight condition" is set by the relation of C_L to C_D, which controls L/D, both controlled by angle of attack, α^o which is controlled by IAS, for a given weight. It's all tied together, and by this time you are primed to get your mind around the whole concept. In the final analysis, it is holding α^o constant that is the most simple concept, that permits holding any selected "optimum flight condition" for any weight, any altitude, an amazingly simple and sophisticated "technically elegant" concept of flight!!! It would clearly be "the only way to fly", except as we have already hinted, and shown you, in Chapter 7, p. 44, 47, One Constant IAS has less cost for weight! Grasp it all, and You Can Become a True Master of the subject, to a degree that you never realized was possible -- a true "Thinking Man of Flight". The learning always takes some effort, but then "doing it" is laughably easy - either Constant Deck Angle, or One IAS!

We realize that we may have dragged you screaming through more formulas, Algebra, Graphs and Engineering like calculations, than you ever thought you'd tackle in your life --- but you realize that you can skip, forget what you wish, or dig for more, **as you choose.** If you're going to spend your whole life flying a plane, loving it, loving flying, it's almost like an "incomplete life" to not end up "savvy" on how "the birds really work", especially if you can find the whole basic grasp in one short book, written especially for you. You can understand the whole logic, the real meat, relatively easily, as deep as you wish!

This book is intended for Pilots, to let you have a sophisticated insiders grasp of flight, not be a limited, unknowing outsider, on your life's work, or avid hobby. Though you won't be an Engineer, when you finish, as a pilot, you can build insights the engineer will miss. As a side benefit, you will have gained a very good insight into what engineering is all about, how our wonderful modern life has been brought to fruition, by just getting to the very essence of each subject. It's not the warriors and "political hacks" that created a world where we can fly, it's the guys that "conceive, manufacture, produce". The game is not to do each other's laundry, be *a service nation,* but "create", produce, be a little smarter, leave more than we took.

The concept now of bringing all our newfound knowledge and insight together, in a grasp that is as simple as holding an "optimum angle of flight" **is truly technically elegant**, an almost perfect example of the wonderful simplicity, classic logic that one finds in the **natural laws,** even for such a complex field.

The driving force is that the basic coefficients of lift and drag change in the sophisticated, yet simple way that you have seen, the optimum found in a simple "discerning" angle of attack, that you will now see is *elegantly precise.*


YOU MEAN WE WENT THROUGH ALL THAT STUFF AND ALL WE HAVE TO DO IS HOLD THE ANGLE?
YEH! BUT NOW YOU KNOW HOW IT ALL WORKS!
YOU DO DON'T YOU!?

Lets be sure, before we go further, that you **understand specifically** ***WHY***, simply controlling angle of attack, α^o, controls L/D, which yields a dead simple, precise logic of flight.

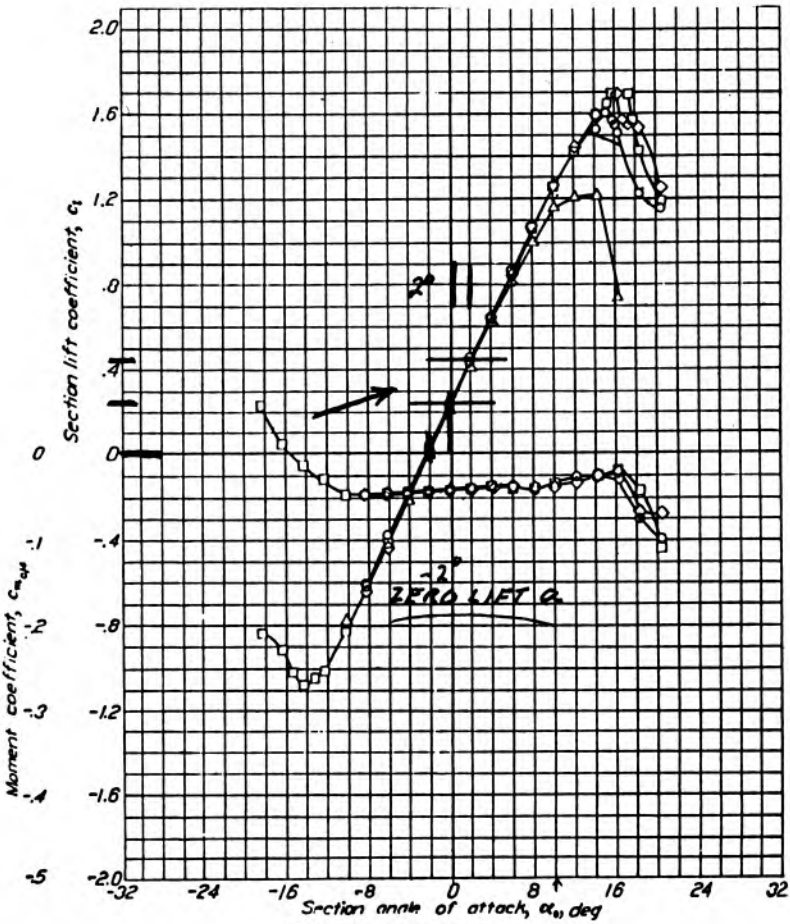
(Recognizing the unchanging Parasite Drag Coefficient), it is the angle of attack that controls the C_L, thus Lift, and all the variable C_D, thus Drag, and thus the Lift/Drag Ratio.

Lets look at the NACA 2412 airfoil data on the facing page, a typical section used on a typical Cessna. The sloping vertical line relates angle of attack, on the horizontal axis, to C_L, the coefficient of lift, on the vertical axis. Notice that if you were to mount the wing on the plane at a 2^o angle of attack, it would develop about a .45 C_L at that angle, a reasonable ballpark, for a slower, efficient IAS. If you speed up enough to get down to zero angle of attack, your C_L will drop to about .25, a C_L more fit for a fast cruise, roughly spanning the useful speed range!

That creates several insights that are very much worth noting. Let's list them, walk around them, come to really recognize their existence and significance.

1. 2^o got us a .2 C_L change! **".1 C_L per degree α" is typical!**
2. **ONLY 2^o α change covered a whole .45 -.25 cruise range!**
3. **C_L vs. α is a very straight line, predictably proportional over a wide speed range, right up until nearing stall!**
4. **"Standard roughness" wings, and low Reynolds numbers, small or slow, stall at a 1.2 C_L, not 1.6!**

Each of these insights are "good rules of thumb" that pro's know and use. It's interesting, easy to remember, that the C_L vs. α^o is such a straight line, and almost exactly .1 C_L per degree α.



NACA 2412 Wing Section

It's interesting to recognize that we only use a very skinny part of the chart in normal flight, a few degrees α, a few tenths C_L. You'll see the angle is very sensitive shortly. We'll do a "fine print calculation", that shows that, and justifies the "roughly" 2^o α nominal cruise range for you. The (-) α^o and (-) C_L only come into play in inverted flight, the high C_L's only come into play in slow flight, landing and takeoff. **Most flying is done in a very small and sensitive angle of attack vs. C_L band!!!**

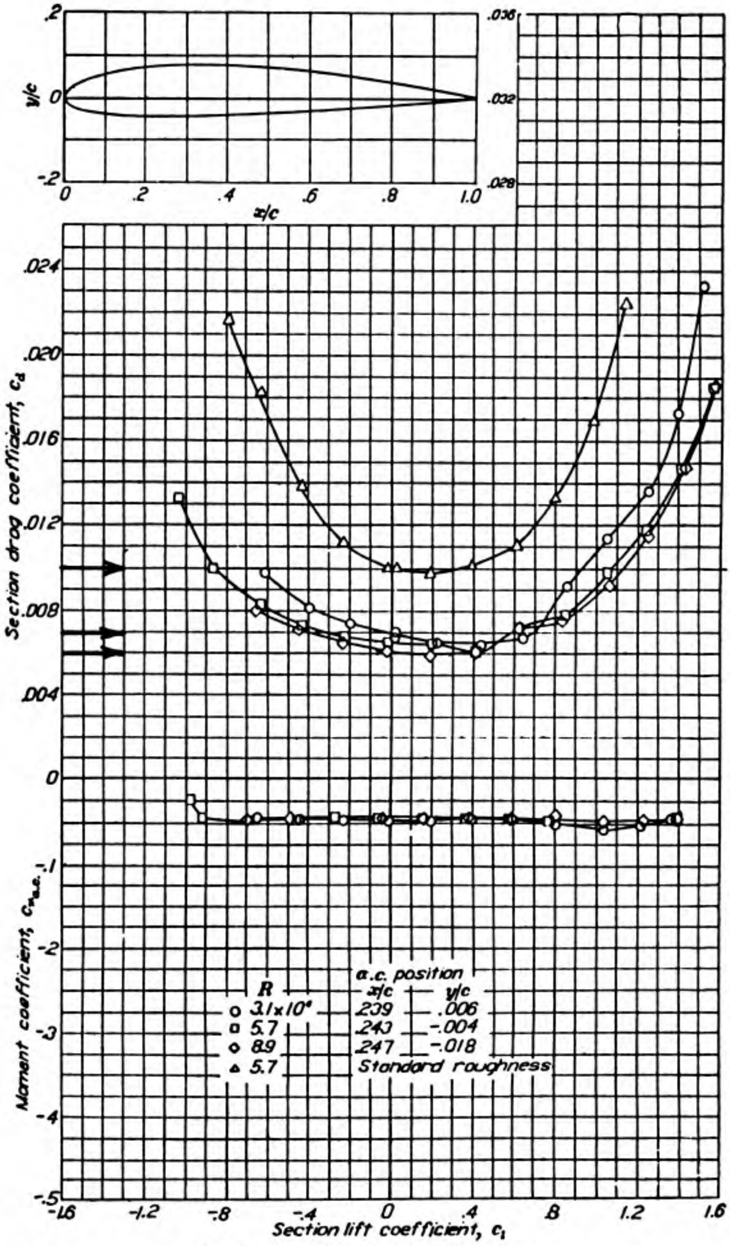
It turns out the newer, faster planes, with a bigger speed range, fly an even narrower, lower C_L range, since all planes start at max C_L at stall, at takeoff, perhaps with flaps, and the fast ones fly at much higher q, thus tend to fly with even lower C_L's, unless they have inordinately small wings. Conversely, a high aspect ratio "cruising classic", like a Luscombe, flown at a lower IAS, as we're teaching here, will fly at a bigger C_L, vs its Vmax speed, especially heavy. We'll show a Luscombe and an RV6, light and heavy, at max gross weight, at cruise IAS and Vmax, shortly, and plot them on their airfoil charts, because that produces a lot of valuable insight --- **will give you a good basic grasp, of the pertinent insights on airfoils!!!**

But first, courtesy of Dover Publications, 180 Varick St., N.Y, N.Y. 10014, "Abbott and Von Doenhoff", their classic 1949/59 basic airfoil reference, "Theory Of Wing Sections", that all the pro's use, we'll look at the drag of a Cessna airfoil, C_D vs. C_L.

Now here again there are some classic insights to recognize!

1. Most foils have .01 min. "Standard Roughness" Drag. Coef.
2. Most airfoils have a .006 to .007 min. Smooth Drag. Coef.
3. Most airfoils are used near their minimum Drag Coefficients.
4. Again, the negative α and C_L range tends not to count.
5. The big swoop up in the drag coefficient, has a lot less effect than it appears because it happens at slower and slower V^2.
6. The big jets, with huge Reynolds numbers, can approximate "smooth coefficients", even with leading edge device gaps!
7. Notice C_D is plotted **vs. C_L not** α^o, but it could easily be α^o.

Nail these key points and you will have nailed the basic insights on airfoils. The small private plane, with "rough wings", suffers a penalty vs. the big guys, .01, more, **but**, those slick composite homebuilts, with near perfect wings can get .005 C_D's, even less



NACA 2412 Wing Section (*Continued*)

using "modern laminar flow airfoils with drag buckets" actually get the wing drag that Aerodynamicists could only dream about, before composites came into use on homebuilts!!!

Now that big upsweep in the airfoil drag coefficient, though not as effective as it looks, since it happens at lower speeds, where the V^2 effect falls off, must be reviewed. It was purposely not accounted for in the drag curves we taught you. We'll deal with that right after we finish dealing with angle of attack sensitivity.

To investigate **angle of attack sensitivity** on **fast** and **slow** airplanes, first we'll tell the more advanced guys, how to calculate it quickly, then show a simple, clear, chart of results.

If I have to do several calculations involving q, I calculate it very accurately once, for 100 MPH, 25.565956 psf, using the modern value for ρ, .0023777, put it into calculator memory, and subsequently "just square the ratio to 100 MPH", for a whole string of quick calculations. Solving the basic lift formula for C_L, you get: $C_L = GW/ S\, q$ **Find C_L and α change.**

The empty weight of a Deluxe Luscombe, and an RV 6 are **both** apt to be something over 900#, so minimum flight weight with a skinny pilot and no fuel can be set at **1100 #**. The **1400#** GW Luscombe has a 140 sq. ft. wing, the **1600#** GW RV 6 has a smaller wing, 110 sq. ft., but goes faster, 200, vs. 116.4 max. I cruise the Luscombe at 85 IAS, will cruise the RV at 140 IAS.

C_L AND α CHANGE		1400#	1100#		
Luscombe	85 IAS	C_L = **.541**	**.425**	.541	max.
	116.4 "	" = **.289**	**.227**	- .227	- min.
				= **.314**	= **3.14°Δα** ✓
		1600#	1100#		
RV 6	140 IAS	C_L = **.290**	**.200**	.290	max.
	200 "	" = **.142**	**.100**	- .100	- min.
				= **.190**	= **1.90°Δα** ✓

LOOK at how low that RV lift coefficient gets, **only .100!** Over its whole usable speed range, light to heavy, the C_L only changes **.19**, the angle of attack, α, **1.9 degrees**, 10 times as much, and still very small, at 1 degree, per .1 C_L!

The RV's wing chord, about 4.78 feet, rotates almost exactly **1 inch per degree.** At 200 MPH, if you burned all the gas, threw out all the baggage, bailed out the passenger, and "lost weight" to get down to 1100#, the wing would only change .42 degrees, .42 inches!!!! Over its whole flight regime, light to heavy, slow to fast, it can only change **1.9^o, 1.9 inches!!**

The Luscombe, a slower old cruiser, changes more, because it's operating at much lower q, so it must change its lift coefficient more, especially slow and heavy, and you can see that in the numbers with the .541 max C_L, heavy at efficient cruise, 85 IAS 5 MPH below its mathematically optimum "max IAS/$" speed.

Now here is where we get to the objective of the whole Chapter, get smart on how practical it is to fly constant α, constant optimum L/D!!! Burning all 180# of gas out of a Luscombe, from 1400# to 1220#, the C_L drops from .5414 to .4718, an .0696 change, **.7 degrees!!!** Burning all 225# of fuel out of an RV 6 from 1600# to 1375#, the C_L changes from .2903, to .2495, a change of .0408, equivalent to **.4 degrees!!!**

My **Sears Craftsman bubble level**, bubble moves .125 inches. **1/8" for 1 degree** change, **.1 C_L**. To hold **.1 degree, .01 C_L** the bubble only moves **.0125"**, 12 1/2 thousandths, *very close to read!* You need to make a little adjustable mount. You can read a ***centered*** set point that accurately, and once set, it's good for life!
You'll see I set, and use, this surprisingly precise angle, but mostly I fly one IAS, all GW!
Changing IAS 5 MPH in the Luscombe changes C_L .052, .5 degrees, .1 degree per MPH. The RV's only .037 degrees per MPH, so you can hold 1 to 3 MPH, right at the limit!

Now on the premise that the way to really learn something is to get physically and mentally involved, go get a pencil and a "highlighter". In Appendix C look up the Luscombe's "old fashioned" NACA 4412 flat bottom airfoil, and the RV's famous 23012 airfoil, the first smart, fast airfoil used on the DC 3, Bonanza, and a bunch of other great planes. Van actually used a 23013.5, half way to a 23015, (13.5% thick), so you'll find the comparable 23015, compliments of Dover Publications.

Actually lightly, but accurately, mark up the C_L vs. α^o, and C_D vs. C_L limits, with the pencil, and then highlight them, when you're sure you have them right. That effort should really bring home to you what we've been talking about here. We really fly a very "skinny" part of the data plot, and you'll better appreciate that the numbers show, there is "very little angle change"!!!

Now you may think that I'm going too far, telling you to actually mark up the data, but you see there is a "method to my madness" a lot of experience in my recommendation. Many of you will be looking at this close for the first time in your life. We are going through the drill here, so you can see for the first time, how it all works, even the math, the formulas, and the curves. But sure, that's not the objective, that's the effort you have to get past, to earn your right to be one of the smart guys.

What we both know, is that like everything you ever learn, it seems hard at first, but then you start "tumbling to it all", pretty soon "you actually get it", and then pretty soon you start "getting a feel for it all", and it quits being a lot of "gibberish", funny engineering stuff. All this stuff ends up making good horse sense, and you can really "make it your own".

I'm giving you the straight line guided tour, the easiest way, through the center of a hugely complex subject,

Aerodynamics. I'm leading you by the hand "to all the key points". I'm hoping that you're reading it as deep as is correct for you, "not letting yourself get snowed". I'm putting in all the key points, making it possible for the broad, diverse audience, to pick up as much as is correct for each individual. I know that those that "highlight" the skinny part of the airfoil plot, are most apt to "grasp" the simple, but sensitive, elegant relationship of lift drag & α.

We purposely did not talk about "moment coefficients" in the airfoil data. That has to do with tail loads and stability, C.G. Perhaps we'll cover that later, less basic, advanced design..

Now, the last thing we have to do in this Chapter, is to dispatch the nasty little fact that there is a big "α sensitive" increase, slow, "in the parasite drag coefficient of all airfoils", that we "purposely did not include" in our drag curve construction. Though the effect looks huge on the airfoil drag plot, its effect is greatly reduced, since it comes into play at low speeds, where the V^2 effect is smaller and smaller. Since it's not induced drag, it must be part of parasite, **but** it swoops up at low speed, just like induced does, and therefore to not complicate the constant, fixed parasite drag coefficient, it's usually either ignored, or treated as an induced "add on".

We found "stable air" Zero Thrust Glide Testing conditions so good in our breakthrough original testing of my Luscombe, "out over the stable ocean at dawn", that we were able to "separate out that alpha sensitive parasite drag". **Look on page 109** in the next chapter, where we discuss "real power, and propulsive efficiency" to see the **real, complete test data curves**. You'll see the extra "alpha sensitive parasite drag curve" at the bottom. It's there, it's real, but it only exists slow and we can ignore it, on the first time through, for the simplified curves for teaching you, with only a small unimportant error, that we'll show you.

MINUTIAE -- SEE IT CLEAR, CORRECT - IGNORE IT

There is a lot of detail in engineering, and it's important for the engineers to dig in, understand it all, to get it all correct, so their work is correct -- "so wings don't fall off", *important*! The problem is, if you're locked onto detail, you can lose track of the big picture. Worse, the minutiae can confuse the learner, stop them from seeing the big picture, any picture!!! This "α sensitive parasite drag" is just such a detail. But we'd make a big mistake if we left it fuzzy, because that would leave some people confused. They'd go off unclear, unsure, not end up with a firm, sure grip on all this. We'll blow two pages to put this chapter clearly, firmly to bed, so all of you can go forward, clear, sure, **confident, with a clear grasp of the big picture!!!**

We very purposely taught you **basic, classical, aerodynamic theory,** the simple, clear version, with 1. a constant parasite drag coefficient, a definite "flat plate area" a simple V^2 parasite drag curve, 2. a normal $1/V^2$ induced curve, with the minimum drag, exactly where they cross and are equal! That's exactly like the great texts like "Aerodynamics For Naval Aviators", so you have the classical grasp, not some "non standard version".

The problem is that big "swoop up" of the airfoil's "profile drag coefficient" throws "a small, but real, spanner in the works" The trick is to deal with it as an "extra little detail", **not** let it confuse you, **not** let it mess up your simple, clear grip of the "big picture". We'll make it perfectly clear, then recommend that you put it back in the minutia category of your mind, at least while you're learning the big picture.

As you can see in the "real Luscombe curve set" that you just looked at, in picture form, that little extra "third basic drag curve" - "swoops up the slow end of the composite drag curve". It will do that little addition to every plane in the world -- **but --**

It's a detail, specifically because that's not where you fly!!!! The variable profile drag has the following characteristics:

1. It acts just "like a little extra induced drag", swoops up slow.
2. It simply "hooks the slow end of the J curve up a little more"
3. It's really a part of "Parasite Drag", an unwelcome extra and "non constant" part of the constant parasite drag coefficient.
4. It causes "the real min. drag speed to increase a couple of MPH", faster, than where our two basic curves cross - equal.

It's a subject that you can pick up, accurately remember, now, if you're at that level of advancement, or forget and roundly ignore if you're a first time learner.

MOST SIGNIFICANTLY -- HOLDING L/D CONSTANT, BY HOLDING α, ANGLE OF ATTACK, CONSTANT, STILL WORKS, ABSOLUTELY ACCURATELY. We said it absolutely accurately at the top of page 86 -- α, the angle of attack, controls all of the variable C_D including the basic "α sensitive profile coefficient"detail. OUR SIMPLE BASIC FLIGHT LOGIC STAYS PRECISELY CORRECT

Our original excellent ZTGT flight testing accurately sorted out this drag, confirmed it agreed with theory. At 1250# G.W. we found a 68.12 MPH min. drag speed. To simulate this accurate data, for the "teaching curves" used in this book, we used the 4.55 ft.^{2} Flat Plate Area we found, times q, for Parasite Drag, the proper Span Loading^2 /πeq for Induced Drag -- except we used .7 for e, rather than the correct e of .74, which kicked the slow end of the drag curve up, a bit, to simulate the missing "third curve drag" while increasing fast drag only a tad, a fair MATCH. The simplified curves still show the min. drag speed 1 to 2 MPH slow, a small error. **IGNORE MINUTIA - GRASP "THE SIMPLE BIG PICTURE", CONFIDENT!!**

Once an "optimum, (or any desired) flight condition" is selected on a drag curve, as represented by a "constant L/D", the most simple, direct way to hold it is to, **simply "hold α^O, constant". That works for any altitude, any Gross Weight, SIMPLE!!!**

The specific reason **why α^0, angle of attack, holds L/D is because, it is angle of attack, that directly controls C_L thus Lift, and all the variable C_D, thus Drag, and thus L/D ratio.**

Looking into required C_L, shows that a very narrow C_L range is used in the "normal cruise and weight range", especially on fast, high q planes, about .2 C_L, a little more on slow, low q, planes.

Looking at basic airfoil data shows C_L varies essentially .1 for each 1 degree of angle of attack change, until relatively close to stall, so a 2 to 3 1/2^0, change will handle the entire IAS, weight range of a fast or slow plane, but **only .4 to .7 degrees change occurs as a complete fuel load burns off typical light planes!**

✓ **With the bubble of a good carpenters level moving a scant .0125" for a .1^0 change, a good level is right at the edge of handling a fuel burn off, or .1^0 for 1 MPH change of a slow plane, ~3 MPH,** (~2.7 calc), **for a fast plane, at .037^0 per MPH.**
I actually use an adjustable, centered bubble, actually readable that close, .0125" for .1°, set once, usable for life, but I actually use one constant 85 IAS, all GW's, less weight penalty ✓

Airfoil data shows an increasing profile drag coefficient, and drag (part of Parasite), that acts like "extra Induced", as the plane slows down, below the normal cruise range, that raises the slow end only, of the normal J shaped drag curve, typically raising the minimum drag IAS, a few MPH. This detail can be ignored for basic flight theory and logic, (or optionally used).

A LITTLE INSIGHT ON FLAPS

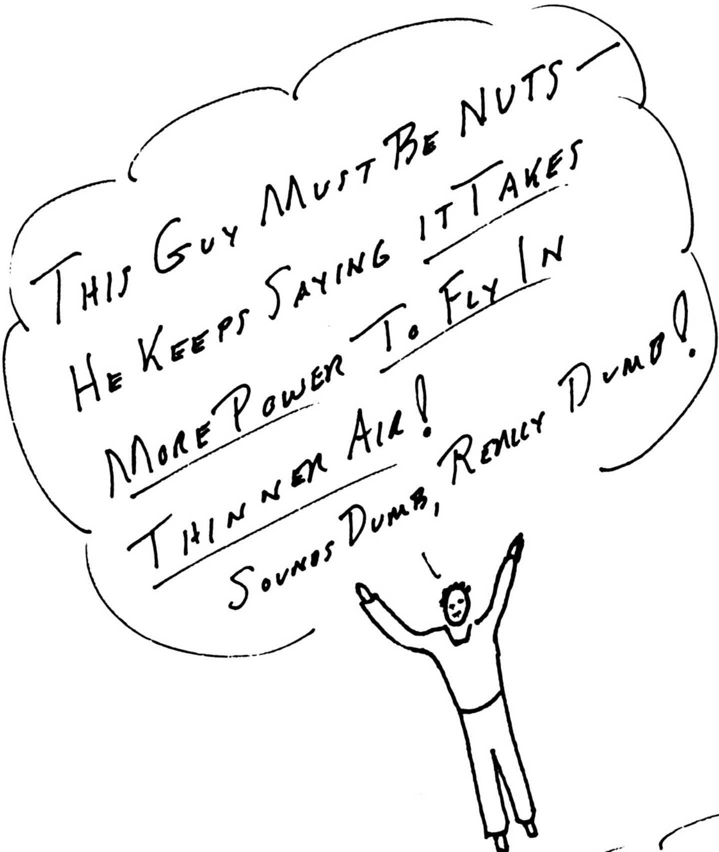
Flaps are a whole other subject, but we'll include a bit of insight for those who wish it.

Flaps, especially the huge extending Fowler flaps, that are used on jets, greatly change the "camber" of wing airfoils, their center of lift, and their moment coefficient, and greatly increase their lift coefficient. In the process of all this, the original airfoil "pitches down" considerably, lowering the nose, because the original wing becomes more the leading edge of the new bigger, much more cambered airfoil.

This puts the tail at a much more negative angle of attack, greatly increasing its down load, but the change in the center of lift, and the moment coefficient of the now much more cambered airfoil, is great enough, that retrimming to get even more down load is typically required. That's all pretty routine, something pilots are well aware of, but there is enough happening there that it's all worth pointing out in passing.

Thinking that through, a bit, the designer has to be sure that the tail is big enough that it can never stall in an extreme case. The pilot must be sure he never gets into an extreme forward C.G., a fluke case like ice on the tail leading edge, some unusual combination, the designer didn't account for. Very highly unlikely, but a dive into the ground, would be a bad result.

That all, of course, is well removed from efficient flight logic, but this book will be short enough that we have enough space to improve the pilots feel and insight, wherever the opportunity arises. Understanding how planes really work, that which is usually not understood, is what this book is all about.

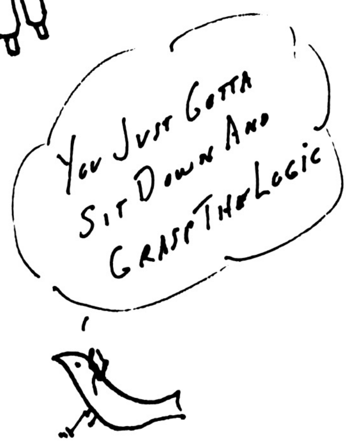


$$\text{Power} = \text{Drag} \times \overset{\text{TAS}}{\text{Speed}}$$

$$\# \times \frac{\text{Ft}}{\text{Sec}}$$

$$550 = 1\ \text{HP}$$

$$\text{or}\quad 33{,}000\ \frac{\text{Ft}\,\#}{\text{Minute}} = 1\ \text{HP}$$



Chapter 8

Power (and its hidden insights)

(and propulsive efficiency too, η_p)

Airplanes fly on IAS, (CAS), but ENGINES FLY ON TAS!! A simple, basic insight, but no other source that we've found seems to offer it --- and you'll really see it in this Chapter on Power where all the engine logic shows up tied to TAS! We'll again make it absolutely clear that, flying at constant CAS, "constant drag", required power increases as air thins, at altitude, because "TAS increases". Amazingly, you'll learn that the RPM increase at altitude is amazingly SIMPLE, fixed pitch. It increases, essentially EXACTLY, as TAS increases, q, all angles constant, Simple, Easy. As complex as propeller math based logic is, that's fantastic!

Remember, Engines have less Power at Altitude, We'll match H.P. to Plane Power!

You'll see that although it takes more power to fly at altitude, that does not hurt MPG, because power increases only as much as TAS, so you use energy faster, but not more energy because your true speed increases just as much as your energy use rate, (power) does! In fact, your MPG will actually improve, because as your throttle opens, the engine breathes easier, pumping losses decrease, engine efficiency increases, and MPG goes up!!! Additionally, with the throttle plate less angled, acting less like a "liquid separator", fuel mixture distribution can greatly improve, permitting much better leaning, and MPG can improve very substantially, much more than you'd expect!!! However, if you try forcing a higher IAS, CAS, higher q, you can wound propulsion efficiency, on many old planes. That's very Important! (Note: CAS is just correct IAS).

This is an interesting, and insightful chapter, because you'll come to understand that it's a ***transitional*** chapter from **Aerodynamics to Engines!** And a very interesting, and incisive part of that transition, is to recognize the obvious change from CAS Aerodynamics to TAS Aerodynamics, something that we've found to not be generally recognized, in the aeronautical literature!! **But that's a very important fact!!**

One of the significant contributions of this book is to equally see and integrate "flight logic" and "engine logic". It becomes obvious that those who specialize in Aero are not thinking about engines, and quite logically, those thinking about engines, quite a different field, never grasped the heart of the Aerodynamic logic. This is the book that found the opportunity to put both subjects together! That's VERY SIGNIFICANT, because the way you want to fly the airplane is specifically dependent on how you also get the engine to function efficiently!!!

The engine must have excess power for safety, speed, and to make it a "fast climbing, high performance craft" --- but that relegates it to being throttled at low altitude cruise --- and that relegates it to a life of even greater inefficiency --- unless the insight in this book is put to work. You certainly do not want to fly it at a wimpy, heavily throttled, min. drag, max L/D IAS, which makes the engine efficiency worse, despite what all the basic Aero literature says. Climbing high, at "max IAS/Drag", getting the engine "wide open and optimally leaned", is "where efficient, frugal Vmax. is found"- The intelligent "Logic Of Flight"!!

THAT'S THE CONDITION WHERE BOTH THE PLANE AND THE ENGINE CAN BE EFFICIENT, MATCH EACH OTHER IN A --- TRULY INTELLIGENT LOGIC! AT A FASTER TAS, BETTER MPG -- TRUE MAX V / $!!

NOW AT THE HEART OF THAT LOGIC IS THE FACT THAT THE ENGINE CAN PUT OUT LESS POWER AT ALTITUDE, WHILE THE AIRPLANE REQUIRES MORE, WHICH MAKES IT POSSIBLE TO GET THE ENGINE and PLANE MATCHED, --- *COMBINED* AS EFFICIENT AS POSSIBLE. IT'S TRUE, THE LOWER THE WIDE OPEN ALTITUDE, THE MORE EFFICIENT THE ENGINE CAN BE, BECAUSE, LOWER THE POWER IS GREATER, THE ENGINE LOSSES LESS IN PROPORTION, THE EFFICIENCY GREATER!!! YOU DO NOT WANT *TOO BIG* AN ENGINE IN YOUR PLANE, BECAUSE THAT RAISES THE WIDE OPEN ALTITUDE, LESS EFFICIENCY -- But it can also get too high to Breathe! Go for sleek low drag, not brute force HP!

In CH 10 —— the TAS/IAS Gain -- Beats Efficiency Loss Breathing Decides!

The wonderful part of this logic --- and a main point that most people miss for a long time --- is that you are NOT flying at a WIMPY SPEED, but WIDE OPEN, V MAX!!! You just happen to be flying at a low drag IAS, where you are buying speed intelligently, frugally, where the engine is perfectly matched to the plane, OPERATING AT THE COMBINED MAX POSSIBLE EFFICIENCY, MAX SPEED / Drag, Gal., $ That's the winning combination!!!

The good joke is that it's so laughably easy!!! What could possibly be easier than 1. Flying a smart IAS, or smart α^o, 2. Climbing until your engine is wide open: 3. Leaned!!!

That's the wonderful situation here. You take people right down the center, through a comprehensive and incisive course in basic Aerodynamics, and you can make all the conclusions come out so easy, it's honestly funny --- but also a wonderful statement on the incisive eloquence of Science, the simple natural laws! **Our fond hope is that everyone will come learn, appreciate, attracted, charmed by the beautiful final simplicity of it all.**

So, we've used a lot of very black ink for the last few pages. Specialists in proper writing form would probably go into shock, over such excesses. But as we told you in the introduction, our central objective here is to really communicate, **teach**, make it possible for you to **learn**, as **easily** as possible. **If** you really got the meat of the last few pages, you already grasp the central core of the book, everything else you learn is just valuable additional insight. Those few pages are so meaty, so much to the point, so clear, it would be a big mistake if we let them look bland, so a "book skimmer", anyone, could miss them. **We told you this book is as much about teaching, learning, as it is about Aerodynamics. We have to get past the BIG teaching, learning barriers, past the considerable complexities of Aerodynamics, so you can actually grasp the meat of Aerodynamics, see that you really can grasp the meat, accept that there are conclusions that are so easy they are actually funny.** I'll willing to risk, if you'll end up **smarter!**

We're using another mechanism here that's worth recognizing. We tell you what we're going to tell you, the conclusions. Then we tell you. Then we tell you what we told you, summing up in "an ever bigger, more comprehensive picture". In effect we're telling you what the course will be, you "see the pattern early", then we say it, then we walk you all around the subject, so you "really get it", really learn it. That's a form of the SQ3R method we introduced you to back on page 5. Some may think that excessive, hard over opposite to the usual terse technical journal, but that's very much on purpose. Our objective is to make it possible for many thousands of pilots to actually see through, and learn the relatively complex Aerodynamics, and grasp the eloquence of the disarmingly simple conclusions.

If we succeed at that here, you've won big, and I've won big, and as many of the pilot population as we can bring to the table, can win. Any minor excesses, or misses, are of little importance!

Those first few pages are so dense, so much to the point, that we really have this chapter *licked*, so per our format, let's be positive we have the fundamentals nailed.

Power is "Drag" times "True Speed", TAS, pounds times feet per second, # ft./sec. in engineering units. Physics defines a horse power as 33,000 ft.# / min., or 550 ft.# / sec., so you just divide by 550 to get H.P. required. See, engineering doesn't have to be scarry, it's just very orderly and logical. Good that it is, so I can cope with the really obscure, complicated stuff!

It's perfectly straightforward then, that if you fly constant IAS, constant drag, (at constant G.W.), at any altitude, **power increases, exactly** as **TAS** increases at altitude, dead simple. Just keep the logic straight.

Now here is a far deeper, but truly elegant insight that we can build from that, and what we've now learned - At constant IAS, constant GW, **RPM** also **increases exactly as TAS** increases at altitude. Grasp this, this is beautiful! ---- **If your plane continues to fly at constant IAS, constant drag, constant L/D, constant angle of attack, it just speeds** up **as TAS increases, as altitude increases --- and your prop does too!!! Fixed Pitch, the same thrust, against the same drag, it "just sits at exactly the same angle of attack, the same L/D"- it just "winds up" to a proportionally higher RPM!!**

That's a truly elegant insight, one of the best I've ever found in all of Aerodynamics, truly eloquent, in its incisive simplicity. It really makes it easy for the pilot to grasp and use --- and for "The Simple, Thinking Man's, Logic Of Intelligent Flight".

There are some great guys in engineering, smart, funny, with a great sense of humor, not at all the "green eyeshade types" that the public too often misunderstands. But then, of course, there are some "pills and oafs", like any group suffers. The first guy that I ever pointed that out to, was one of those "full of himself, know it all" guys, that had it in his mind that he was smarter than everybody else. He stormed out of the room, blustering "it couldn't possibly be that simple". I had to laugh at him, but I felt sorry for him too, wondered if he ever did catch on. Life can be so much fun, and discovery. The poor guys that get too full of themselves, or just never learn how to simply enjoy good friends, suffer a terrible penalty, in a life where people just like a good egg, someone who's simply genuine. That alone almost guarantees a "full happy passage". I cherish "Auntie Mame's admonition, "Life is a banquet, don't bring a brown bag"!

Ah, but now, just look at the wonderful insight we've created. **A plane doesn't know, or care, how fast it's going, it can only sense IAS, q. -- But the engine sure cares, cares a lot -- Fixed pitch, constant q, it "linearly senses TAS", puts out proportionally More RPM --- More Power!!!! That proves Airplanes fly on IAS, Engines fly on TAS! I'LL BET YOU NEVER FORGET THAT, SUCH A GREAT INSIGHT!!!!**

Regarding the next basics, I'll bet that by now you've got it clearly and correctly in mind that: **DRAG, thus energy required per mile, controls MPG. Higher TAS, more power required, simply using energy proportionally faster, as you go faster, does not hurt MPG. MAKES SENSE. Believe it!**

We'll be covering engine efficiency, pumping losses, altitude effects, leaning, not letting your throttle plate be a liquid fuel separator, thereby ruining fuel distribution and leaning, those things that we introduced in the opening, -- in the next chapters.

So now we're ready to look at a really **new** subject, one that's right on the leading edge of flight, "less than wonderful propulsion efficiency", η_p, "eta sub p", the Greek h, even if it looks like a fancy n, --- and a "lumpy engine power supplied curve", fundamentals that have not been well understood. Before Zero Thrust Glide Testing, for Drag and η_p, fixed Pitch there was not, for ninety years, a good way to test for Prop Planes, *flight test* answers, η_p. **It was the most fundamental, longest unsolved problem in Aerodynamics - with Props too!**

Gus Raspet, Miss. State, did the great, breakthrough, towed up, Propless Glide Tests.

So, let's discuss it all a bit, "then look at the insightful curves, *a picture you can see* ". Jets took over the research during WW II, before propellers and things like propulsion efficiency were completely figured out. With sparse tests, the facts were sparse. To a degree the technical end of the industry charged off in a new direction, before it was completely done with prop planes. And it never went back to finish the job, because with jets, the post war world, it was a whole new challenge, a new era.

There were some early insights. NACA Report 680, (1939) showed a 10% efficiency loss if the cowl was half the prop diameter, none at 1/3, but the party line was pretty much, if you have an 80% efficient prop you have 80% propulsive efficiency, (overall), no loss for blowing back in your own face! That just never made sense, never rang true to me, because there were some pretty ugly airplanes out there, and most were a lot less than perfect. It hardly seemed possible that a poor little propeller sitting on the front of a normal airplane, would work with the same efficiency as a prop in a free stream. Not likely!

The first ballpark testing that I did in 1982, with a preliminary method, clearly said "no way". Even if the first answers were more inaccurate than I thought they could be, the test said there were big losses there, for sure. Dr. Andy Bauer, a lifelong friend and a fully experienced, serious Aerodynamicist, from Douglas Long Beach, and I went to work on it testing, analyzing, looking for a valid test method, recognizing we were working on the longest unanswered challenge in Aerodynamics.

A few years into a serious, if intermittent, part time, hobby effort , we knew we were right, there were big losses. Then presenting our findings to a local EAA group, one Friday night, **Bob Archer**, a local Bellanca Cruisair owner and antenna expert introduced me to the lore of the famous, ***Dr. August Raspet***.

"Gus" Raspet, was head of the Aerophysics Department at Mississippi State, teacher and mentor to many well known and respected Aeronautical Engineers, among them Sailplane and glide test expert "par excellence", **Dick Johnson**, and **Bruce Carmichael**, a friend, author, Personal Aircraft Drag Reduction, a jewel, and "laminar flow expert". Raspet, genuinely creative, had done propless, towed, free glide testing, in the 50's, with a series of light planes, a Cub, a Cessna 120, an early short wing Whitman Tailwind, then a Bellanca Cruisair, Bob Archer's craft.

Gus was great, challenged students to practical tasks, George Lambros's Bellanca tested

Voila, he found the well respected Bellanca had terrible "propulsive efficiency", only 58%, comparing level powered flight, with "sealed cooling duct" glide testing. That gave the true gliding drag of the airframe, unpenalized for cooling losses. He found cooling losses could be 10%. The nominal η_p, 58%, started better at low power, sagged at cruise speeds, and inexplicably got a little better at max speed. That was just wonderful, because that was what we had found, η_p down in the lower 60's. Cooling drag would drop it into the 50's. **Science demands independent corroboration, before work is accepted as truth, and we now <u>both</u> had that, <u>confirmation</u>!**

Significantly, Raspet seemed to "introduce propulsion efficiency" in one of his papers, which pretty well confirmed to me that it was <u>not</u> a well defined, understood subject earlier. Unfortunately, the field never seemed to either appreciate or catch on to his very fundamental breakthrough insight, and with dead stick landings required, no one ever took up his method. Dead stick landings involved more risk, but he found the **truth**!

The way Science works, the next guy starts, standing on the previous guy's shoulders. Though I never knew Raspet, didn't know he existed until half way through our work, he surely placed us on his shoulders. His student, Dick Johnson became world famous, working his milestone R.J. 5 sailplane up to a 40:1 glide ratio, then World Championships, then his "more than professional" sailplane glide testing. Those even showed subtle knees on the drag and sink rate, power curves, as laminar flow broke to turbulent. It was reading his work in "Soaring" magazine that set me on course, challenged me to find the final answer, for the propeller airplane, that had been so long denied! What August Raspet had begun had found its way to Andy and I through Dick Johnson, before I even knew of Raspet.

When our work, Andy's and mine, prepared me to be able to see and invent the "thrust sensor switch" in 1989, a simple, "stiff, vibration proof, feeler" that lit a bulb, when the prop and its crankshaft face moved in the engine's thrust bearing clearance, from thrust to drag, we finally had the key to a valid, "bias free, glide test method". Zero Thrust Glide Testing, ZTGT, was practical, safe, accurate, in fact more accurate because we had the engine available, could go find truly dead air, "stable air at dawn, out over the ocean", for near perfect test results. Raspet had been tied to the airport, and dead stick landings, unsatisfactory test conditions, that could distort desired precise test data accuracy!

Fixed Pitch ZTGT just needs practical Engine Bearing End Play, say ~.015"!

The following is from ZTGT! Drag is measured by "sink rate", accurately knowing "Gross Weight and TAS". The real key is finding true stable air to "eliminate any biasing lift or sink, while gliding". Working out how you also get truly accurate data from your instrumentation, is always the heart of any good engineering test work. The bottom line however, is that we are about to see "***flying* propeller plane facts", unavailable for 87 years! The CAFE group in Santa Rosa, CA did fantastic instrumentation and test work on an RV6, Whitman Tailwind!**

LUSCOMBE 8E Aerodynamic Data

We'll list the many basic insights that a complete Aerodynamic data set shows, but the breakthrough insights are Real Drag and, readily obtained Propulsion Efficiency!!

1. **A classic V^2 Parasite Drag Curve, 4.55 ft.^{2} F. P. A.**

2. **A core $1/V^2$ Induced Drag Curve, from $(W/b)^2 \cdot (1/\pi eq)$**

3. **The actual Induced Curve, increased by a .74 Oswald, e.**

4. **The additional "α^o sensitive profile Drag Curve", Ch. 7.**

5. **The Total Drag Curve, combining the 3 basic curves.**

6. **The Gliding H.P. Required Curve, (Drag# x V ft/sec. / 550).**

7. **The *Actual* Engine Power Curve, from speed-power tests**

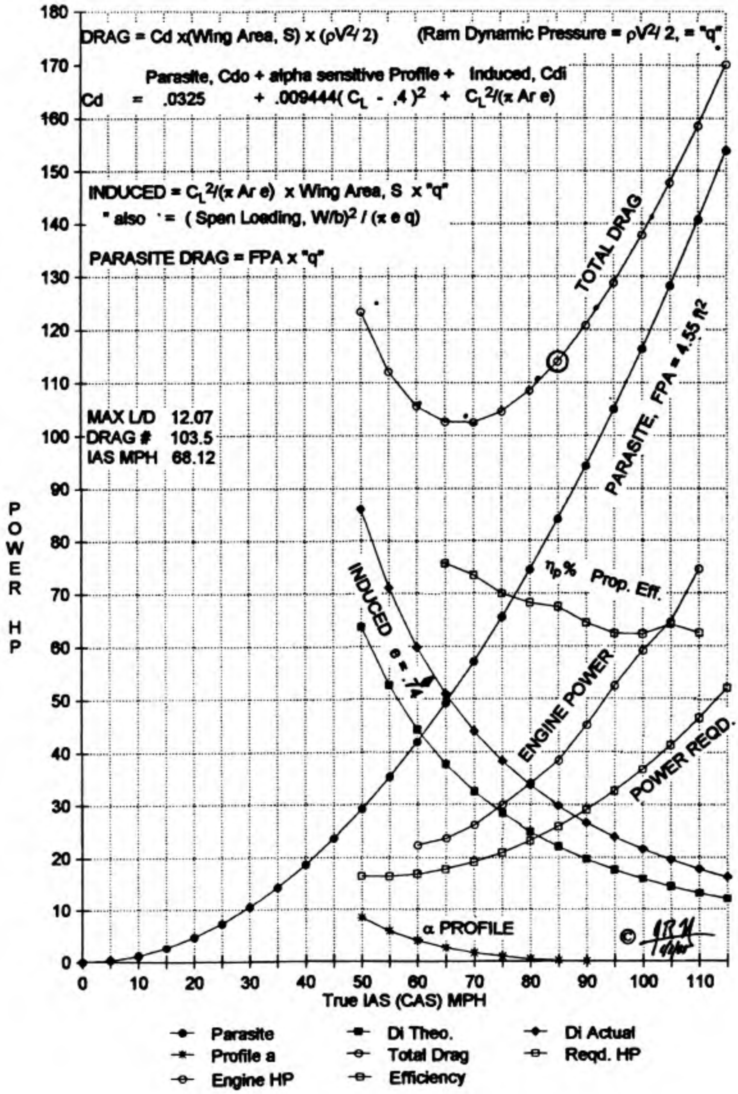
8. **The real Propulsive Efficiency %, (Reqd. H.P./Actual).**

All of the test data and curves are exactly what one would expect from theory, *until* the Actual Engine Power Input, from near sea level "speed- power tests "were plotted, and the resulting propulsion efficiency percentage plotted!!!!

The Luscombe propulsive efficiency started off reasonably good at low power, considering that the propeller efficiency is nominally 75%, **but** η_p fell substantially, and proved to be quite irregular as power and speed were increased!! **The obvious favorable place to fly is at 85 MPH CAS, right where I do fly! You can now see why I fly there, a favorable η_p knee!!** √

LUSCOMBE 8E

Drag - Power 1250# GW



There is considerably more valuable, but semi hidden insight available there. The numbers do some tricky things. If one takes Raspet's 10% factor for cooling drag, (if we had rigged tightly closing cowl flaps), thus multiply the apparent .67 η_p times .9, the result is only 60.3% overall propulsion efficiency. **The brutal facts apparent there are that you have lost nominally 40% of your available power, no small loss, *off the top*, and if you have a ~30% engine thermal efficiency you are at the 18% overall efficiency we showed you in Chapter 2. Again that says that you are using 5.5 times the true energy requirement, at your best, smart point! You can easily go well over that, far worse, being more sloppy!!!**

Further 11,100' Camarillo CA Runway length, Sea Level, Speed Power Testing of Propulsion Efficiency is intended, using CAFE RV6A, ZTGT glide test Drag Data, as time becomes available. Approximate conclusions from accurate Theodorsen Prop design results show the modern sleek low drag planes will be far better, enlightening, interesting to designers, and pilots.

The Luscombe η_p **irregularity** suggests variation in the airflow, under power, perhaps some separation, and that seemed to be supported by a patterned variation in the drag coefficients that the data analysis generated. Looking at Raspet's data on propulsion efficiency, each plane seems to have it's own particular characteristics! With the sleek, far cleaner modern designs we'll find far better propulsion efficiency. A P 51 with a **big**, **geared**, **slow** turning prop, a relatively small fuselage, has far better potential. A good RV 6, 6A η_p test will be valuable.

Facts: Being able to nail Real Propulsion Efficiency, with ZTGT is the first time we've been able to accurately accomplish that on functioning Propeller driven planes. **We got good data on a Classic Luscombe, an RV 6A, and a Whitman Tailwind**. Excessively tight new Lycoming Engines, some even zero slop, hot, bad, prevented more testing. If we can get good planes with loose engines, in the future, we can do a lot more!

Readily Testing, Knowing Real Propulsive Efficiency, That's a Breakthrough!!!

Minutiae: Aero engineering pros will see minute variations from the clear simple rules pointed out in this chapter, but they truly are minutia, that should be avoided, for a clear understanding of the big picture. A small Reynolds number change, as prop RPM goes up with TAS, would naturally occur, but its effect would truly be minutia, as would second order effects, that could be pointed out as Power, RPM and TAS changed. We purposely use terms like "essentially exactly", throughout the book. Other places we purposely avoid the ill advised complication, when the central task is to inform and teach. The picture presented here is an accurate, clear concept of what happens physically in logical flight, and scant apology for minute simplifications, is needed. There are important concepts here that have never been pointed out. Pro's are not normally thinking of engines, or the pilot's lack of insight, so this presentation can be a good mind jogger for the pro to look from a new perspective, as we teach the pilot who has never had the chance to grasp what a pro can see! If you're a pro, see further insights, refinements, corrections, call us. We're after the ultimate truths.

Max L/D IAS. The three element drag curve causes a subtle change. The α sensitive parasite curve increases the slope of the induced curve, increases the "min. drag speed" an "extra amount" due to the extra slope, faster than "where the combined curves cross", because of the extra slope!!!

POWER, Its Hidden Insights, and Propulsion Efficiency, η_p.

Airplanes fly on CAS, (correct IAS), **ENGINES FLY ON TAS, more power**, and fixed pitch **RPM**, required as **TAS** increases!

POWER is **rate of use of Energy, (ft.# / sec.)**, DRAG #, times true V, ft./sec., (or 2π RPM / 60 x Torque, ft #). One H.P. is 550 ft.#/sec.

Flying at constant CAS, constant q, both **Power** and fixed pitch **RPM** increase essentially **exactly** as **TAS** increases at altitude!

Realize Prop q, and all Flow Angles stay essentially Exact!!!

MPG, which is dependent on **Drag**, thus "**energy** use per mile", is not hurt as altitude increases TAS and Power, up, same ratio!

Actually,

MPG is a lot better at altitude. Throttle open, pumping losses decrease, fuel distribution can be more even, *low HP*, leaning safer!

August Raspet, and **ZTGT**, have both shown **major η_p losses as power is increased**, on old design planes. With ZTGT, true facts are available for new homebuilt designs, any plane. All we need are engines with normally loose end play, ~.016" hot!

Realize ZTGT uses Fixed Pitch Props, No oil Pressure Bias!

Engine **efficiency strongly favors flying wide open, at altitude, leaned at lower power, where it can be properly, safely done, with the plane at a low drag IAS, but gaining free, faster TAS at optimum IAS/Drag. That yields "frugal speed, max efficient Vmax.", wide open, engine optimally matched to the plane, MAX TAS/$, "best *fast* MPG"!**

AN IMPORTANT SUMMATION

Believe it or not, we have completed the basic course in Aeronautical Engineering! YOU MADE IT! This chapter began the transition to "engines, an equal fundamental" in this book, and all the side issues will be easy to pass on to you, now that the big, hard, central issue, "Aero", has been swallowed!!??

You can see that your view and grasp is becoming broader and deeper, but **still centers around the beautifully simple conclusions we started with**. Your view is getting far more knowledgeable and sophisticated at this point, however!

Hopefully, you can see that it's unnecessary, undesirable to have too big an engine, to try brute forcing a fast speed, when the plane and engine really want to fly at Vmax., but at a not excessive IAS, at moderate drag, at an IAS where speed is maximized vs drag, fuel used, and cost, at altitude, where TAS is *essentially free*, (except for climb fuel, a good investment, even at some loss of unusable engine efficiency, that we'll soon show you.) The engine which "must be too big for the plane", for climb performance, "**can't fly efficiently at low altitude**, but would love to fly wide open, properly leaned, with good potentially undistorted fuel distribution, at altitude, where it can be safely and properly leaned, at lower power, actually at a point where it, and the plane are at **Max Possible Combined Efficiency.** There is quite a hunk of favorable logic, and you're getting closer and closer to making it your own.

The real way to go fast in an Airplane is with low Parasite Drag, low flat plate area, where you can effortlessly scoot out to higher IAS at low Induced Drag, low total drag, go fast, but we also *want to understand how to fly it economically*.

We're going to look at propellers, engines, all usable for modern homebuilt designs, that give us such great characteristics, **but NOW, let's really nail, the sophisticated core of this book!**

1. It is necessary, but not sufficient, to know how to fly the plane efficiently. You must know how to also fly the engine efficiently, furthermore, you must know how to get both, at the same time, know what flight condition does BOTH!!!

2. You must grasp, that a plane is properly not really an economy vehicle, (and you can't get the engine efficient at max L/D anyway), but rather a "speed vehicle", and the real proper objective, is maximizing speed vs. cost -- efficiently!!

3. You will learn an engine is an "efficiency disaster", its best "efficiency" is supposedly wide open at sea level -- but oversize, to fly the plane, AND climb it fast at the same time, throttled for cruise, low, it's an unmitigated disaster! So - How do we maximize Combined efficiency?

4. With the plane at max IAS / $, high, wide open, but at lower power, leaned, with good even fuel distribution, the engine is at max possible efficiency. Combined with your Plane, max. TAS /Drag, Gallons. $, and *fast*, at High MPG!

RECOGNIZE

You're going to see in a Voyager engine chart in the 10th. chapter, **why** you really don't want too big an engine, **why** you really don't want to fly a slow Max L/D speed. BOTH force you to a **"too high wide open altitude", which starts killing engine efficiency, killing BSFC. Excessively high altitude causes a significant reduction in the max. engine efficiency.**

BSFC, Brake Specific Fuel Consumption, #/ HP Hr, shows Engine Efficieny!

That MAX IAS/DRAG plane is at an efficiency optimum for a "speed vehicle", a valid technical justification, but it also is a "practical balanced objective" where you can get a properly selected engine "wide open, lean", at a reasonable altitude - thus "as efficient as it can be, used in that plane", and at a true, technically valid, MAX TAS /Drag, $ point!

We hear the engine is supposedly at its max efficiency wide open at sea level, but it can't be leaned there, will be set "over rich to cool, protect the valves", can't be run too long at excess power, certainly doesn't match any efficient "Aerodynamic IAS" point for the plane!!!!! Conversely, "too high", power has dropped , losses too big, a fraction of the power, resulting efficiency low, and excess RPM hurts!!

The Voyager Engine Chart gives Incisive Overall Insight!

If your engine is a reasonable size, you'll be going V max, at a place where your engine is as efficient as you can get it in your plane, you'll find good MPG, Max TAS/Drag, Fuel, $.
NOW, TO AN INCISIVE LOOK AT, PROPS, ENGINES!

Are you a Tech Pro, *one of the Smart Guys*, or a Novice?

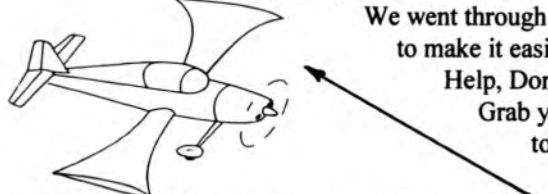
Even if you're a pro, it's probably best if you go back to the **Book II Introduction**, and **Primer** to start to learn Prop Logic, because it's designed to **Blast Everyone into Huge Awareness, *Quickly*.** Though one wag described the **key 2 pages** as like *drinking from a fire hose*, (I laughed at that funny insight), it has very good practical purpose, because **everyone gets his first look at the big picture, specific Logic ASAP**. I don't expect anyone, especially Novices, to really fully grasp the basic logic immediately, but it's then much easier to proceed, look back, come forward more slowly, for the Novices, show everyone the *simple enough* horse sense of Propeller Logic. Everyone gets it *Quicker, Better*, if they **quickly see the bottom line insights!**

I get Everyone aboard in an hour, or less, then 2 pages of X Ray Insight!

In the early Primers, and Chapters we start from the same basis, but soon go ever broader, deeper, start tying in new concepts, **superemphasizing everything** so novices see it super clear, and pros who thought things were different don't miss it either. **If pros didn't understand the system they'd quickly think I was being too repetitive,** *probably not like the super emphasis.*

Pros, here's what I expect you to clearly understand! With your training and experience **you can read this much faster, get it much quicker than the Novices I intend to help get it!!** I expect you to see that everyone from salty old pros to brand new greenies, Pilots who never tried anything like this before represent *the full bell shaped normal distribution curve*. The ***Book is written to help the New Guys. It should be a snap for you!***

Accept it, do your part. Help the new guys!



We went through all the Math
to make it easier for all ---
Help, Don't complain.
Grab your chance
to get it all!

Simply: **Understand Aero 101, don't let your prop load inside out,** DEAD WRONG, **like this!**

Look at the Prop Airflow Picture on the Book Cover*. Betz teaches us to create a **Constant Pitch, Pure Helical Air Inflow** to each propeller blade, a **slightly stretched, slightly higher Pitch, still perfect helical screw shaped outflow, downwash, backwash**. It's just a perfect helical **Archimedes Screw inflow, stretched outflow** *from each blade*, ***two*** **perfect screw surfaces, constant stretched pitch out, all radii!** (Inflow and Rotation Combine.)

Archimedes died 212 B.C. His Screw still pumps irrigation water in Egypt.

Now, what that means precisely, is that **the inner radii are at a progressively steeper pitch angle**, the smaller radii are screwing, **flowing in exactly the same distance each revolution, equal pitch, like a perfect screw at all radii**, then **flows back**, still a perfect screw surface, **at a slightly stretched pitch**. If we think of **the prop** with a constant angle of attack, thus constant C_L, it would have exactly the same pitch as the air **inflow**, but **with the constant angle of attack *added*, slightly steeper, not quite a perfect helical screw surface***. Now here are **3 secret, hidden insights.**

***Of course the prop is *basically* pitched for Plane Speed vs. RPM, inflow extra.**

1. The prop is pulling in air, a slightly reduced pressure in front, **$\Delta V/2$**. **Inflow adds to the prop pitch**, not outflow. **2. The air speeding up a similar amount flowing out**, **$\Delta V/2$**, a slightly higher pressure behind the blade. **3. The Prop Slips a little**, overpitched a little to pull in the air, thus **actually Advances a little less per rev than the pitch! Yes props are tricky, the challenge!**

ΔV, Delta V, is just how much airflow speedup is needed to make the thrust.

Now that's great, but **how do we make that magic happen??** The **secret there** is that **we load the prop exactly correctly**, and we do that **by precisely Shaping it, with exactly the proper twist,** simply because **chord represents area, thus load capability**, as we integrate out along the blade. Now if you jump ahead to **page 147, or 11-II** you'll see that perfect, **constant α^o, constant C_L Betz props** have **very characteristic loading and Blade Shape**, that **varies vs. Advance Ratio**, (most easily understood as the actual advance angle of the prop tip), very much tied to Low Pitch or High Pitch, Slip being the difference). We'll teach you the 2D, 3D **Airflow Geometry**, in **Ch. 3 - II.**

 Of course that's complex, dense, when you first see it. Think, Go slow, Get it.

Better understanding of Superemphasis, and the wording.

Now, as a pro, naturally I started out to write this in the **"good professional writing style"** that I'm used to and capable of. The smarter I got on props, the more I found out that I was **NOT in charge of the wording, or the writing style!** Getting smarter, I found out that there were enough things happening at the same time, that had to be tied together, qualified, that the **Logic**, the **Physics**, the **Math** (unseen, operating behind the scenes), **were telling me very explicitly what <u>wording</u>, what <u>phrasing</u>, what <u>qualifying phrases</u> *<u>must</u>* be said to most incisively nail the Logic**, to make it **clearest, easiest for you!**

Swell, here I am with a lifetime of professional experience, not in control, being a typist, a slave to what the complex 3D flow logic dictated, as it did its task perfectly. The **good news** was that I could see through the wild technical complexity, never explained before, got to where **I could explain it** as the ***technical horse sense*** found in **1. Newton, 2. A Rotating wing, 3. An Airscrew, 4. Betz's Logic - exactly solved by Goldstein Theodorsen Math** -- then many more great finishing insights.

Many of the **great insights**, and **the phrases that best state them, and qualify them** were ***<u>learned over a 10 year period</u>***. Naturally, I realized that <u>the little gems could be missed by brand new technical Novices,</u> Pilots, in many cases struggling to get aboard on all this new technical logic they never saw before. <u>Many might need to have things repeated a few times before the little gems really register in their brain.</u> Pros sometimes don't catch on too quick to completely new thoughts, I've seen, so don't feel too alone and lonely out there. ***<u>Everyone needs time with this!</u>***

Props are just not for speed reading, a challenge for us all.

So naturally we highlight, superemphasize the key phrases, and the little qualifying, limiting phrases, that the Logic, the Physics, the Math demands, to **help the novice see, grasp the crucial key insights. <u>Often it gets busier than we'd like</u>, but the game is to <u>nail the key insights for you</u>, <u>make it as easy as possible for a Novice to grasp the keys</u>!!! Notice, it is possible to <u>speed skim in review</u>!**

The **Simple Enough way to Basically Understand Prop Logic** is to just be able to grasp the **Horse Sense of the basic 4 steps** that the **11 page prop Primer** and this **Chapter 9 are based on**:

Here's a compact way of seeing the basic Overview of Basic Prop Logic.

1. Learning that There is a *tricky* basic Logic to Props, their Induced Efficiency loss, most easily learned through **Newton's Laws, Minimizing the ΔV,** Delta V, **throwing of air to make Thrust.**

Big Ṁ, (Big D", or just go Fast), for small ΔV, Small ΔV/2V, axial loss.

2. Counteracting Excess Tip q with **Narrow Tip Chords**. Especially on **slow planes**, the **dynamic pressure**, q, **of rapidly rotating prop tips is so much greater** than the **slow inner radii** that the prop is **trying to work Inside Out, Dead Wrong** vs. the **horse sense of a proper lift distribution** of a proper wing, high at the center, zero at the tip. ***Excess* Lift or Thrust** at a wing or **prop tip *must* fall to zero**, the **air escaping, swirling around the tip into excess** *costly* **vortex loss**. **So here's the dumb prop trying to operate inside out,** *excess Tip Load!* **Our job is to be smart enough to counteract that** with **tapered tips**. ***Simply***, **chord represents area**, and **low area lowers** the **loading**. **Ideal Props are Properly Loaded by Proper Shaping,** and twist, **tapered tips!!**

Get It --- Narrow Chords Counteract excess Tip q, Dynamic Pressure!!!

3. Only Hi Pitch Propellers can have max efficiency, a **short spiral path to the destination, less profile drag energy cost, min induced loss, a minimum of ΔV wind thrown, vs. the V_1** wind speed coming at the prop, **helped by a big Ṁ, mass flow rate, for a min ΔV,** **a big diameter prop disk size, or twice helped by just going fast**, a small **$\Delta V/2V_1$ axial**, (and in addition total) **induced loss**.

4. Betz Constant Pitch, constant Slip, Pure Helical Inflow, stretched pure helical outflow, Ideal Min Induced Loss by **Ideal Blade Shape, thus Ideal Radial Loading,** (if Zero Drag), proper Twist and Pitch, **constant dT/dQ, a Constant Ratio of Thrust to Required Torque, equal efficiency at every radius!!!** *WOW!*

And Goldstein-Theodorsen Math ~ perfectly solves the Ideal Betz Prop!!!

Watch how we build this same Basic Logic into answering the 10 basic questions a prop designer wants to know!!! If you just work your way through the explanation, we lead you to all the secret insights!!!

The Wise Old Bird

Props!!! Here's the Big challenge ---
Props can be the ultimate technical Swamp,
if not explained Incisively. We've found a logical way to
fairly quickly get you a great, basic, incisive grasp, 20 pages.
***Then* - It's much easier for you to learn the whole story,**
***if* you choose to go for *the whole Magilla* in Book II ---**

Props can be Pretty Efficient, nominally **85% to 90% +,** for **slow to fast planes**, ***Good!!! But***, **Gus Raspet** showed us **Overall Propulsion Efficiency**, eta sub P, η_P, can be **terrible! 58%** on a **Bellanca Cruisair**, propellerless **glide tests, (cooling sealed), vs. Engine Power Required.** ***(1/.58***, is ***172% More H.P.!!!)*** **Ducts open,** (charging cooling drag to the airframe), it's **maybe .67 to ~.85** η_P. An **Embedded Body** can have, **extra scrubbing drag, pressure drag, variable separation**, worse faster, **power on!!!**

We invented a way to Glide at Zero Thrust, to get real drag, real η_P, *facts*.

There has never been a comprehensive, understandable, *incisive* explanation, *Zilch*, if you're looking for the genuine bottom line insights, the clear Truths. I've looked for that as a kid, an industry pro, it never happened, not even close!

We did all the Math, but we teach it all in Words, Logic, Pictures.

Two of us tackled it, two lifetimes of professional insight, the **biggest, most fundamental gap in Aeronautical Engineering, a total technical morass, as you first wade into it, *a pro killer!***

For Pilots, *this is for pros too*, to Learn the Logic - before the Math.

But, **Nature, Science, is always Orderly, Logical, Explainable. Marvelous Technical work was done by 7 historic Masters, over 83 years, 1865 to 1948, *for us to use, explain*. Once we show you the logic of it all in 20 basic pages, the complexity starts to melt away --- so you can go as far as you choose ---**

This primer, a 10 & 20 page core, incisive, is extended, can get you a great base.

Props try making, max thrust and drag, at the tip, at high q, where thrust must fall to zero, zero inboard, at low q --- *inside out, dead wrong! We teach you* - just tapering the tips fixes that error, and you're on your way to a *marvelous*, optimum solution.

CHAPTER 9

THE PROPELLER

PROPELLERS FOR A PILOT'S *Insightful* GRASP

Fixed Pitch Propellers are harder to design than a "Constant Speed" that adjusts Pitch. First, we'll teach you the Ungeared, Normal Disk Loading, Fixed Pitch Prop.

The Norris - Bauer Law: It is the ***Ideal Shape*** **of a Prop, with the** ***correct Twist and Pitch*** **that determines if you have a** ***Triple Ideal Prop*****, or not. The Game is to actually achieve** ***a constant Ideal Angle of Attack, a Constant Ideal C_L, with pure Helical Inflow***, **by** ***Ideally Loading the Prop vs. Radius, by setting Ideal SHAPE vs. Twist that*** *actually achieves* ***Ideal Minimum Induced, Profile Loss, and Torque* - *min. area optimally placed!***

AT A LIGHTER WEIGHT, NEAR IDEAL, .55 C_L, DRAG IS NOMINALLY 1/3, INDUCED 2/3 OF THE LOSS.

An explanation like that has **never been available. Let's list the proper questions, right up front, then explain the core** logic, **then answer these key, core questions**, get you some **great early insight in an hour or two, only 20 basic pages!**

1. Is there an **Order** and **Logic** to Propellers? If so, What is it?
2. **Why** do **Speed** and **RPM** set the **max efficiency limits**?
3. Exactly what **Shape** should a prop blade be?
4. Exactly what **Twist** is correct?
5. How do I understand how to get **Pitch** exactly correct?
6. Do I want a big area and diameter prop at a low C_L, or a high angle of attack, high C_L smaller prop? **What C_L** is Ideal?
7. Do I want a big **Diameter** with narrow blades, or a smaller diameter with greater **Blade Width**? In other words, what **Aspect Ratio** is best, stubby blades, or narrow blades?
8. Can I get super performance, with a super **Airfoil**?
9. Are **Mach 1, Sonic Tips**, a real private plane problem or not?
10. **What Thrust is required? What must we design for?**

DIAMETER? THE PLANE SPECIFICS AND PROP SPECIFICS -- SCALE "D" UP OR DOWN.

Jack Norris's Basic Horse Sense Insight into Propeller Logic. Just about everyone sees a prop as ***"kind of a rotating wing"***, but right there answers stop. ***No one ever tells you what's next.***

 This is the First Page of the 20 Page Core

There is a **very fundamental**, ***very important difference between a wing and a prop***, and **grasping the simple horse sense** ***is the first thing to learn, perhaps --- the easiest, most important insight that you will ever learn about propellers!!!***

A prop, in spinning as it moves forward, has **much higher velocity at the tips** vs. the root, and since **dynamic pressure, q**, the **basis of lift and drag**, is a strong V^2 function, **q** is *dramatically greater at the tips!* They are **trying to load up, work much harder, produce the most lift, Thrust and Drag way out at the tips --- and that is *Bad*, quite undesirable!!!**

A ***Wing center*** **can maintain high lift --- but it must, and does fall off to zero at the tip**, swirling off each tip in high energy, wasteful vortices --- nothing to dam the high pressure bottom from the lower pressure top. So here's the prop with low q, low thrust at the root, ***trying for max thrust, max drag at the tip, Inside Out!!!*** Do you see the horse sense of the problem? It makes: **1. max drag at the tip**, and **2. at a max lever arm, bogging down the available engine torque, limiting RPM, and thus Power, 3. extra tip vortex loss, 4. loses the** ***paid for*** **Lift-Thrust, which must Fall to Zero ---** ***losing four ways!!!***

We'd like max lift at mid span, zero at the tip --- and q is opposite to that!!!

The optimum configuration is narrower chord tips to set up the mathematically optimum Thrust vs. Radius Loading - to limit the tip overloading, get optimum Thrust vs. Torque!!! We do have an **optimum theory**, optimum, indeed **marvelous math**, but do you see, **once you understand**, this can be **just good technical horse sense?** You can **see the optimum T vs. r loading and the blade shape** that gives it on **page 11-II**, for a Luscombe and an RV 6 -- **see it as a picture -- GRASP WHY!**

Betz will teach us how to do it right - optimally.

The **problem is worst on Slow, high RPM** planes, **tip q 25 x the root** on a slower Luscombe, **7 to 10 x** on a faster RV, **2 1/4** on a fast, geared down Reno racer. Those post WWII square tip paddles - absorb power - ***but inefficiently*** - avoiding .9 Mach.

<u>The Basic Actuator Disk</u> - <u>Logic and Insights</u> - <u>NEWTON</u>

It's much too oversimplified, inaccurate, to be used for final design of a propeller, but we can gain a **huge amount of very basic, very important insight** on how propellers work by **seeing that propellers**, in essence, **<u>pull in and throw back air</u>**.

Newton teaches us **T = $\dot{M}$ ΔV**, Thrust equals **$\dot{M}$, M dot, <u>Mass Flow Rate</u>,** times the **ΔV**, delta V **speedup**, a **very simple** basic of Physics, a basic insight of **huge importance, dead simple**.

What it teaches is Tricky, but the formula is Dead Simple, just 2 items multiplied.
(***<u>Later</u>***, for those who go on, we'll learn that mass, M, *<u>slugs</u>*, is like Weight, W, but actually **<u>pounds weight divided by the accelleration of gravity</u>**, **(32.174 feet per second, per second), used because we're speeding up, accellerating**. We use **$\dot{M}$, a flow rate**, because we're not throwing a hunk of air, but reather **dealing with a steady flow rate**. ***Mass, slugs*, is just a smaller number of bigger units, to get <u>Thrust in Pounds</u>***, the answer we want.
***g gets involved in Dynamics problems - gets answers in <u>pounds</u>!!!**

Skip the fine print for now, realize **T = $\dot{M}$ ΔV** ***<u>is easy</u>***, **helpful insight!!**

You'll learn that the mass flow rate of **air through a prop disk is much heavier than you would ever guess**, even pros are surprised, and thus **a surprisingly small ΔV, delta V, speedup** is all that is required to make even huge thrusts on big, fast planes. You'll learn an RV 6 at 200 MPH, Vmax on the deck, can get by with **only a 10 MPH ΔV**, and make **280 # of thrust**, because it's throwing back **615 # of air per second!*** To fully grasp the significance of that number, realize that's a **1 1/4 cubic foot block of steel**, that three guys would strain to lift, and only if they had a good way to grasp it, and that's **every second**. Would you believe a Reno Racer at 480 MPH, with a Skyraider prop is pulling in and throwing back **4 1/4 TONS per second, 8500 # /sec?!** How's that for a wild insight you'd never guess?!

*615 # per sec./ 32.174 = 19.11 slugs per sec. x 14.66 ft / sec. ΔV = **<u>280 # T</u>.**

Notice the **<u>RV's 10 MPH ΔV is only 5 % of 200 MPH</u>**. You'll learn that **~half the speedup of the air is pulled in as inflow, a slightly lower pressure created in front of the prop**, and **half the speedup happens as outflow, downwash, backwash**, the second 5 MPH, a slightly higher exit pressure caused by the prop. An RV at economy <u>altitude</u> cruise of 140 IAS, 170 TAS, less thrust, ~163 # needs just about 9 MPH **ΔV**, in thinner air. A

 60 MPH is 88 ft./sec., so 22/15, or 15/22 converts. (for **ft.**, **lb.**, **sec.**, system) slower 100 MPH Luscombe at ~136 # T needs more, maybe 13 MPH, **(a much bigger13%)**, depending on the case. A **Reno** racer **with that Huge Mass Flow Rate** needs **less ΔV_{Avg} than an RV**.

The **Stream Tube concept** is a basic of the **Actuator Disk** concept, pulled in and thrown back, **assumed to be uniform velocity***, **(which is quite incorrect, inadequate for detail design,** *example* **ΔV varies a lot vs. radius)**, but can **teach us a huge amount**, relatively **easily**.

******Also* **Backwash at the prop has a much higher ΔV than the average ΔV.**

It turns out that the **$\Delta V/2$**, **the average of the speedup**, is the most basic driver of the **Induced Drag Loss** of the Prop, raising the **power loss cost** of **throwing the air, making the thrust**. **$\Delta V/2V_1$** is the **basic measure of axial efficiency loss** for Induced Drag, half the **ΔV, $\Delta V/2$,** the average, vs. the plane speed, or the speed of the air coming toward the prop, **V_1**, ***before*** the prop effect. **(We say it that way, because later, in the advanced explanation, we deal with a variable velocity at the nose,** ***slowdown*****, where we** ***adjust the ideal prop for velocity profile*****.**

That $\Delta V/2V_1$ formula is a key teaching insight! We'll use it again!!! .

So, **(ungeared)** ***realize*** **the basic game of propeller efficiency** is to **go fast**, **get both a big mass flow rate $\dot{M}$**, **thus a smaller ΔV,** *and* **also divided by a bigger V_1, --- a two way lower loss ratio** ***winning twice going fast***. It turns out that **Going Fast** is the **most important factor in getting an efficient prop**, **more important than perfect design!** ***When you grasp that, you have grasped the core of prop logic, of huge importance!!!!!!***

(We'll cover ***geared props, heavy disk loading, Advance Ratio*** **soon.)**

But the **marvelous, quick insight goes on**. It turns out that for ***two reasons***, you **want a High Pitch, High Advance Ratio prop for max efficiency**. First, quite naturally, a **High Pitch, High Advance Ratio prop goes with a fast plane, a big $\dot{M}$, a low ΔV, high efficiency**. Second, an equally marvelous insight that no one ever tells you, **a high pitch prop* has a short steep spiral path to the destination** --- which **saves profile drag energy**, less skin friction energy loss, **marvelous basic insight**, a **low pitch prop spinning an excess distance** to get home. The ***High Pitch Prop Wins Twice, Least Induced, Least Profile*** *too*.

 We'll learn a **~ 45° Blade Angle is Best**, Air Inflow, ϕ, a tad Less!

Now, of course, **you can only use the pitch you really need**. You just can't arbitrarily slap high pitch on a slow plane. The **game finally becomes using the genius level math that is available to pros, to precisely predict the air *inflow angles into each radius* of the prop, to actually get the ideal angle of attack, the ideal C_L** ***to get an ideal prop at its design point.*** To know how it works at its other test cases, Vmax, Climb at S.L. and Altitude, Takeoff, we do **an incisive study in Ch. 3-II**

Remember, a prop is *pitched for inflow only* half ΔV, ΔV/2, NOT ΔV .

Now, with all that insight, you can see that **you must finally Pitch your prop to accurately account for Speed, RPM, Inflow, (ΔV/2 + rotation) and desired angle of attack, alpha** and finally to account for the highly variable speed profile vs. radius one finds at the nose of a plane --- in the plane of the prop.

You Must leave the **Design Task** to a Pro, a Computer with **Theodorsen's Math.**

Now this brings up the point that **RPM is very important**, much more important than you probably thought, because, **with Speed, it is fundamental to Setting Pitch. Excess RPM, will limit the Max Efficiency Cap that your prop can attain.** In wanting Low RPM for High Pitch, High Advance Ratio, High Efficiency, a fixed pitch prop is in **direct conflict with the engine, which wants high RPM for High H.P. at low Weight. RPM *is second only to* Speed in setting max Efficiency!**

You've been wondering what Advance Ratio is? .

Now, we've brought up the subject of **Advance Ratio**. Look at the graph and explanation **on page 58-II**. Finally done with all up Math, it's the professional's **graph of max potential Efficiency for *any* Prop**. In its most simple *modified* form it is a graph of the Actual Advance Angle of the prop tip, **vs.** Max Potential Efficiency: **Poor efficiency at low Advance Ratio, Low Pitch, it swoops up as Advance, and the closely allied Pitch increase.** Have you figured out yet that **since a Prop must have extra Pitch to account for inflow and angle of attack, the *prop seems to Slip,* Advance a little less than Pitch, but each closely related, *the Slip + α° the difference!***

Pitch over Diameter, P/D Ratio, is the **even easier great insight** into **Max Potential Prop Efficiency**. The game is simply to **hope you need a P/D Greater than 1 --- because** (at a nominal Aspect Ratio of 14:1, based on the outer 90% of the Diameter), a **P/D of 1** gets you a **max efficiency Cap of ~88%**, only 85% at a Luscombe's 51/71, .718 -- **a very good 89% Cap on an RV 6, 79/70, 1.126. About 1.27 P/D, RV 8 gets ~ 90%**, but in that range the prop is **high pitched enough that you might want a variable pitch constant speed prop**, because if fixed pitch, the inboard blade angles are so steep they're **stalled at runup, slow, at takeoff**. But, most interestingly, **we'll learn that the major inboard blade angle *correction for Slowdown* gets an RV Prop fully unstalled at liftoff, 50MPH!**

You'll learn Excess Disk Loading, HP/ ft², hurts efficiency, *but not normally*.

Aspect Ratio Since the job of a Prop is to make Thrust - like a sailplane, **High Aspect Ratio minimizes Induced Drag**, the **higher the A. R., the more efficient a prop can be. A Big Diameter**, low span loading, **narrow blades**, **tapered tips** are the **real keys to efficiency**. The problem is that a **metal prop is just as vibration prone as a tuning fork**, and **too long and skinny is more likely to get into trouble with ever lower natural frequency, multiple modes of vibration, vulnerable to all the forcing frequencies that can come out of an engine, a total can of worms**, technically, that takes a lot of experience.

Aspect Ratio, Definition? See Below. **See Full Definitions after Ch. 1-II**

Indeed, the primary job of a metal prop designer is not to give you an ideal prop, but rather, **one that can be made from one of the long paid for forging dies --- that won't kill you**. We base the Aspect Ratio on 90%* of the Diameter, divided by the Average Chord, [or $(.9D)^2$ / Area], and **use a nominal max A.R. of 14:1, that of a Luscombe Prop, as a working start, here. It took 2 years to develop a set of safe props for the RV's ---**

***90% -- of course the prop hub makes no thrust.**

We don't try to cover all of the vibration subject here, because it takes a graduate course understanding of vibrations, and a **ton of special experience. Composite props can be less vulnerable**, more damping. ***But always be watchful, Caution!***

 ***With an 18% D, RV Spinner, later we analize 19% to 99%, ten 8% steps.**
A 14:1 A.R. over 90% R, equals a 12.6 A.R. over 81% R., .81/.9, a .9 ratio.

Constant Slip: The Core Logic of the Ideal, Minimum Induced Drag Prop

A Prop, like a wing, *would* like to have max thrust at its mid span, like an Elliptically Shaped and Loaded Prandtl Wing, with its Constant q, C_L, and Downwash, controlled loading dropping to zero at the tip for min induced drag --- BUT a prop has highly exaggerated q at the tip, low at the root, ***inside out***, --- and also acts as **two separate rotating wings, 180 degrees apart** - with **a root vortex too**. How about that surprise, deeper insight?

We've learned that ***we counteract the excess q based tip loading by more severely tapering the blades*** to **pull the max loading back away from the tips, toward mid span, the inner blade q loading weak, a weaker root vortex, *teardrop loading!***

Notice that ***High Pitch*** **Betz Props Taper Inboard Too**.

Thinking of the *Actuator Disk* it might be **nice if we really did have a *uniform axial velocity across the disk****, but we'll soon find the **axial and rotational inflow vary hugely**, but there is an ***amazing trick in the Betz Pitch that makes it act uniform!***

*We actually don't want uniform load, rather **Betz's Pure Helical Flow**.

The **Plot Thickens**, ***or so it seems***. The tips at small blade angles pull more straight forward, the steep root more sideways, actually pulling against engine torque, not pulling forward well, and at low q, weak! An angular trig mess to sort out? No! Look.

***As a Screw**, Drag free, **Betz gets a constant ratio of Thrust vs. Torque at all radii!**

Now, **here comes the Central Secret of Propeller Design!!!** Next, (and Ch 3-II), we show you how we set up and understand the air flow geometry into, (and finally out of), a prop blade, the **airplane forward velocity**, the **prop's rotational velocity** *at any radius*, *and* the **axial and rotational components of the airfoil inflow**, (and ultimately outflow). It turns out that **it is possible to set up *constant helical pitch of the air inflow*, a perfect screw surface, stretched helical outflow**, which *looks like* **constant velocity at all radii, a constant slip, vs. the constant airplane speed. The constant slip isn't, but acts like constant axial velocity!!!**
That Constant Slip minimizes radial flow, tip induced loss!!!

Here, in Two Pictures, is What we're Trying to Do!!!

Pure Helical Airflow *Into* a Propeller, Stretched Helical *Out*

Picture shows Outflow

Note: Pitch looks like half of what it is -- ***a dual screw!*** Follow it 360 degrees ---

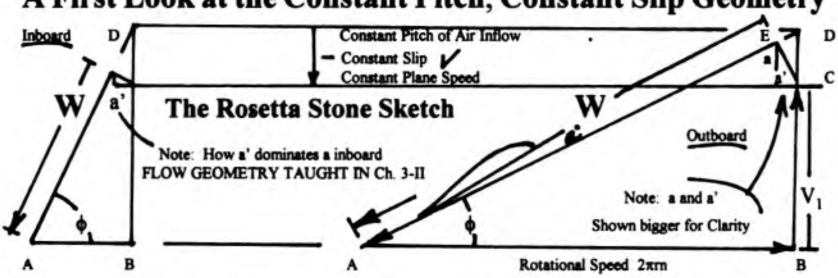
Each adding ~ half ΔV, ΔV/2

Betz's Rigid Vortex Sheet

***Outflow*, Two Perfect, Archimedes Screws, Blended, at the center, *one from each blade, 180° apart*, *two* perfect screw surfaces. Next, *Constant Pure Helical Pitch of the Air Inflow*, as in the sketch below, the Wind line W at all radii is pitched exactly the same to point D - But *with inflow, a and a'*, it *Actually Advances Less, only to point C* --- Giving the Constant Slip in the sketch below, at all radii. The prop** is at a **small angle of attack to the W wind, which sets Prop Pitch**. Then, the *equal outflow* downwash, backwash, **+ΔV/2 (not shown)**, not involved in prop pitch.

The Following is How we get Pure Helical Inflow.

A First Look at the Constant Pitch, Constant Slip Geometry



Notice that the **a and a' representing the air inflow and rotation,** (as a decimal ratio to plane speed V_1, and rotational speed, at each individual radius), are ***not*** constant at each radius, but are **highly variable, their resultant perpendicular to the wind line W.** ←

The tricky thing that happens here is that, quite non uniform, a and a' work together to raise the *Pitch* of the air inflow to be constant, to what we call the tippy top, (corny, but people get it,) **pt. D**, ***constant pitch, constant slip*** **vs. plane speed, pt. C, at every radius. It's the constant slip that creates the most uniform, least loss airflow!!!!!**

 Realize the 3D Potential Flow Math also **handles 3D Radial Flow ⊥ to the page!**

Albert Betz was a contemporary of **Ludwig Prandtl** (who conceived the Ideal Elliptically Loaded, Elliptically Shaped, Minimum Induced Loss Wing Theory). **Betz**, amazingly, conceived the **Ideal Minimum Induced Loss Prop Concept in 1919, post WWI, in Göttingen**.

- **It is First Done with Zero Profile Drag, drag added later.**
- **It Yields an Ideal Minimum Induced Loss Prop by**
- **Creating the exactly Ideal Thrust vs. Radius Loading by**
- **A Perfectly Shaped and Twisted Prop from Great Math** *also*
- **Setting up Perfect Helical Air Inflow, stretched outflow.**
- **Which is Constant Pitch Inflow, stretched outflow which**
- **You'll learn sets up a "Constant Apparent Slip Prop".**
- **All yielding a Constant dT/dQ, Thrust / Torque Ratio.**

REMEMBER, THIS IS ALL DONE PROFILE DRAG FREE -- AT FIRST.

The **Ideal Helical air Inflow, Stretched still Helical outflow**, a **perfect Screw Surface** downwash, **Backwash, the Ideal Thrust vs. Radius Loading**, the **Ideal Shape vs. Twist** can all be **seen, understood with pictures, No Math needed to Understand!!**

The Constant Slip produces the most uniform, least loss airflow.

The ***constant dT/dQ***, simply a **constant ratio of Thrust to Torque or HP, equal efficiency at every radius**, (drag free), becomes the **Magic Bullet that *makes the complex flow and forces* SIMPLE**

If you wish to go all the way through propellers, in Chapt. 3-II, we teach you how to set up the geometry, little sketches of the airflow geometry, that does all this. It's easy enough in picture form, but most interestingly, it does all these subtle, tricky things, that all work together to make all this work out. The **constant apparent slip**, above, happening with **constant plane speed, constant helical pitch of the wind inflow**, (which accounts for the prop also pulling in air, and needing an angle of attack) --- is **the nifty, tricky key, because it achieves constant slip** even though the axial inflow is not equal at all radii, but the **geometry makes it act like it is**. And this, it turns out, is ***the real hidden key to Betz theory***, because **it's the constant apparent slip that minimizes the radial flow, basic to minimizing the tip & root vortex, the induced loss, the little secret, obscure point that is central to everything!**

Betz logic demands highly tapered outboard blades to prevent excess tip loss, max chord set vs. J/π, Advance, with weak inboard thrust due to low q, at constant C_L twist, the blade shape and loading you can see on p. 147.

 This is the clearest statement of Betz Logic you'll ever find!!!

Despite wild 3D flow complexities, **the key fact is, we have an essentially exact math solution for Betz Logic, that allows a pro with a computer and a program to totally analyze an ideal prop in seconds after entering all the spec. details.**

Betz's technical insight was marvelous, but it finally **took 83 years** from **Rankine's** first Newton based water prop analysis in **1865 to finally solve the math. Goldstein** did a genius level basic solution of the **3D Potential Flow** Differential Equations in **1929**, which he thought was only valid for multi-blade, light loading. --- Then **Theodorsen** recognized that it was good for **heavy loading**, Betz's helix moving back through the Stream Tube *faster than the Stream Tube average*, all if you *simply considered* **a Higher Advance Ratio, and *a slightly reduced effective diameter far back***, usually ~ 99%, (low advance, maybe 97%). His 1948 book has all the design formulas, extra multi-blade and counter rotation solutions using very accurate analog Voltage Field simulation, **a rare genius level of work too!!**

You'll see Ribner and Foster have checked it all by Modern Computer.

The beauty of the method is that it uses a **simple chart of prop circulation** equivalent to **Thrust --- vs. Advance Ratio and Radius**. You put the chart in the **computer**, which **accurately interpolates the correct blade loading from the chart - designs and gives you full details, lightning fast!**

The key Kx Circulation Chart is held to be accurate to 1% or better.*

Now, that gets you an Ideal Prop design quicker, easier than you would ever believe. There is actually much more to know and understand, of course, and you need the computer program with Theodorsen's math to actually do that nifty trick, but we have the math and program available, conquered, actually in the most simple **"*Basic* Language"**, (and we expect to make it possible to buy a copy). **We'll stop the *core* explanation here, because our first objective is to help you quickly enough get the basic picture of prop logic so you can grasp how to fundamentally understand --- a 138 year mystery!**

To understand fully, the final sophisticated game is: You 1. Add Low Reynolds Number Drag, and its Early Stall. 2. Adapt the Ideal Twist and Chords, for the Nose Velocity Profile, "Slowdown". 3. Use a special Program to analyze Performance at different Speed, RPM, Altitude. 4. Learn how to pick a "Design Thrust" for a *poor* Interference Efficiency! The last steps are Andy Bauer's *final completing contributions* to the field.

*** In 1963 Tibery and Wrench at Divid Taylor Model Basin got Higher Kx Blade Loading for very High Pitch, High Advance Props above a Lambda, of .5**

 Now, we'll just refine and expand on what you've learned in 10 pages.

How Betz's Narrow Tip Chords and Load Distribution fixes the Problem of Excess Dynamic Pressure at Prop Tips.

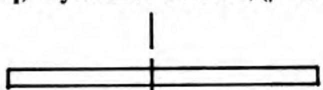
See in Pictures **<u>How to Load</u> an *<u>Ideal</u>* <u>Wing or Prop by Chords</u>!**

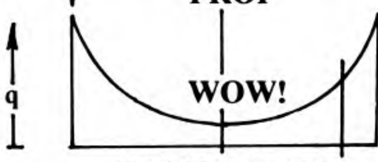
- **Lift or Thrust --- <u>MUST</u> --- <u>DOES</u>, fall to Zero at the Tips!**
- **Shaping Chords, *<u>thus</u>* Loading vs. Span, creates Prandtl's Minimum Induced Drag Loss Ideal <u>Wing</u>, chords representing area.**
- **Tapering Props <u>more severely</u> <u>does the same thing for a prop</u>, *<u>counteracts</u>* greatly excess Dynamic Pressure, q, at tips.**
- **Lift or T# = Dynamic Pressure, q, x (Area-Chord) x C_L**

√

WING **PROP**

1. q, Dynamic Pressure, (ρ $V^2/2$)

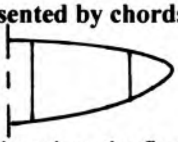




<u>Same</u> over <u>entire span</u> on <u>wing</u> <u>Greatly bigger</u> at <u>prop tips</u> x

---

2. Area, (represented by chords), as you integrate across entire span.



* max chord located by J/π. Kx, narrow at root too.

Exact (K_x) Shaping gives the final Ideal Minimum Induced Drag Loading

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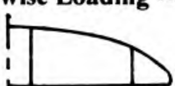
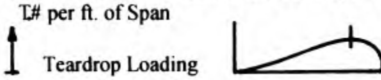
3. Radial, Spanwise Loading --- <u>The Result of: Chords</u> (Area) x q x C_L

T# per ft. of Span

Elliptical Loading



Teardrop Loading



Ideal Loading for a Wing vs. a Prop

<u>The wing is Ideally Loaded</u>, <u>high at the center</u>, far from tips and their Vortex Loss --- <u>shape sets the Loading to be Ideal</u>.

*Theodorsen's **K_x (Circulation) Factor** shapes **exact loading vs. Advance & Radius.**

<u>The Prop when Ideally Loaded</u> --- <u>can't be high at the root</u>, <u>at low q</u>, <u>is heavier outboard</u>, but *<u>not excessively</u>*, *<u>max load pulled back from tips</u>*, to 75 to 80% r. ideal, <u>actually constant dT/dQ, if drag free</u>.

The Max Chord on a Betz Prop is **set by J/π, Advance, Kx,** losely tied to ~ 45° β, **you'll see.** *

Now, let's give you the 10 Basic Answers to Propeller Logic:

1. The Basic Understandable Logic of an Efficient Prop is: **Go Fast** to have a **BIG $\dot{M}$**, Mass Flow Rate through the **Prop Disk**, thus need **only a SMALL ΔV**, a **Doubly Low $\Delta V/2V_1$**, for **Low Axial Induced Eff. Loss* - LOW enough RPM** for **HIGH PITCH**, **HIGH ADVANCE RATIO**, which naturally goes with that **Low Induced Drag**, and with a **Short Spiral Path** to the destination, for a **Low Drag Energy Loss *also***, ---- Then, with that foundation, use a **Betz Detail Design**, which produces the **Ideal Minimum Induced Drag Prop**, initially **done Drag Free**, (which requires **correct radial loading, Ideal *Shape*, vs. Twist**).

***Eta, η, the Greek h, is the symbol for Prop Efficiency.**

2. (***If not geared***)^, **High Speed**, **Low RPM** are the **two most Important Fundamentals** to achieve **High Propeller Efficiency**. They produce **High Mass Flow Rate, thus low ΔV, low $\Delta V/2V_1$, thus Low Induced Drag Loss --- High Pitch, thus** a short spiral path to the destination, **minimizing profile drag energy loss too.**

Gearing^ can *also* give Max η, Lo RPM, Hi Torque, Hi Pitch, Bigger Diameter.

3. It is the **Characteristic Tapered Narrow Tip Chord Shape** (and accompanying proper Twist) that **gives an Ideal Betz Minimum Induced Loss Prop**, the **Ideal Thrust vs. Radius Distribution**, best done with an **Ideal Constant Angle of Attack, Ideal C_L**, for any given case, because that produces **the ideal min. area, properly placed, the least profile drag *too*!!!** (Chord vs. α^o and C_L can be swapped, but that is less Ideal.) It is **the loading of the narrow tip chord Betz Prop** that fundamentally, **Ideally corrects the tendency of excess tip q to overload prop tips, create Extra Induced and Profile Drag!!!**

GET IT --- IDEAL PROP SHAPE vs. twist is the ***Key BASIC FIX!!!*** (p.147) ✓✓

4. Ideal Prop Twist (and Shape) is **automatically produced by Betz-Goldstein-Theodorsen Math, for Ideal Thrust vs. Radius Loading.** Since the fundamental objective of a Betz Prop **is to produce a Pure Helical Air Inflow to the Blade Airfoils**, and subsequently a stretched, still pure helical outflow, downwash, backwash, **and the best chord distribution is**

produced by an Ideal Constant Angle of Attack, Ideal C_L, the **ideal twist** is a **pure helix air inflow**, **plus a small constant angle of attack**, **perhaps only 1. 1°, for a .5 C_L, very close to pure helical blades, but just a tad different.** This is the easy way to understand ideal twist --- (but do understand that in advanced chapters we correct twist and chords for slowdown).

5. To understand **Precise Pitch***, realize that a prop must be very accurately **overpitched to account for the inflow of air, ~ half** the Δ**V plus a small angle of attack,** (the **second ΔV/2 thrown back by pressure is NOT involved in prop pitch).**

***Theodorsen *Does* account for Rotation and 3D Radial Flow too**, and Heavy Loading.

The whole concept of a **Betz Minimum Induced Loss propeller** is simply to accurately - **Shape - Twist - and Pitch** - the Blade to **precisely pull in a perfect helix, a perfect screw shape of air at all radii**, ***all at a constant inflow pitch***, **big enough pitch to account for the air pulled in, plus the necessary small angle of attack.** When the (*Constant*) **Plane Speed is subtracted from the excess pitch airflow, you get a CONSTANT SLIP**, ***each radius of the prop working equally hard***, for the **most uniform airflow, no radial unbalance causing extra radial flow, the perfect minimum induced loss design, drag free.**

The **constant dT/dQ** that also results, the **Thrust perfectly proportioned to the Torque at every radius, every radius equally productive, equally efficient** --- is not only a magnificently ideal outcome --- but it **beautifully cuts through all the flow, math, and conceptual complexities** of **propellers**, and teaches us **the bottom line is Dead Simple drag free when you do it right, do an ideal design. It's actually easier to do it right, ideally, than to flail around guessing!!!**

Constant dT/dQ Shows there is NO FUNDAMENTAL PENALTY TO PROP TWIST, (drag free).

Now, all this is true **only at the Design Point**, and **only on a zero profile drag basis**, but that's ***not*** **bad**. You can easily **run the computer with and without drag, easily see where it costs and how much**, *also* **evaluate what happens when you fly off design point. A computer can give marvelous insight.**

 ***Heavy Loading** also has **significantly more than average ΔV and Pitch at the prop.**

6. Ideal C_L .5 to .55 Propeller design, which can be extremely demanding, requires great precision to get computer answers that match actual results, (but with Theodorsen's math it works fine), but can also show the propeller can be quite forgiving, flexible, (in some ways). Nothing shows this better than the final C_L study we do on page 131-II through 134-II. It turns out that if you design with a .6 C_L an **RV 6 prop** only has to have a **69.1"** diameter, whereas a .3 C_L requires **83.7"**, and there is **surprisingly little difference in efficiency**. **C_L vs. D** can float around with only minimal effect, in some ways, ***(some ways not).***

Induced Drag, and Profile Drag simply swap, surprisingly evenly. ✓

When you leave the **Design Point, Altitude Cruise**, look at Altitude and Sea Level **Climb, Takeoff, Vmax** on the deck, **there is a winner, .5 C_L,** (72.68" D) with enough differences, that it's **worth picking the Ideal, the winner, but a .55 C_L is quite close, and lighter, -7.6%,** a *Diameter Cubed* volume function, diameter x chord x thickness. **(The 83.7", .3 C_L costs +53% more weight!!!)**

But now the catch ---

Understand, **here is where props are not at all flexible!** Design a **big prop** for a **low C_L**, miss your calculation, get a **high C_L**, overpitched, and your engine won't turn up enough, a real dog from a performance standpoint. Slow down and it's worse. A **small prop** with a **low C_L**, underpitched, will overrev, unacceptable, though slow it will correct the loading at high α^o, but you're slow, missed your design point. **The flexibility only works if you very accurately hit your design point C_L.**

You need math that gives *accurate, Pitch, Twist, Size answers*.

How accurate do you need to be? McCauley's shop tolerance is +/- **.1 degree**, yes one tenth degree, to ship a +/- 2 % consistent product. **Theodorsen can beat that accuracy**, but amateur computer programs just won't correctly calculate the ***real*** **flow**.

A better version of a much used misguided fix ---

On **fast, ground loving planes with a High Fixed Pitch Prop, Stalled α^o and C_L inboard at Takeoff**, *bad*, an **unwound broader outer prop, less α^o slow**, are tried to shorten the T.O. run, the **lower angle, broader chord tip, seemingly better slow. Better, to do that at the 3/4 radius, not create extra tip loss!**

Going for more tip thrust is a bad idea, creates Greater tip Loss, Loses the Thrust!.

7. __What Aspect Ratio do I Want__? The **job of a Wing** is to **make lift**, hold the plane up, the parallel **job of a Prop** is to make **__Thrust__**, **__both cause induced drag loss__**. You **__Reduce Induced Loss__ by going __Fast__, *__or__* having __High Aspect Ratio__!!! The Plane Controls Speed here! __High Aspect Ratio is GOOD__!** That's __how Sailplanes go slow__ with very low total drag, both __low Induced__, and low Profile, Slow *hurting* Induced, helping Profile. High A.R. is an absolute necessity for Slow Soaring.

Remember, it's really lower span loading that's key.

The **__higher the Aspect Ratio__** ***__the better it is for Prop Induced__!*** **EXCEPT __long skinny things vibrate at lower frequencies,__** potentially get the prop down to reacting to more engine frequencies, failing, tearing the engine out, maybe killing you. That's nothing you want to risk. ***__Don't tinker with props__***. **Prop engineers lose sleep, serious sweat getting you a safe prop!!!**

Definitions, A.R., Rn, etc listed after Chapter 1 Book II.

We use a favorable 14:1 Aspect Ratio, that of a Luscombe, which works OK for vibration on a Luscombe, but may not in another case --- simply to be consistent in our examples. It's **actually two 7:1 blades**, **__two separate blades 180 degrees apart, with root vortices__**, but props look like high A.R., so to not confuse people we do it that way - but __do our calcs correctly__.

Blades generate *__separate__* Archimedes Screws *__affecting each other__*.

8. __Airfoils__ The truth is that private plane props have the Speed of Jets, but the *__small chords__* of Model Planes, and thus regularly have Reynolds Numbers, *__Rn, down as low as__* 200,000, up to 1,000,000 +, bad news, *__significantly higher drag coefficients__*, also bad, *__early stall__*. __Flat bottom airfoils__, unsophisticated, do help a lot for **__easy accurate measurement__**, an important basic. The **__Low Drag Coefficients__** that the **airfoil guys go for are __just not real here__!!!** Of course, you can always do better tailoring a perfect airfoil, **but there is *__no super performance to be found here__*. __Thin airfoils, especially at the tips, maximize L/D, a key routine plus on metal props, composite props a little thicker tips__ - inboard always thicker.**

9. <u>Mach Limit</u> The easy way to understand the Speed of Sound **Drag Rise Limit** on Props is **<u>simply stay below .9 Mach tips</u>, compared to the <u>vector combination of the rotational and forward speed</u>.** Do you remember back in School how the square root of the sum of the squares of the sides - finds the hypotenuse of a right triangle? So a good calculator can find that vector speed - or by trig. Sure, I know most never did serious math since High School --- just understand.

The **Standard 59 F° day Speed of Sound is 1116.46 ft./sec.**, **761.243 MPH**, and decreases as the **square root of the Absolute Temperature**, (**-459.7 F°** --- thus **F° + 459.7**, ie. **59 F° = 518.7 R°**), thus **<u>968.1 ft./sec.</u>, 660 MPH at the <u>-69.7 F°, 36,089'</u> constant temp. Stratosphere.** **For Info**: 60 MPH = 88ft./sec., so **15/22, or 22/15 converts**. **R° is Rankine Absolute.**

So, **<u>.9 Mach is 1004.8 ft./sec.</u>, 685.12 MPH sea level std. day**. Just keep your prop tips below that and you're OK, a specific answer, easy enough, and it's faster, hotter in Summer. But, it's **slower, colder at altitude!!!** You get a speed-up going over an airfoil, but the reason **it stays simple, .9**, is that there is a **tip relief, overpressure escaping out the side door, the tip.**

Remember <u>1000 Ft./sec.</u>, the <u>easy to remember limit</u>!!!!!

On <u>most private planes</u>, <u>Mach is just not a problem</u>, but faster planes, a bigger diameter prop, high RPM can get you into it. A fast Harmon Rocket going 255 MPH with a 7', 84" prop does ***<u>not</u>*** go faster when you go from 2500 RPM to 2550.

Next, **Gus Raspet tried to open our eyes in the 50's ---**

10. <u>Thrust Required</u>, a basic question with an intriguing insight. If you knew an **accurate gliding drag** for your plane, or had an accurate drag calculation that, big surprise, happened to be correct, that may well ***<u>not</u>*** be the design thrust you need. **Thrust may *<u>not</u>* equal real Airframe Drag!!! When you turn on the fan it can cause an <u>extra drag, a significant interference inefficiency</u>**, and actual power required may be 10% or more, than drag **and prop eta**, η, would predict! That has been a very big hole in Aerodynamic knowledge, and ***<u>a central objective in our work</u>***. There is Scrubbing Drag, Pressure Drag, separation. A ***Luscombe flown Ideally has ~.893 interference efficiency, a ~75% prop*** η, ****<u>only 67% overall</u>.*** **More to come!**

 ***.67 inverted demands <u>150% more H.P. vs. Plane Drag</u>!!!**

Actually Designing a Prop --- **10 Specifics define the task!!!**

1. The **3 Basic items** of a **Prop Specification** are: **Speed**, **RPM**, and **Altitude Density rho**, ρ -- set by the application ***objectives***.

2. The **3 Chosen items** are: **Aspect Ratio**, **Coefficient of Lift** C_L, **Coefficient of Drag**, C_D, **Physics sets the** C_D – ***but poorly defined for low Rn.***

3. The **3 Design Steps**: **Sizing, (Diameter), Pitch, Twist vs. Shape**

Use H.P. (or find the correct Design Thrust is # 10 --- covered later).

a. SIZE the Prop Right to **deliver the required Thrust** at the **3 Spec Conditions,** the **3 Choices** above. It turns out that with the **highly variable Dynamic Pressure q, Diameter, Area, Shape *are interdependent*, can't be separated**, but ***simply setting*** a **desirable, high aspect ratio**, puts them **in strict proportion** so we just **scale them all up or down** to give the **H.P.** or (**T# Reqd.**)

b. PITCH You'll learn that one of **the important capabilities of Theodorsen's ~Exact Math is to set actual Advance and Pitch to *account for inflow and rotation with heavy loading* - where the *ΔV at the prop* - is faster than the stream tube average --- everything to better than .1° accuracy, < 1%.**

Geting the Precisely Correct Thrust vs. Radius Loading is the Game.

c. Shape vs. Twist Getting these **Precisely Correct** for the spec is the ***core objective of Betz-Goldstein- Theodorsen Math*** and happens automatically, *2 printout pages nails everything.*

One computer run solves everything, at every radius.

So, you can see that **the bottom line** is that **using the Aspect Ratio you set**, the **math and the computer simply scales the prop up, or down to meet all the spec conditions, the H.P.**, or **T # reqd, 2 or 3 pages of data covering everything** you would ever want to know about the prop **at every radial division set.**

We now use 10, 8% Divisions from 19%, outside the 18% Spinner, to 99%.

Andy has actually set up his program to be more in his control. He **guesses at Theodorsen's $\overline{w}$ factor, essentially the full ΔV of the pure helical downwash sheet, maybe 2, 3, 8 times *bigger than the stream tube average ΔV*** (!), and iterates **D"** vs. **A.R.**, **T#**, **H.P.** to just what he wants, **a modern computerized miracle.**

 If you don't know the Thrust Required -- Go for Tmax, at design V, HP available.

Gearing for Ideal Efficiency --- Disk Loading H.P./ ft^2

We've just learned that the **Plane *spec specifics*, sets the prop design**, the **math** simply carries out those given Specifications for an **Ideal minimum loss design**. We also saw that once you've **selected Aspect Ratio, and all** the other spec specifics, the **math simply scales the prop diameter, the blade area and shape up or down to fit the demands of the case**, pretty **simple, logical** really, **something you can easily understand**.

Designing a 4 Engine Plane? Simply divide the Prop Thrust by 4!!!

But the case may, or may not have an **ideal efficiency, ~ 90%, maybe 91%, depending on Aspect Ratio possible, pitch, etc**. The **Advance Ratio Graph on p.58-II shows us that**. If you can just get an **optimum Advance Ratio**, closely tied to the **actual advance angle of the prop tip**, thus the **pitch**, or P/D ratio, which always has a little extra pitch to account for inflow and angle of attack, **you can get such great prop efficiency!!!**

Gearing down RPM increases Pitch, Torque, and Diameter. ✓

So theoretically, ***actually***, if you could **gear the RPM vs. Speed** for the **Steep Advance and Pitch angles**, **(*~ 45° Blades best)**, you can *(always)* get those amazingly good propeller efficiencies. Of course we've already shown you that there is an interference efficiency loss that can really hurt the overall results in some cases, and gearing is often not worth the weight, and complexity. Man powered planes, the Wright Flyer, Ultralights, **all slow**, are **all geared**, chained, belted, and do great - the maybe 5000 RPM ultralights, undergeared to not have excessive diameters, poorer.

*We'll soon analyze how we get ~ 45° optimum blades from ϕ - drag angle/2.

Disk Loading: The Luscombe, 85 H.P./ 27.5 ft^2, **3.09 H.P./ ft^2** max, the RV 6, 160 H.P./ ~ 27.5, ~ **5.8 H.P./ ft^2** max with ~ 6 ft. props, man powered, ~.25 H.P./ 100 ft^2, **.0025 H.P./ ft^2** all work out with prop efficiencies right in line vs. Advance Ratio, Pitch. **Reno Racers, NASA Advanced, very high H.P., multi-blade props, 30 to 37.5 H.P./ ft^2 are hurt, below 80%, what's going on?** Simple, the ***Diameter is Artificially Restricted by Mach***. **If you can let math and a ~.5 C_L set D - Advance *&AR* sets efficiency!** ✓

Jack Norris's Incisive, Bottom Line Understanding of Props

Propeller Logic starts with a **terribly exaggerated "q"**, **Dynamic Pressure at the Tips**, trying to **grossly overload the Thrust and Drag at the Tips, where *Thrust must fall to Zero*, Paying for extra Profile and Induced Drag Created -- Losing the Thrust.**

Not Counteracting that Flaw is The Basic Mistake in Propeller Design!!!!

Since the formula for *Lift*, **Thrust** *and ~Drag* is **T# = q (Area) C_L** we can **counteract the excess q** by **simply tapering the Tips,** (cutting the Chords which represent the area per inch of Span) ***thereby pulling back excess loading from the tips*, cutting profile drag at a max radius - and stopping the generation of excess Induced loss!**

In fact, you can *taper them back ideally*, for *minimum induced drag* by simply using Betz-Goldstein-Theodorsen Math which will **exactly Shape, Twist and Pitch the prop** for any *chosen* **Speed, H.P., RPM, Thrust, Aspect Ratio, C_L, Altitude** ρ, **density**, (on a drag free basis). By choosing and designing for a **constant, optimum C_L** (and adding proper Low Reynolds Number Drag C_D's) **you can also achieve min. Profile Drag, (min. Area precisely placed).**

Analysis of the case shows that there is ***no basic inherent loss because of prop twist*, a constant dT/dQ** results, **a perfectly constant ratio of Thrust vs.** ***required* Torque** at every radius, *if drag free*. Also **Constant Pitch, perfectly Helical Inflow,** ***stretched* helical outflow, Constant Slip vs. Constant Plane Speed, which minimizes radial flow, tip vortex induced loss, *no extra radial imbalance* to the inflow and rotation of the air, though highly variable radially, work together to produce the Constant Pitch, Constant Slip, acting like the axial inflow were constant --- constant dT/dQ, *if* drag free.**

Newton - Actuator Disk Logic - teaches **Fast Planes produce Big $\dot{M}$, min ΔV, min $\Delta V/2$** x T# = ft.#/sec., the axial induced drag energy loss/sec **=Min Power loss**, **min $\Delta V/2V_1$ axial efficiency loss**, also tends to produce **High Pitch, High Advance Ratio,** thus with sufficiently **Low RPM, High Pitch, *a min steep helix path, min profile drag loss also!***

Adding Andy Bauer's: 1. Low Reynolds Number Drag, Early Stall. 2. Retwist, rechord, for nose velocity profile, (slowdown). 3. Analysis Off Design Point. 4. Design Thrust accounting for Prop-Body Interference Loss, (Gus Raspet). --- Finishes the Job that took 138 years to complete, 1865 to 2003!!!

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There Are Practical Confirmations that Betz is Correct

The **Curtis-Reed,** (and the Fairey-Reed props from the UK), had blade shape pretty much right in the 30's, with highly tapered blades, and the smart guys remember those were the best props of that time. Reed, actually a smart Dentist, got it reasonably correct early. In WWII the big engines forced the pros to wide tips to absorb gross power and stay below Mach, but less efficiently. Some believe *unwound wide tips* are better for takeoff, fast, high pitch props, excess α^o slow. The ***falacy is you lose the tip thrust you try to make***, the proper insight on loading vs. radius, shape lost.

And every time you Compromise with a Wide Tip it Will Cost you all day.

But in the 70's **Paul MacCready**, an indoor model builder in the 40's, conquered man powered flight by **creatively making an outdoor-indoor Gossamer Condor, substituting Mylar Film for a modeler's bathtub Microfilm! He won the long unfulfilled *Kramer Prize* for *Man Powered Flight.* But then Bryan Allen just couldn't pedal an incorrect broad tip prop on the Gossamer Albatross for 45 minutes to win Kramer's next challenge of crossing the English Channel by Muscle.**

Paul did have a Geared, Big Diameter, High Pitch Prop, smart like the Wrights.

To the rescue came Eugene Larrabee of MIT and his Star Student, Mark Drela with their own code for narrow tip ~ correct props, that had everything except Theodorsen's perfection, and MacCready made history again! Simply, Bryan Allen *could* pedal a ~ properly configured narrow tip Prop, the kind of Practical Proof that everyone sees is real!!

The final proof is B-G-T Props are *Quiet*, the Excess tip Loss Gone!!!

Confirmation by Ribner and Foster, University of Toronto.

Ribner and Foster, using modern computers in the 90's, .did a great service to the engineering profession and all people interested in propellers by **checking and confirming that the key Goldstein-Theodorsen work was correct to nominally 1%, modern confirmation**, a little more error on some of Theodorsen's pre computer, less important peripheral numbers. No one need think the work was old, unreliable, ***it was genius work.***

Everyone missed that in 1963 Tibery and Wrench at Divid Taylor Model Basin got Higher Kx Blade Loading for very High Pitch, High Advance Props above a Lambda .5.

 This completes the basic 20 page core — but there's more, then Book II.

An Overview and a Look Ahead. I started looking for that explanation in the mid 40's, a model designer competing and winning at the National Championship level, (46 and 48 in the Senior Age Division) where I needed real, factual answers to optimize my props. Working as an Aero Industry pro, I looked and watched for a half century, a professional lifetime. The explanation never happened. **It remained the one central unexplained major subject in Aeronautical Engineering**, which had refocused on Jets, **left this job of bringing together and explaining undone!**

Yes, there had been decades of testing, a lot of reports written, **unfortunately most before Theodorsen got it right**. There was marvelous, genius level work done, that made our work possible. **Rankine, Froud, Betz, Prandtl, Goldstein, Glauert, Theodorsen are the 7 Historic Giants who made all our work possible**, each standing on their predecessor's shoulders, the ***building block milestones*** that created **the Ideal Propeller in 1948, 83 years after Rankine's 1865 first *water* prop analysis.**

What remained undone was reading and truly understanding, *using* **Betz, Goldstein - Theodorsen's marvelous book,** ***adding*** **Low Rn Drag and Stall,** ***figuring out what it all really meant*****, then accurately adapting the theoretical ideal prop to a *real* variable velocity nose, what happens "off Design Point",** *realize* **Gus Raspet** showed us **propulsion efficiency** could be **as bad as 58%** **on a Bellanca Cruisair, 172% more power required than the plane's drag said. WOW! Raspet deserves to be Historic Person # 8. Doctor Andy Bauer, my partner, brought it all together, finished the engineering job, deserves to be # 9, a decade long final red ribbon on the propeller!!!**

I invented ZTGT, Zero Thrust Glide Testing to get Real Drag, Real η_P.

My job in the collaboration has been how the entire order, logic could be understood, made logical, explained. It's now been 138 years since Rankine's 1865, maybe the longest challenge in Engineering. **If you grasped those 20 pages you are well launched, the comprehensive explanation is Book 2.**

A Look Ahead to Book II, Propellers

In hindsight, you'll see that this **Primer on Prop Logic** can get you **a giant step toward a complete understanding**. Just give it your best shot, **maybe reread it, think about it, soak it up**.

I've found that no matter who you are or how smart you are, it **takes at least a little time to soak it all up, truly get it**, be comfortable with it. None of us, including Engineers, usually come across a subject where so many things happen, all interdependent. Figuring out just how to get this basic meat across, frankly, is almost as tough as figuring it all out in the first place. **The challenge is to not drown the new guy, help him!**

Superemphasis, always tieing together, finally helps Novices see it all.

In Book II, Propellers, we simply, flesh it out, for those who want to go all the way, to dive in, learn it in more detail, **slowly enough that a novice has a shot** at what engineers never quite got their head around well enough to write it out in understandable English ------ but also with enough disciplined detail, that your final grasp ends up genuinely correct, so Engineers, everyone, can get the final correct grasp.

---- I send you to the final conclusions early, which helps a lot too ----

Looking to Book II, *a few examples*, **$\dot{m}$ to $\dot{M}$** to start. In pulling in and throwing back air, **the prop pulls air in from a slightly bigger diameter**, and that, naturally enough, ***raises*** **the natural streamtube mass flow rate $\dot{m}$**, (the plane Speed -- times the prop disk area -- times the density ρ) --- to **the final correct $\dot{M}$**.

Happily, that Δ**V/2V$_1$** factor, we learned and used for efficiency loss, is also the correct increase here. **$\dot{M} = \dot{m}\,(1+ \Delta V/2V_1)$. We teach you the $\dot{M}$ does NOT increase behind the prop as the second ΔV/2 is added** - understandable enough when you think about it, because the prop can't create air, only shove along what it pulled in. We found that when we laid that extra complexity on Novices some drowned, so we left it to Book II.

But, here it is if you can grasp it now.

There are many finer points like that -- you learn in Book II.

The concept of ΔV, and $\Delta V/2V_1$, is really useful, helpful, because it helps you understand the basic logic of the **Actuator Disk - Stream Tube**. You'll learn that it most directly ties into Glauert's **a factor**, ***the axial inflow***, **(a decimal ratio of Plane Speed, or V_1)**, 2a equal to the full, ΔV, ***(but different at every radius)*** ------- his **a'** and **2a'** likewise handling the rotation. You saw that first on the ***airflow sketch*** on ***p. 124***. Now in the real world and Theodorsen's math, the ***"Vortex Sheet" speeds up much more than the Stream Tube Average ΔV***, maybe **2x, 3x, 8x** so you'll ultimately learn Theodorsen uses his $\bar{\bar{w}}$ **factor**, bigger than 2a.* His **kappa** factor is used to knock down to the average effect, but the **prop correctly pitched for the bigger $\bar{\bar{w}}$ factor, actually $\bar{\bar{w}}/2$!**

You can see that it **would be a big mistake to drown everyone with all the detail at first, better to help them get the basic concept first,** then become aware of the precise **details** in a **longer, slower more comprehensive Book II.**

I expect many professionals to hate the Super Emphasis, the constant repeating, summing up that I do, but I've found that's the only way the Novices can get it, and frankly I find the pros need more help than they realize. **Everyone needs time and all the help they can get**, because it takes everyone, amateur and pro alike, time to soak it all up, **absolutely needing the summing up, because no one, not even the pros can sort this swamp out while they're learning**. I think, I hope you'll end up appreciating the Super Emphasis, and always summing up, because **all you have to do is read through it, and I keep leading you to the correct conclusions --- that took a long time to sort out, check out.** ***No vanity here, it took long hard work!***

If you can get a good first grasp in an hour or so read, a professional grasp of what's never been explained, understood ------ in a day or so ---- we've both won Big!

We'll look at Engines, then Leaning, then those who wish can nail props in Book II, ***all laid out on a platter for you.*** **Now a little Extra.**

*** With Theodorsen's Heavy Loading his $\bar{\bar{w}}$ is bigger than Glauert's 2a, which is NOT normally in a BGT Analysis. We synthetically calculate one for insight, less than $\bar{\bar{w}}$.**

Prop Vibrations

Prop Vibrations are such **a complete snakepit**, that frankly, I hesitate to get into it very much, since sorting out props is enough complexity and potential success for one book, but there are several insights that are worth grasping, and ***one great big, pretty simple fundamental that I want you to grasp clearly.***

We probably all think that the marvelous Emmmuuugghhhh **Doppler Frequency Drop Sound of a V 12 Merlin Engine passing overhead and away** is the **most beautifully smooth sound in flight**, and it is, at least it's my vote. But to fully appreciate the fatigue failure challenge the prop engineer faces, look at the vibration output on the facing page of that Merlin, a **hidden nightmare for the prop Vibrations Engineer**, all that rotating, reciprocating, twisting, flexing machinery, a **myriad of forcing frequencies, and notice Torque Vibration changes as Blade Angle**, β^o, **thus Torque Load changes, a *tech horror.***

It's chance matching of forcing and response freq.'s that's trouble.

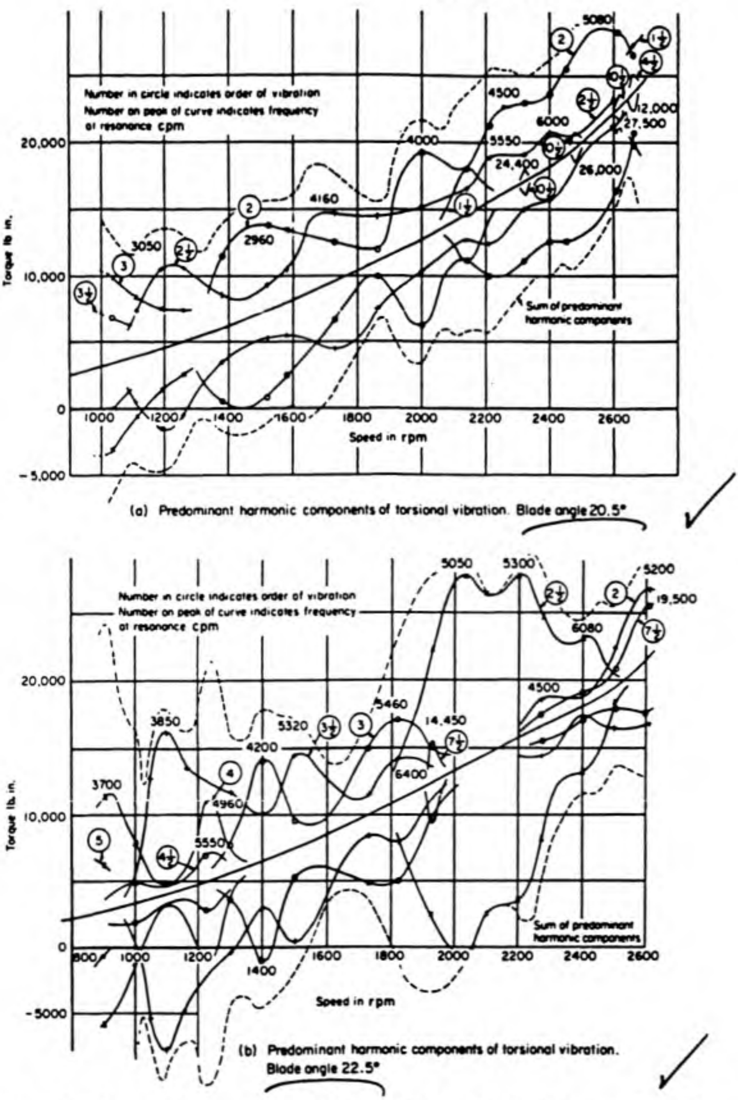
Now, realize **the prop has more than the one main natural frequency (the bending vibration, generally perpendicular to the blade face),** that it will respond to. It can twist, lag-lead in torque, bend with nodes, the center of the prop moving forward, the tips and hub moving back, for example, respond to **harmonics**, multiples of the forcing frequency or natural frequencies, getting hit in tune every other cycle, or 1 out of 3, for example. Should I use the word **nightmare again? Sharp Guys like Brian Meyer at Hartzell, with huge experience and feel for the real possibilities hiding in that swamp of chance matches deserve our profound respect and thanks for a safe prop. Could you cope? Marvelously they develop a feel for where trouble can be!**

Don't start reshaping, messing with your prop. You could get dead ---

Now here's the **one simple key insight** I want you to **grasp clearly.** If you go for a great, but **too high Aspect Ratio, a long skinny prop, you lower the natural frequencies of the prop, *maybe* down into matching more engine frequencies**! ***Caution!!***

Torsional Vibration of Rolls Royce V-12 Merlin Engine

ENGINE VIBRATION



(a) Predominant harmonic components of torsional vibration. Blade angle 20.5°

(b) Predominant harmonic components of torsional vibration. Blade angle 22.5°

Fig. 8–29. Torque at drive end of crankshaft of Rolls-Royce *Merlin* II aircraft engine with variable-pitch propeller, 1-to-2 reduction gear (Carter and Forshaw, 8.492).

Data compliments of Will W. Mathews, Director of Manufacturing Engineering.
Engine and Foundry Division, Navistar International Transportation Corporation.

The Ideal 45 Degree Blade Angle, and **where it's located**

When I was a late teenager competing and winning Nationally, I had very good plane designs, but was really frustrated trying to find correct prop design specifics. What was the **really *correct* *shape*, *twist*, *pitch*? It seemed that those high angle prop root radii, pulling sideways against engine torque, more than forward, could not possibly be good.** ***But***, we've learned here, that **drag free, a Betz prop can have a constant Thrust vs. Torque Ratio, every radius equally efficient, productive,** ***(if first considered drag free)*****.** We'll look more at high inboard blade angles shortly, see that they're perfectly OK, **working as a screw** on very high pitch props. We'll also see a **Blade Angle of ~ 45° is optimum**, thus it's insightful to see ***where*** the **45° blade angles are vs. Advance.**

Also — Where is the Max Chord vs. 45°?

The study below looked at **J/π**, (Lambda's, λ's), of **.2 to .88, (of low to very high pitch props)**. **(J/π, λ Lambda, is the advance ratio of Prop Tips.)** The chart below and the chart and Shape Plot vs. load distribution on the next page give great insights into the characteristics of ideal propellers and are worthy of your study.

	Reasonable Advance		**Extremely High Advance**				
J/π, λ	**.2**	**.3**	**.4**	**.5**	**.6**	**.7**	**.8**
Overall η	.8607	.8940	.9068	.9125	**.9149**	.9144	.9112
45° β,% r	23.25%	33.60%	44.15%	54.82%	**65.74%**	76.70%	87.82
Local η	.8781	.9018	.9104	.9141	**.9159**	.9158	.9135
Max Chord.	25%r	38%r	43%r	47%r	**49%** r	53%r	56%r

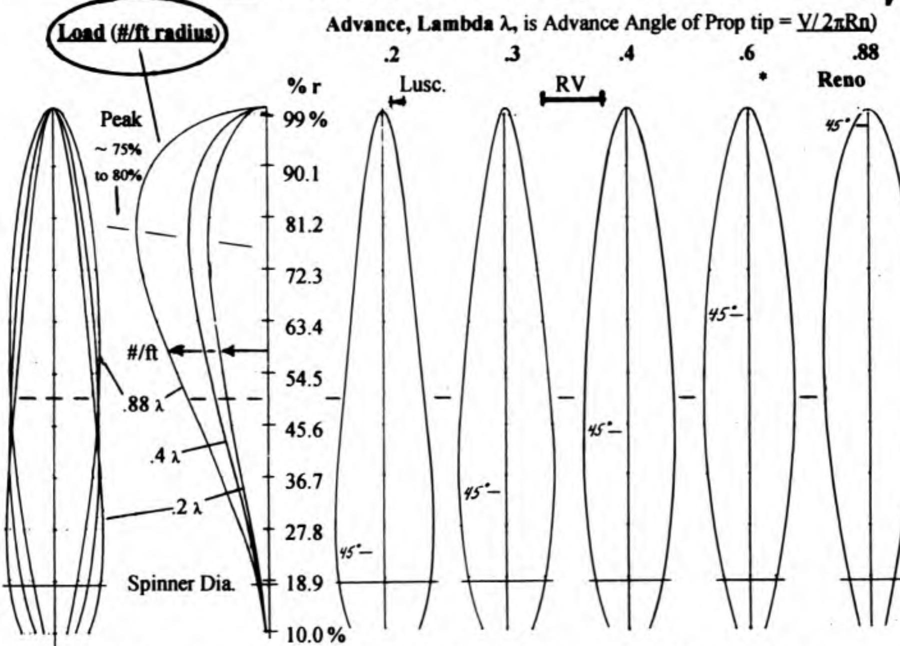
Amazingly, a Reno Racer can have a .88 λ, almost a 45 degree Tip!!!

So we see the most efficient **45°** blade can fall way inboard to way outboard - but is **most efficient at the ~2/3^+ Radius at .63 λ.** Now if the ~**45°** Blade Angle is most efficient, it might be that the splendid Math might put the **Max Chord** there. Well, if you look close at the data above, the interesting insight is that's trying to happen, at the lower J/π, λ's where fixed pitch props operate --- but are pulled outward a little at the low J/π, λ's away from the inner root vortex **--- much stronger inward at high J/π, λ's away from the stronger tip vortex!!! Now, isn't that *smart*! It fits right into the logic, not overloading tips!!**

 Interestingly, the max chord is at ~ 50% r. on the max η ~ .63 λ Prop!!!

The Change in Blade Shape and Twist — Low Pitch vs. Steep Pitch.

We know it's the **Slow planes, Low Pitch, <u>Low Advance</u>,** that have **the *huge magnification of Dynamic Pressure, q,* <u>tip vs. root</u>,** thus **need the <u>most highly tapered blades</u>**. ***<u>Conversely</u>***, the **<u>Steep Advance</u> props will be <u>less severely tapered</u>**. Below, see the blade outlines for this blade study, λ from **.2**, low, to a steep **.88λ**, (a Reno Racer class prop, though this study of all 6' props for comparative consistency is a miniature for Reno). Note how the **<u>steep λ props</u> *<u>taper in greatly inboard</u>***. (**<u>Slowdown</u> *lowers blade angles, especially inboard, widens blades*.**) ✓



– –RV 8 Cowl Width -- Locations of 45° β °. Ideal ~.63 λ * ~364 MPH.

To keep all props on the same apples vs. apples comparison, starting with a 6 foot prop we end up with low thrusts and H.P.'s for the fast planes, like a miniature, slick Reno Racer finally, but this shows shapes and twists well, the intention here, so just imagine and understand.

***<u>Prop Blade Study basis</u>*: 6'Dia, α° 1.1°, .5 C_L, AR 15, <u>2700 RPM</u>, 8000', Area 1.944 ft²**

Ref. Data pages 99.56 -1 to 99.56 - 8.1 BLADE ANGLES ARE *<u>BEFORE</u>* SLOWDOWN CORRECTION ✓

λ	Vmph	$HP_{8000'}$	Thrust#	Eff. η	β°, 18.9% rad.	β°, 99% rad.	ΔTwist°
.2	115.6	56.5	155.3	.8607	50.365°	13.600°	36.765°
.3	173.5	94.4	179.7	.8940	60.583	19.046	41.536
.4	231.3	140.5	203.6	.9068	67.053	24.263	**<u>42.790</u>** ✓
.5	289.2	195.9	228.5	.9125	71.382	29.142	42.240
.6	347.0	260.5	253.8	**<u>.9149</u>** ✓	74.440	33.634	40.806
.7	404.8	334.5	279.1	.9144	76.715	37.760	38.955
.8	462.7	418.4	304.3	.9112	78.482	41.556	36.926
.88	508.9	494.2	324.6	.9058	**<u>79.653</u>** ✓	**<u>44.411</u>** ✓	35.242

Multiple Blades (If You'd Like a Little More Insight)

Generally, it's Most Efficient to use 2 blades, a Max Diameter Stream Tube -- **use *multiple blade* props if you have *BIG Power* to absorb,** particularly if you're **diameter limited, up against the .9 Mach limit. It will cost you** a little to a lot in efficiency vs. what it might have been with 2 Blades.

Staying with equal Aspect Ratio, 3 Blades gets a smaller Diameter.

People like **3 Bladed Props**, often feel they're **smoother**, but it **costs them a ~1/2% efficiency penalty, *smaller Diameter!!***

3 Blades, it can come out narrower, High AR, balance Diameter Loss!!! ✓✓

The **WWII big recips**, had to go to **3, 4, 5, 6 bladed props to absorb the gross power of bigger and bigger engines, as do Turboprops,** right up against **Diameter and the .9 Mach limit. As you go faster vs. tip speed, less q ratio**, you can use **less severely tapered, broader tips and still have ideal shaping.**

But Physics works and you still DO NOT go to Excessively Broad Tips.

Unfortunately our guys seem to have lost their way, going for square, or nearly square, broad tips, not really an OK move, pumping big power into Excess Tip Vortices. **A High Activity Factor**, good Power Absorption with broad tips, must have mesmerized our people into Thinking Broad is OK. If you look at a **Mark 22 Spitfire**, you see a **5 bladed, (probably close to Ideal Shaped) Rotol** prop used to absorb the 2375 H.P. of the Rolls Royce Griffon Engine. **The Brits were maybe a bit smarter than our guys there, *credit to where credit is due.***

BUT, *if Smart*, A *Thin*, *Unwound*, lower C_L broader tip can work better near Mach! ✓✓

An extremely high pitch, geared down, low RPM, Reno Racer, **37.5 foot advance** per rev, can have **a Theodorsen's $\overline{w}$ factor, a local ΔV, ~ 8 times bigger than the average ΔV of the stream tube -- hardly utilizing the stream tube! More blades helps there** logically - but you can have **a Very High Disk Loading vs. Power**, in **a limited Diameter, which costs efficiency, (in a way the opposite of a Big $\dot{M}$ for a small ΔV),** though the **$\dot{M}$** is huge. The many bladed swept Turbo Props NASA tried to replace Fan Jets were **79%** efficient at best, better than the **Fan Jets, 65% or less, with duct loss.***

 * Later BIG Fans are getting better.

A Pro's More Subtle, Incisive, X-Ray Grasp

When you first dig into Prop Analysis History, Betz's Ideal Minimum Induced Drag Prop Theory, as we did, you first realize that the game is to simply produce **a constant pitch, pure helical inflow, stretched pure helical outflow, constant 2 π r tan φ** mathematically, ***which is constant air inflow pitch.*** It takes a lot of time for all the full significance of all the other characteristics that are created to become completely clear to *us mortals*, and I expect it will take time for it all to become completely clear to you. ***I can help you by superemphasizing insights,*** **hammering home the many key basics!**

Only in time do you **fully realize** the **subtlety** that the **constant slip** that results, despite highly variable axial and rotational inflow, **acts like constant inflow at all radii, balances the flow across the full radius, *minimizes* the radial flow, *minimizing* the tip vortex, thus minimizing induced drag - right at the Heart of Betz Minimum Induced Drag Logic!**

Theodorsen Minimizes Root Vortex too – Tapered Inboard Blades!!!

Only in time do you pick up and **realize the full significance that a constant dT/dQ results,** and that implies that there is **no fundamental penalty to a twisted prop,** that on a drag free basis it means that **every radius is equally productive, equally efficient, drag free,** that it **slices like a razor** through the **twisted trigonometry and complex 3D heavily loaded flow, genius level math,** to **a magnificently dead simple ideal outcome** --- that you **can run the computer with and without the low Reynolds Number drag and precisely see the drag effect at every station & overall.**

You only fully understand, when you grasp props from *all* vantage points!!!

Only in time does one fully realize the **Really Simple Point** that the **Dumb Prop has a Bad Basic Problem, *trying to get max thrust at the tip*** --- ***where it Must Fall to Zero Thrust*** --- **making excess profile drag at max lever arm, a stronger tip vortex, *thus* unnecessary excess induced drag, losing the paid for thrust** - that we **play right into that fundamental flaw by making wide tip props, UGH! - But Great Fundamental core Insight!**

We purposely start you out with the Norris - Bauer Law, emphasizing SHAPE!!!

So we purposely start out showing you that narrow outboard chords can physically fix that Dumb basic problem of overloaded tips, that enough taper can actually ideally solve it all in such a magnificently logical way!

It's funny to watch some busy Critics – Just not get it!!!

I expect plenty of grammarians, and technical purists will be all offended, and in blind wrath criticize that I've broken the usual style rules, used *super emphasis* - **never realize** that this has always been the subject that was so technically complex that it was never comprehensively, incisively, understandably explained, but that there is magnificent, simple enough order and logic, ***if one can only figure out how it can be explained - understood. My core objective has been to figure out how such a complex subject can be explained and understood by everyone who wants to understand props!***

Reorienting Your Thinking --- to a 45° Helix Blade Angle, β.

Thinking of your propeller as an Actuator Disk, whose job is to produce Thrust, a **Disk, perpendicular to the crankshaft Pulling Straight Forward - Limits Your Thinking *vs. the final truth*!**

A little bit of math will show you that **nominally a ~45° Blade Angle, Beta, β, is most efficient, screwing you ahead!!** A little classic math derivation shows *the* **optimum airflow angle phi, ϕ, is 45° - γ/2**, 45° minus half the drag angle, gamma, that is **half the C_D / C_L**. If the **L/D** is **nominally 50:1**, $.5C_L/.01C_D$, the inverse is .02, a **2 % D/L**, an interesting insight. Trig will show us that's a ~ **1.1457°** drag angle, half that ~**.573°**, so the **optimum air inflow angle ϕ is ~ 44.43°**. But, you see that if we want a .5 C_L, that needs a ~ 1.1° angle of attack, **45.53°**, so the bottom line is: forget the detail, the complexities, ***about* a 45° β Blade Angle is optimum** - **Easy**!

Now that you've been through the build up of the basic core Logic of Propellers --- It's now proper to **fundamentally reorient your thinking** and ***realize the proper bottom line*** way to think about an ***optimum*** **propeller is as a 45° Helical Screw** (*average*). **Most Efficiently Screwing to the Destination!** ***Voila!***

Let's Understand Flight Physically - Get a Proper Feel for it.

It's this simple. The **Atmosphere** is far more **massive** than we all realized, and what we learn here is **the efficiency game** is to **use its Mass, disturb it as little as possible, the least ΔV**.

Think of a **long wing 22 Meter Sailplane skimming along,** ***only*** a **whisper of downwash**, with a **60:1 glide ratio**, able to **land** ***anywhere***, **out past the horizon**, ***120 miles*** from 10,500', 2 miles! **Wow!** A **747 - 400**, 940,000# GW, **nearly a million pounds**, also able to skim along in /on the atmosphere, **at any given C_L** only the **same angles of downwash as a 1400# *put put*, *if equal AR*, Wow!**

The **Job of a Prop** is to **Screw through its Stream Tube**, at a **High Pitch Angle, use the considerable Mass of the Stream Tube, *but* disturb it as little as possible -- only a small $\Delta V/2V_1$.**

 Betz teaches us to go for a Pure Helical Downwash Sheet, *not* a constant angle!!!

Physical Examples Really Help cut through the Complexity.

An **RV at 200 MPH** x 22/15, **293.33 ft/ sec**, at **2700 RPM** /60, **45 RPS** divides out to **6.5 feet per revolution Real Actual Advance**, thus **needs more than a 78 inch pitch or it can't physically do it**. **There's a really interesting insight there:** We know now that a prop must be **overpitched to allow for Slip**, the necessary **inflow**, plus a small angle of attack, yet a typical wood, fixed pitch prop is apt to be **70"D x 79"P --- no allowance for slip, what's going on???** The actual velocity profile at the cowl nose, a highly variable **slowdown**, that requires **depitching** the prop to be correct, **almost exactly equals the Slip**, **(in this case)!!!**

The Dreadnaught, or Furias, British Sea Furys, **Reno Racers** are the ultimate example for **teaching us about Props Screwing Ahead**. Pratt & Whitney 4360's with a Boeing C - 97 **3/8 ratio gearbox**, driving a ~13'5" Douglas Skyraider prop, 1125 RPM at 3000 RPM engine Speed, **18.75 Rev's /second**, at **480 MPH** x 22 /15, **704 ft/sec** divides out to **37.5 feet / rev Advance, WOW!!!** ----- **That's real easy to do on a calculator.** ✓

Do the numbers yourself, for the RV and the Furias and you'll **really get it, believe it, never forget it, really grasp props correctly. Props really are an Airscrew - and that's really the correct way to understand them.** ✓

Let me show you that there is a **big side benefit to correctly understanding props as a Steep Airscrew**. As a kid, looking for the good prop explanation and finding absolutely nothing incisive - I was really bugged that I could see that **steep inboard blade *angles hardly pulled forward***, ridiculously pulled against engine torque -- very undesirable *it seemed, hurting, hardly helping*. **Wrong!** ✓

Visualize that prop blade screwing up a perfect steel screw.

Well, the prop doesn't have a steel screw to push against, its **Airfoils have to fly, (lift) it up that imaginary screw, min. slip.** That's why steep pitch angles are OK, **(Maybe a lot more than 60°)** **The prop is *not trying to pull forward!!! - rather screw forward steeply!*** ***The blade angle is correct when it's correctly alligned with its helix angle!*** !

Seeing Through the Morass of Prop Physics - Our Hero Dr. Andy Bauer

The whole History of Science, of Invention, of man's progress toward a better life has been one of years of Perspiration, followed by an instant of Inspiration, of seeing the final answer. Seen more clearly, *only the prepared mind* can finally *see through all the complexity*, to the simple final, *invention*, solution. Well this task was **a long string of inventions**, insights to cut through the prop logic swamp **to finally see the total logic of props**.

My partner, and lifelong friend, **Doctor Andy Bauer**, had the raw **intelligence, advanced education, and lifelong experience**, specifically in **Aeronautical Engineering**, to incisively go through this grossly complex, multifaceted problem of propeller logic, **that no one else ever mastered well enough to explain**, see the logic, make it explainable in words, not impenetrable math, that prevented real understanding --- **the final insights**.

Over a ten year retirement intellectual challenge, we sorted out all the obscure hidden insights that are seldom, if ever, seen. Andy saw that Glauert's 1934 great work, was based on Prandtl's F factor at best an approximation. Goldstein's brilliant 3D 1929 math, and Theodorsen had the essentially exact math!!! Others failed to understand. Andy, smart enough, read, understood, and correctly used Theodorsen's masterful, final, exact heavy loading solution with Goldstein's 3D math. With Thrust and Pitch Errors in Glauert-Prandtl, **Theodorsen-Goldstein was clearly the way to go.**

Others who tried B-G-T math simply didn't understand all it implied!!!

Most significantly, Andy was smart enough to see that the bottom line result of Goldstein-Theodorsen was a **Kx blade loading chart vs. radius for the various Advance Ratio's** that a computer able guy could use, a **practical world usable tool**, for **quick, easy ideal prop design**. Most significantly we sorted out all the separate integrated great, but very obscure, basic points of **Betz's brilliant 1919 Historic Insight**, many never appreciated before. **Constant dT/dQ**, drag free, showed that there is ***no penalty to a twisted prop***, drag free, cutting through all the complex Trig., 3D flow and loading complexity to **a dead simple, magnificently desirable final outcome, every radius equally efficient, valuable and usable**. **Constant Slip** is the obscure balanced flow vs. radius core of **Minimum Induced Drag**, that is based on **Ideal Loading, through Ideal Shaping** of the blade, with matching **Twist**, that gives **constant Helical Pitch** of the **air inflow**, **constant Slip**, a one page explanation that nails what was **just never correctly understood**.

Andy, very early was able to see that there is **a highly variable velocity profile in the prop plane**, that acts like a **slowdown** in inflow, the body pushing a bubble of air forward. **Unlike others, Andy knew how to correctly calculate that profile** and **accurately correct the prop for it!!!!**

Slowdown - Adapting a Perfect Prop *for* Nose Velocity Profile.

Amazingly, the Slowdown was **nominally 50%** at the 19% radius next to the Spinner -- 67% at the next 27% station, 33% slower -- only 75% at the 12.6" r., 35% radius, on an RV 8, ***Big, 2 1/2% out at the tip!!!*** Obviously **we needed both a Blade Angle and Chord Change** to adapt a mathematically perfect prop **correctly** to a slower, lower q, variable Nose Velocity Profile.

What **Betz** did **in 1919** was **adapt a Rotating Wing, a prop**, for the **Major Rotational Slowdown**, Root vs. Tip, and he did that perfectly, logically, by demanding, **holding Constant Slip, Constant Pitch of the Air Inflow. We had to now deal with Axial, not Rotational, Slowdown**. At first, it seemed we should set up the modified blade angles and chords to **continue to hold, Demand Constant Slip**, still hold constant angle of attack, constant C_L in the **new Velocity Profile**. If we'd **widen the chords to counterbalance the now lower Dynamic Pressure, q,** we could potentially have **a still perfect Betz-Goldstein-Theodorsen prop, perfectly adapted for the Real Velocity Profile of a Plane's nose**, hopefully to the desired and Mathematically possible .1 degree, the proper prop tolerance for a consistent manufactured prop product out the door, McCauley's tolerance.

Well that doesn't work, and neither does holding the original thrust vs. radius load distribution. We started generating **ridiculous wider chords inboard, truly ugly props mathematically, 15", 18" root chords.**

More happens with the lower q field. Running in a slower airstream, you can generate the same thrust at lower H.P., but you develop a counterbalancing pressure drag on the fuselage that requires that you raise the gross thrust, now requiring the original H.P. to get the same original net thrust, potentially a new situation causing no new loss, cost free drag!!?!!!

What makes sense is to design a new ~perfect Theodorsen Prop to get the original required (gross and) net thrust, at the original H.P., now running in the slowed air to achieve **an essentially perfect new Theodorsen prop** that, of Prime importance, **holds the thrust distribution on the crucial outer blade**. What happens is that we **get wider blade chords on a still normal looking Theodorsen Prop with a little lower Aspect ratio**, to make the higher gross thrust in the slower air, at the original H.P. Actually we get a tad less thrust, at maybe **.3% lower efficiency, a little less thrust as we move inboard toward the already weak root, no big bad effect**, since we designed for the proper gross and net thrust. We do lose the constant Slip, but blowing less in the plane's face, and less root vortex, it's **the best fix.** Using **Source Sink Analysis**, we got **new insight on the whole flow field**.

Maybe Explaining Terrible Overall Propulsive Efficiency - ***on Slow Planes.***

Gus Raspet, somewhat of a Maverick, head of the Aerophysics Department at Mississippi State in the 50's, was a creative force in Aerodynamics, very much deserving of important Milestone Recognition. Among many other accomplishments, he did towed propellerless glide tests of several private airplanes. He found normal, expected drags, but **often terrible overall propulsive efficiencies, a startling 58% on a Bellanca Cruisair**, when a taped, sealed, clean plane's drag was compared with actual power required!! Other light planes, a Cub, a Cessna 120/140, etc. showed similar results -----

Still almost unaddressed a half Century later, this is perhaps the largest data and basic technical hole in all of Aerodynamics, matching the prior lack of a valid propeller explanation, a key part of our overall propeller quest. By inventing Zero Thrust Glide Testing, a simple, insulated feeler wire that lit a bulb when the prop quit thrusting and slid rearward in its, maybe .016" axial crankshaft endplay slop, I found a 14.94 RPM per MPH relationship *near cruise* on my 71"D - 51"P Luscombe Prop. I found **Real Drags**, for the first time in a normal flight configuration, a nifty little breakthrough in itself, and like Gus, found terrible overall propulsive efficiencies, (reported at the Reno, Dec 1990 AIAA Conference, and our J of A. Vol. .30, No 4, July - Aug. 1993 paper).

Leaving the cooling open, *of course*, for otherwise normal flight, we found only a 67 % overall propulsion efficiency, charging cooling to the airframe, quite comparable to the 58 % Bellanca, since cooling drag is often expected to be ~ 10 % of overall loss. Interestingly, glide testing 5 miles out to sea at dawn, (out of heavy local sea-shore lift, sink, and circulation), in dead stable air, I got excellent, amazingly reproducible data, as good as we might ever expect to get, we found ragged, but speed reproducible overall propulsive efficiency data, η_p showing, I thought, variable flow conditions over the embedded body, tail etc. Interestingly, with subsequent CAFE team testing, we found little extra propulsion efficiency loss on a faster, clean, RV 6 and the excellent Whitman Tailwind --- that, perhaps most significantly, would have faster, more efficient props, smaller ΔV's and $\Delta V/2V$ axial loss, the ΔV extra propulsion wind, a much lower percentage of the flight speed, much less extra propulsion wind effect over the ~ 1/2 of the wetted area exposed to the slipstream Now, **What was the Explanation of all this???**

Early on, in our work, we presumed that my McCauley Luscombe prop, which could have an 85 % B-G-T efficiency, might be down to only 82.5 % η. However in Van's RV Prop Test Program we found a European RV 8 prop had double the B-G-T loss, an 80% η, not the 90 % η of a proper prop! With low pitch props logically bigger losers a 75 % η was quite possible.

To explain: Low pitch props like the Luscombe, a P/D less than 1, 51/71, at a slow 100 MPH, there is a huge q ratio, tip vs. a slow root, airplane speed, a ~ 500 MPH Tip, and the need for an almost triangular blade shape to pull excess tip lift inward ***to better place Thrust, kill excess tip losses***. The very non triangular, square klip tip McCauley prop could easily be worse than the European RV 8 prop, easily lose 10 % efficiency vs. an 85 % max. potential BGT η, we realized. Most Significantly, at 100 MPH TAS Altitude Cruise, at 75 % η, the 49 H.P. Altitude Cruise would only produce 137 # Thrust. Then, at .67 overall propulsion efficiency, η_P, a .75 prop efficiency, η , that would mean a .89333 interference efficiency, η_i. (Realize .75 x .8933 = .67.)

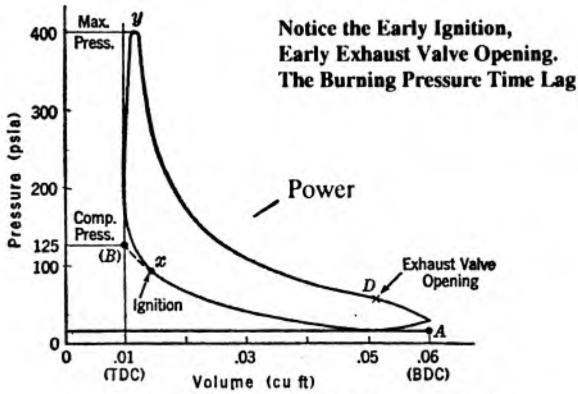
So, bottom line, the 137# Thrust developed at .75 η, at 49 H.P. at 100 MPH, TAS, at altitude, (not 182.6 # T, at 100% η), the resulting 137# Thrust, working at only .98333 η_i, would only produce **122.38 #** of resulting Thrust, a long way from 182.6 # T!!! (Notice 186.6 x .67 = **122.38 #**). Now that's **just beautiful**, because the Luscombe Zero Thrust Glide Tests at 85 MPH, IAS, 100 MPH TAS at 10,500' Cruise Altitude shows **~123 # Drag**, ***Viola!***)

If you go through the drill of determining the extra ΔV wind to make 137 # Thrust at the $\dot{\mathbf{M}}$, mass flow rate at Altitude, at 100 MPH TAS, you get ~ 12 MPH. Now 100 MPH + 12 MPH, $(1.12)^2 = 1.2544$. Now, the 123 # gliding drag divides up into ~ 83 # Profile Drag, and 30 # Induced at the 1250 # Gliding test weight. Nominally half the profile drag skin friction, and messy Aerodynamic intersections would see the stream tube ΔV, and 41.5 # exposed profile drag x the 1.2544 scrubbing factor would be 52 #, 10.5 # extra drag, a major part of the 123 to 137 # difference, 14 #, leaving 3.5 # to be explained by variable separation drag, just the kind of variation we saw on the bumpy, slightly irregular Propulsive Efficiency Plot that went from ~ 76 % at extremely low Power and Thrust to only ~ 62 % at high power, hi Speeds, all seemingly making sense with some variable separation drag, just what we'd expect on a less than pristine first Sheet Metal airplane.

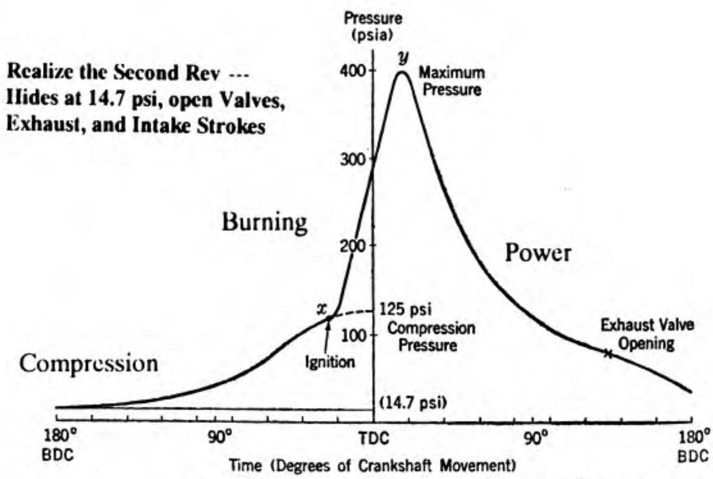
All the other gliding data plots were smooth, gliding in pure air, at dawn, out to sea, all looking like the best data we could ever possibly hope to get. So the slightly bumpy Overall Propulsive Efficiency looked absolutely genuine, just exactly what would seem reasonable, certainly making sense with better efficiency slow, degrading as more and more ΔV and power was applied

Subsequent CAFE Testing on the RV 6 and Whitman Tailwind, far better Aerodynamic Planes were harder to do because new Lycomming Engines, with hardly any axial slop, after the hot aluminum crankcases swallowed the axial slop vs. the steel Crankshaft. Very significantly, a ~ 9 MPH ΔV vs. ~ 180 MPH on a fast plane, is only a 5 % Stream Tube Speed Increase, a ~ 10% increase on maybe half the profile drag, much less crucial. **More work on this subject, to further nail it, is fertile research ground!!**

The UnThrottled Thermodynamic Cycle



pV Diagram for SI Engine at Wide-Open Throttle.



Actual pT Diagram for SI Engine at Wide-Open Throttle.

The PV, **Pressure, Volume**, and the **PT**, **Pressure, Time** Diagrams for a Spark Ignition Engine. A **Four Stroke Engine** takes **Two Revolutions** -- **Intake**, **Compression**, **Power**, **Exhaust**. This page emphasizes the Actual **Compression**, (burning), **Power** Revolution, the **Exhaust**, **Intake** on the Second Revolution, nominally at the 14.7 psi Atmospheric Pressure line. The next Throttled drawings makes it more clear.

BDC is Bottom Dead Center TDC is Top Dead Center -- Crankshaft Position

CHAPTER 10

THE ENGINE, Leaning

Where do we want to run our Engine? Wide Open, Unthrottled, Max RPM, less RPM, where vs. Friction, Pumping Losses, Efficiency, Sea Level, Altitude, best Fuel Burn, Economy, best matching our Plane?* It will be **Leaned for Max Economy!** Of course, we can't do that at High Power, low, or we'd burn the Exhaust Valves. **You can't lean at max. power!** You may well realize that a typical carburetor will kick in an **extra rich, wet cooling mixture at WOT**, Wide Open Throttle! ***Full story*:** **Rich delays the pressure rise, more margin vs. detonation!**

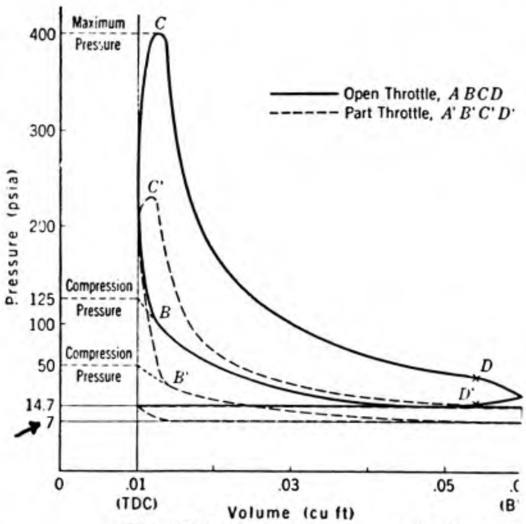
***In a few pages, a Voyager Engine Graph will help sort it all out!!!**

We **need an extra Powerful engine** to be able to **climb, hoisting the plane's weight**, at a fast enough rate, **just like Elevator Power! We also need to hold up the plane**, the **Induced losses from throwing air down** to get a **Newton's equal and opposite reaction force to hold up the Weight, of course, more power to overcome Profile Air Friction Drag**.

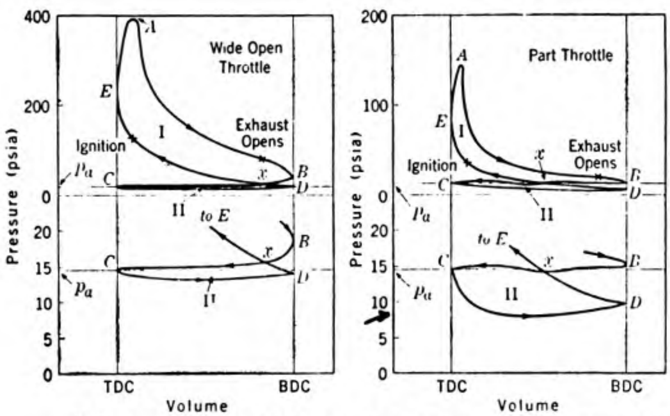
So, the **normal mode** of an engine is to **run well throttled**, at **Lower Power** for moderate cruise Speed, either **Plane or Auto!** We might be running our car at ~25% Power, our plane at ~65%.

Look at the Labeled **4 Stroke, PV**, Pressure Volume **Thermodynamic Graph** of a **Spark Ignition Engine** on the facing page. The **available Work, Energy** is represented by **the area inside the 4 Strokes**. The **Efficiency is that enclosed area, vs. all the area below the power stroke to absolute zero temperature**, and Pressure, 0°R, Rankine, **- 459.67 F°!!! Throttled that area is greatly reduced**, **worse**, the **lower throttled loop is subtracted from the reduced work area, next!**

The Throttled Thermodynamic Cycle



Effect of Throttling on pV Diagram of SI Engine.



pV Diagram of SI Engine (Induction and exhaust to magnified pressure scale).

The quite instructive **Throttled PV Diagram, shows why we don't want to throttle an engine, rather, simply cruise it at Altitude, where less power is available, matching the plane's real cruise need, where we want best efficiency.** The **Throttled, engine is Required to Pump In it's Working Air --- against the Vacuum created by a throttling plate --- thus work, energy demanded - subtracted from the working Area of the PV Diagram!! It's much better to simply cruise unthrottled at Altitude!**

The Thinking Man's Way to Fly -- Low Drag IAS, Max TAS Altitude Cruise -- Engine, as Good as Possible!

We can do what the Automobile can't **We can climb up, fly at Low IAS, Low Drag**, but needing **ever higher required Power as our True Airspeed, TAS Increases.** As the air **Density Thins,** our **Available Power Falls,** so maybe **by 8 to 14,000 feet we don't have to Throttle, we can eliminate** that little **pumping loop, no longer having to subtract it from the now weaker work available area inside the PV Diagram!!!**

That is where the Logic of Flight Maximizes!! Your Engine loses Power as you Climb, so at some Altitude your unthrottled Engine Power exactly matches required power. Altitude decreases the Thermodynamic Efficiency, arguing against too big an engine. **But**, we'll learn shortly, **the Altitude TAS/IAS Speed increase -- beats the Fuel Ecconomy loss!**

In a nutshell, that's how we can **optimally, efficiently match your Engine to your Plane, for Max Efficiency Cruise!!! Pretty Simple, Nifty, no Brain Strain there, just Fly High!!!**

When I fly the Luscombe at 85 IAS at all Gross Weights, at 10'500' Density Altitude, Lean of Peak, I burn only 3 3/4 GPH at 100 MPH, 26.66 MPG!!! Van Flying his original **160 HP RV 6 at 140 IAS, at 12,500'DA, 170 MPH, burned only 6.1 GPH, 27.87 MPG,** even better, Faster!!! **That's 6 hours Range,** at **170 MPH,** a **1000 Mile LA to Seattle*,** no wind, no reserve **Range, so on any tail wind day, we could do that*!**

I've Flown LA to McCall ID, 800 Miles*

Realize what the Game is Here: You'll learn next how terribly inefficient your Thermodynamic Heat Engine is. Worse, it must be considerably oversize to give you Climb Performance Heavy, is normally run throttled, significant extra loss. You'll soon see, next, how really bad it can be, **using 5, Five times, 500% extra fuel. SO, THE WAY WE GET THE BEST USABLE ENGINE EFFICIENCY IN OUR PLANES, IS TO CRUISE THEM INTELLIGENTLY, WIDE OPEN, LEANED, AT ALTITUDE, UNTHROTTLED!!!**

A Little Insight on Thermodynamics: Real Core Insights!!!

We don't want to get all complex here, and turn this into a graduate course in Thermodynamics, *rather* there are some **quite simple, quite Important, Big Picture things to realize here!**

Thermodynamic Efficiency is Terrible, for a Simple Reason! Quite simply, in a heat engine, to get the max., full energy from burning fuel, **we'd like to compress the mixture to very high Pressure, burn it as hot as possible, expand it to Absolute Zero Temperature, -459.67°F, get all the energy out!! BUT,** in the real world, we **can only have a limited compression, or the fuel detonates**, and we **dump the gasses while they are still red hot*,** no where near room temperature, Absolute Zero, not even a dream, **can't have a longer expansion ratio mechanically than the compression ratio**, have to get the heat out, to not overheat the engine. Steam Engines can have a secondary expansion, energy recovery, but with heavy machinery

*** They're really Yellow, Blue, White Hot, DC 6 or 7 Exhaust!**

A moderate Compression Ratio **Otto Cycle** gasoline engine may only have **a ballpark 32% Thermal Efficiency**, maybe 25% heavily throttled, worse when mechanical friction is added. With a 67% to 85% overall propulsive efficiency, η_p, worse, if cooling drag is charged to the engine, not the Airframe, like Raspet's eye opening 58% η_p 1950's benchmark glide testing of a Bellanca Cruisair, and you easily get to the **18% overall ballpark** we speak of in the prop book, which **uses more than FIVE, 5 times the theoretical fuel need!!!**

For those who are interested, want to look at the Pressure- Volume Thermodynamic Graphs a little deeper, you can see that **we light the spark a little before Top Dead Center**, TDC, going over the top of the crank throw, where it doesn't really hurt, **let the burn pressure lag, build, max. ~16° after TDC, open the Exhaust Valve before BDC**, get the hot gasses out, for less cooling need. We even open the intake valve, before the exhaust closes, optimum **valve overlap!** There could be additional Chapters on Thermodynamics, Engine Design, Lightweight Engine design, Vibration. Rather, we want you to **grasp how to optimize your engine** - ***in your plane*** !

Realize, Understand all that's really happening here. A four stroke engine, Intake, **Compression, Power**, Exhaust, is only really **working, firing, <u>making power, every other revolution</u>**. The second revolution, it is dumping the exhaust, intake valve closed, exhaust valve open, then opening the intake valve, closing the exhaust, starting the next intake cycle, pulling air in.

You'd like to get a good full, strong, Power Stroke, but most of the time throttled, you have a weaker, throttled power stroke, as the picture shows, but worse, that little throttled, pumping intake stroke, must pull the air in against a throttled vacuum, requiring work, <u>energy, that must be subtracted from the weakened power stroke</u>. **WOT, at altitude, engine power now exactly matching the plane demand, helps a poor situation!**

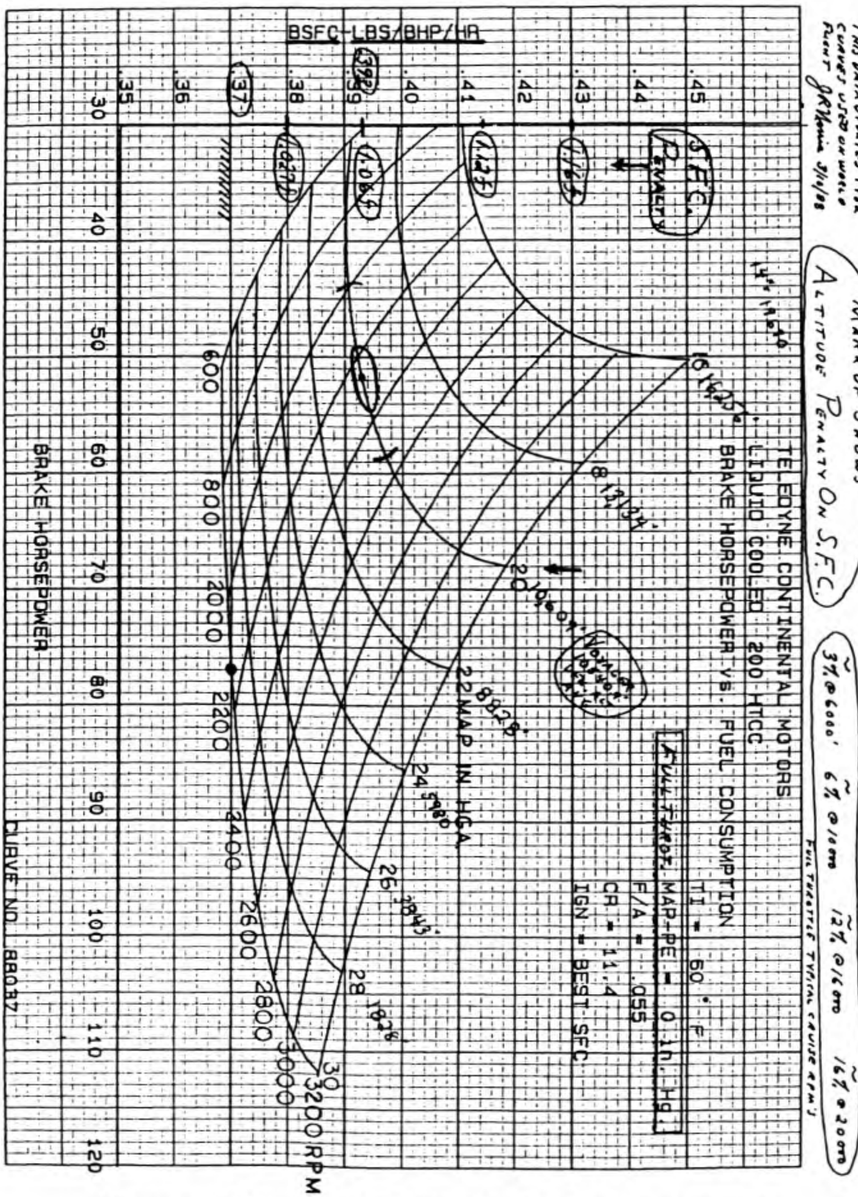
Now, of course, we'd like to get every bit of Power out of the Power Stroke, **expanding the gas out to zero temperature, and pressure**, but instead **<u>we have to dump it as very hot gas</u>**, still well above atmospheric pressure, sonic flow barking out the exhaust, **<u>a major part of the heat energy lost</u>, <u>wasted</u>**, the reason we have terrible thermal efficiency, maybe like the 32% efficiency stated. Then we lose the engine cooling drag loss, usually blamed on the plane, maybe 10% of Plane drag, and the overall propulsion efficiency loss, often a lot worse than the propeller efficiency loss, especially on old draggy slow planes, that require an extra big Delta V, ΔV wind thrown back, increasing the body and intersection drag, maybe some flow separation, a **pulsing, higher ΔV prop flow - <u>overall terrible</u>!!!** ✓

In the propeller book you can learn that the fast planes have a big $\dot{M}$, Mass Flow Rate through the prop, only need a small ΔV to make the necessary thrust, but the slow planes, low $\dot{M}$, Mass flow rate, need a big ΔV*, Big vs. a slow plane speed which creates a bigger prop efficiency loss. **A <u>clean</u>, <u>fast</u>, <u>low drag plane</u>, <u>efficient prop</u>, <u>an efficient engine</u> <u>are all important</u>!!!** ✓

•ΔV, Delta V is is simply the Speed Up of Air, Thrown by the Prop, to make Thrust.

Marvelous, Rare Insight --- BSFC vs. H.P., RPM, Altitude

The Great Continental, Water Cooled Voyager Engine, WOT, Wide Open!
Extra Efficient, But, you can see How Your Engine Works



Voyager Engine B.S.F.C., Brake Specific Fuel Consumption

Altitude Loss of Engine Fuel Efficiency, BSFC

You're about to learn how much Higher Altitude Flight, Hurts Engine Brake Specific Fuel Consumption, BSFC --- --- But then find out that the TAS/IAS Speed Increase at Altitude gives you a net gain in MPG, Big Important Insight!

BSFC, Brake Specific Fuel Consumption, is in lbs / H.P. Hr.

On the Facing Page, is the best Engine Insight ever, the actual **BSFC Graph** vs. **Altitude**, **H.P.**, **RPM**, for the **Wide Open**, very Special **Water Cooled, Rear Cruise Engine that made the Voyager World Flight possible. With a high 11.5 : 1 Compression Ratio, a Special Combustion Chamber to tame detonation, the BSFC of the 110 H.P. Continental** is much better than you'll get on your engine*, but **Great Eagle Insight!**

***Though this Engine is Superior, The RPM, HP, Alt. Insights all Work!**

Now remember, this Graph is all WOT, Wide Open Throttle, no Throttling Losses!!! Notice this Engine can have .38 Pounds of Fuel per H.P. Hour, where .4 is great! Notice that at 10,500', the Voyager Average Altitude, the BSFC was hurt ~6%, the 1.06 increase marked on the Graph! On the next page the Square Root of the Air Density Ratio that sets the TAS/IAS speedup is ~1.16 - Viola, 10% Gain!!!

Of great interest to me, 10.5 Density Altitude, is where I regularly fly my Classic Luscombe, a great old Classic, used as an accurate test bed to nail all the Insights you see herein!

There's a lot more Great Insight on this Graph. Notice how the very High RPM, high H.P. hurts BSFC, especially as you go higher. Notice how WOT Manifold Pressure is a telltale of Altitude! LOW RPM, HP, ALTITUDE are BEST!

The Atmospheric Chart on the Next Page, shows that at 16,000', the TAS/IAS factor is 1.2815, still well ahead of the 1.16 BSFC increase that handles 16,000' and high RPM, HP. Study this Graph, and Altitude Chart, and be Smart for life!

Altitude Atmospheric Chart

ICAO STANDARD ATMOSPHERE (NACA TN 3182)

Geopotential ft	t °F	T °R	P lb/sq ft	P in Hg	$\rho \times 10^3$ slugs/cu ft	$\frac{T}{T_0} \times 10$	$\frac{P}{P_0} \times 10$	$\sigma \times 10$ $\frac{\rho}{\rho_0}$	$\sigma^{-1/2}$	$\rho g_0 \times 10^2$ lb/cu ft	$\mu \times 10^7$ lb sec/sq ft	c_s ft/sec	$\frac{c_s}{c_{s0}} \times 10$	Geopotential ft
−2 000	66.132	525.820	2273.71	32.1481	2.5192	10.1375	10.7442	10.598	.97136	8.1052	3.7860	1124.54	10.0685	−2 000
−1 000	62.566	522.254	2193.82	31.0185	2.4473	10.0688	10.3667	10.296	.98552	7.8738	3.7656	1120.73	10.0343	−1 000
0	59.000	518.688	2116.22	29.9213	2.3769	10.0000	10.0000	10.000	1.0000	7.6475	3.7452	1116.89	10.0000	(
1 000	55.434	515.122	2040.85	28.8557	2.3081	9.93125	9.64387	9.7106	1.0148	7.4263	3.7248	1113.05	9.96556	1 000
2 000	51.868	511.556	1967.68	27.8210	2.2409	9.86249	9.29809	9.4277	1.0299	7.2099	3.7042	1109.19	9.93101	2 000
3 000	48.302	507.990	1896.64	26.8167	2.1752	9.79374	8.96241	9.1512	1.0454	6.9984	3.6836	1105.31	9.89633	3 000
4 000	44.735	504.423	1827.69	25.8418	2.1109	9.72499	8.63661	8.8808	1.0611	6.7917	3.6629	1101.43	9.86153	4 000
5 000	41.169	500.857	1760.79	24.8959	2.0481	9.65623	8.32047	8.6167	1.0773	6.5806	3.6422	1097.53	9.82661	5 000
6 000	37.603	497.291	1695.89	23.9782	1.9868	9.58748	8.01377	8.3586	1.0938	6.3923	3.6214	1093.61	9.79157	6 000
7 000	34.037	493.725	1632.93	23.0881	1.9268	9.51873	7.71628	8.1064	1.1107	6.1994	3.6005	1089.68	9.75640	7 000
8 000	30.471	490.159	1571.88	22.2249	1.8683	9.44997	7.42780	7.8601	1.1279	6.0111	3.5795	1085.74	9.72110	8 000
9 000	26.905	486.593	1512.70	21.3881	1.8111	9.38122	7.14812	7.6196	1.1456	5.8271	3.5585	1081.78	9.68567	9 000
10 000	23.338	483.026	1455.33	20.5769	1.7553	9.31247	6.87703	7.3848	1.1637	5.6475	3.5374	1077.81	9.65011	10 000
11 000	19.772	479.460	1399.73	19.7909	1.7008	9.24371	6.61432	7.1555	1.1822	5.4722	3.5162	1073.83	9.61442	11 000
12 000	16.206	475.894	1345.87	19.0293	1.6476	9.17496	6.35980	6.9317	1.2011	5.3010	3.4950	1069.83	9.57860	12 000
13 000	12.640	472.328	1293.70	18.2917	1.5957	9.10620	6.11327	6.7133	1.2205	5.1340	3.4737	1065.81	9.54264	13 000
14 000	9.074	468.862	1243.18	17.5773	1.5451	9.03745	5.87453	6.5002	1.2403	4.9711	3.4523	1061.78	9.50655	14 000
15 000	5.508	465.196	1194.27	16.8858	1.4956	8.96870	5.64340	6.2923	1.2606	4.8121	3.4309	1057.73	9.47032	15 000
16 000	1.941	461.629	1146.92	16.2164	1.4474	8.89994	5.41969	6.0896	1.2815	4.6570	3.4093	1053.67	9.43395	16 000
17 000	−1.625	458.063	1101.11	15.5687	1.4005	8.83119	5.20322	5.8919	1.3028	4.5058	3.3877	1049.59	9.39744	17 000
18 000	−5.191	454.497	1056.80	14.9421	1.3546	8.76244	4.99380	5.6991	1.3246	4.3584	3.3661	1045.50	9.36079	18 000
19 000	−8.757	450.931	1013.93	14.3360	1.3100	8.69368	4.79126	5.5112	1.3470	4.2147	3.3443	1041.39	9.32399	19 000
20 000	−12.323	447.365	972.490	13.7501	1.2664	8.62493	4.59542	5.3281	1.3700	4.0747	3.3225	1037.26	9.28705	20 000
21 000	−15.889	443.799	932.429	13.1836	1.2240	8.55618	4.40611	5.1496	1.3935	3.9382	3.3006	1033.12	9.24996	21 000
22 000	−19.456	440.232	893.715	12.6363	1.1827	8.48742	4.22317	4.9758	1.4176	3.8053	3.2786	1028.96	9.21272	22 000
23 000	−23.022	436.666	856.313	12.1074	1.1425	8.41867	4.04643	4.8065	1.4424	3.6758	3.2565	1024.79	9.17533	23 000
24 000	−26.588	433.100	820.188	11.5967	1.1033	8.34992	3.87573	4.6416	1.4678	3.5497	3.2344	1020.59	9.13779	24 000
25 000	−30.154	429.534	785.308	11.1035	1.0651	8.28116	3.71091	4.4811	1.4938	3.4270	3.2122	1016.38	9.10009	25 000
26 000	−33.720	425.968	751.638	10.6274	1.0280	8.21241	3.55180	4.3249	1.5206	3.3075	3.1899	1012.15	9.06223	26 000
27 000	37.286	422.402	719.148	10.1681	.99187	8.14366	3.39827	4.1729	1.5480	3.1912	3.1675	1007.91	9.02422	27 000
28 000	−40.852	418.836	687.803	9.72488	.95672	8.07490	3.25016	4.0250	1.5762	3.0781	3.1450	1003.64	8.98605	28 000
29 000	−44.419	415.269	657.575	9.29748	.92252	8.00615	3.10731	3.8812	1.6052	2.9681	3.1225	999.362	8.94771	29 000
30 000	−47.985	411.703	628.431	8.88541	.88927	7.93740	2.96960	3.7413	1.6349	2.8612	3.0999	995.062	8.90921	30 000
31 000	−51.551	408.137	600.342	8.48826	.85695	7.86864	2.83687	3.6053	1.6654	2.7572	3.0772	990.743	8.87054	31 000
32 000	−55.117	404.571	573.279	8.10561	.82553	7.79989	2.70898	3.4731	1.6968	2.6561	3.0544	986.405	8.83170	32 000
33 000	−58.683	401.005	547.212	7.73705	.79500	7.73114	2.58580	3.3447	1.7291	2.5578	3.0315	982.048	8.79269	33 000
34 000	−62.249	397.439	522.113	7.38218	.76534	7.66238	2.46720	3.2199	1.7623	2.4624	3.0085	977.672	8.75350	34 000
35 000	−65.816	393.872	497.955	7.04060	.73654	7.59363	2.35304	3.0987	1.7964	2.3697	2.9855	973.276	8.71414	35 000
36 000	−69.382	390.306	474.710	6.71194	.70857	7.52487	2.24320	2.9810	1.8315	2.2798	2.9624	968.859	8.67460	36 000
36 089	−69.700	389.988	472.679	6.68322	.70612	7.51874	2.23360	2.9707	1.8347	2.2719	2.9603	968.465	8.67107	36 089
37 000	−69.700	389.988	452.434	6.39698	.67587	7.51874	2.13794	2.8435	1.8753	2.1746	2.9603	968.465	8.67107	37 000
38 000	−69.700	389.988	431.203	6.09679	.64416	7.51874	2.03761	2.7100	1.9209	2.0725	2.9603	968.465	8.67107	38 000
39 000	−69.700	389.988	410.968	5.8106"	.61393	7.51874	1.94199	2.5829	1.9677	1.9753	2.9603	948.465	8.67107	39 000
40 000	−69.700	389.988	391.682	5.53801	.58512	7.51874	1.85066	2.4617	2.0068	1.8826	2.9603	968.465	8.67107	40 000
41 000	−69.700	389.988	373.302	5.27813	.55766	7.51874	1.76401	2.3461	2.0645	1.7942	2.9603	968.465	8.67107	41 000
42 000	−69.700	389.988	355.784	5.03045	.53149	7.51874	1.68123	2.2361	2.1148	1.7100	2.9603	968.465	8.67107	42 000
43 000	−69.700	389.988	339.088	4.79439	.50655	7.51874	1.60233	2.1311	2.1662	1.6298	2.9603	968.465	8.67107	43 000
44 000	−69.700	389.988	323.176	4.56940	.48278	7.51874	1.52714	2.0311	2.2189	1.5533	2.9603	968.465	8.67107	44 000
45 000	−69.700	389.988	308.011	4.35497	.46013	7.51874	1.45548	1.9358	2.2728	1.4804	2.9603	968.465	8.67107	45 000
46 000	−69.700	389.988	293.557	4.15061	.43853	7.51874	1.38718	1.8450	2.3281	1.4109	2.9603	968.465	8.67107	46 000
47 000	−69.700	389.988	279.781	3.95584	.41795	7.51874	1.32208	1.7584	2.3848	1.3447	2.9603	968.465	8.67107	47 000
48 000	−69.700	389.988	266.652	3.77020	.39834	7.51874	1.26004	1.6759	2.4428	1.2816	2.9603	968.465	8.67107	48 000

The Square Root of the Altitude Density Ratio Shows the IAS-TAS Ratio

A Really Good, Incisive Overview

No big surprise, the **Aerodynamic Pros seldom understand the Engine, the Engine Pros even less likely to understand the Aerodynamic Implications**, especially the subtleties, how you can put it all together, in the **simple but sophisticated way we do it here in this book: Intelligent High Altitude Cruise, The Logic of Flight, The Thinking Man's Way to Fly.**

We're purposely avoiding going too deep on the engine subject, rather trying to give you the **key essentials** to **incisively optimize how you fly your plane**, **matching the engine and plane to each other**, and the **Prop Book** shows you how you can **understand Props correctly**, **precisely**, **essentially exact, Optimum Designs, preferably targeting Altitude Cruise!** ✓

Since, to a degree we're **just Skimming Engine Logic here,** purposely avoiding drowning you with yet another technical subject**, it may be best if you read this concise overview a few times, be sure you really grasp the charts and graphs, the really quite incisive grasp that is here, easily enough --- gain a really incisive pro grasp of the whole flight Logic!**

If we went a lot deeper, took a lot more time you might just **remember, and use what is here**, so maybe it's desirable to **keep this simple, but to the point,** of **how the Engine is used in High Altitude Cruise**, **Wide Open Throttle**, WOT, **leaned at low power**, where you can **avoid burning the Exhaust Valves, often exotic materials**, that **often requires cautious, intelligent insight, covered next! Leaning covered next!**

(Would you believe, on the GE 90, 100,000 Pound Thrust Jet Engine, used on the Boeing 777, a 40 : 1 Compression Ratio, far above our *old* engines, day in and day out, they are running the Gas Temperature above the Melting Point of the Turbine Exotic Alloy Material, Bleed Air Cooled Blades, WOW!!!!! I once asked a very smart engine designer of our engines what exotic Valve Alloys were used, and was shocked by his answer: TRW won't tell us what they're using!) ***Considering that*** **-- Next, Leaning!**

One might think that a chemically exact, ~**14.7 (stoichiometric) mixture*** of **air and gasoline** would be central in teaching fuel mixture management, but, looking back at my graduate course engine text books, that word is not even mentioned! Rather, they immediately make clear that the **chemically correct mixture does not produce either the max. power, or max. economy**. ***See the Graph below.*** Rather tests of a one cylinder engine teaches the **12.5/1 max. Power** mix, and the **16/1 Max. Economy Air / Fuel Mixtures, by weight. Simply, with less than full vaporization, all the fuel, especially the heavy ends of the distillate, do not evaporate, and do not find oxygen.** Also, as previously mentioned, at **WOT, an extra rich cooling mixture is purposely used to protect the exhaust valves.** (**The truth is more complex: A richer mix burns slower, delays peak Pressure, thus extra margin vs. detonation, especially at slower RPM, fixed Pitch.**) Engines are very much a subject of **testing, learning** to **find the real truths**, in a complex subject, **to find what is really true !**

*** Get it: Mixtures by weight, Air the Heavy part. O_2 weighs 23% of Air!**

First, we'll **learn what is fundamentally happening** in a **perfect one cylinder test engine**. But even before we start, it is necessary to say that **air-fuel distribution will almost certainly vary a lot**, and **only rarely will *all* cylinders act this perfect! But learning in orderly steps here, is the way to the truths!**

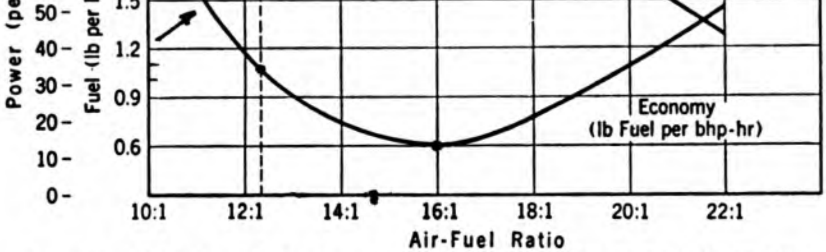


Fig. 123. Variations of Power and Economy of an SI Engine with Carburetor Adjustment (Constant speed and wide-open throttle).

That is a great old correct teaching graph, for 1940's auto engines, from my old text, but notice that it's minimum BSFC is .6 # Fuel / H.P. Hr., not the .38 we saw on the Voyager engine graph. But **it correctly shows max. Power is 12.4, to 12.5 Air Fuel Ratio, max. Economy is 16/1 A.F., much leaner!**

Now below we have a more modern Continental Graph for a **Fuel Injected TCM IO 550 Operation Manual** that brings in **EGT, Exhaust Gas Temperature**, crucial for Exhaust Valves, and **CHT, Cylinder Head Temperature, for Temp. critical Aluminum Cylinders. That gets us into the nitty gritty of the temperatures, the leads, and lags that we need to learn very well to protect our engines, and be proficient here!**

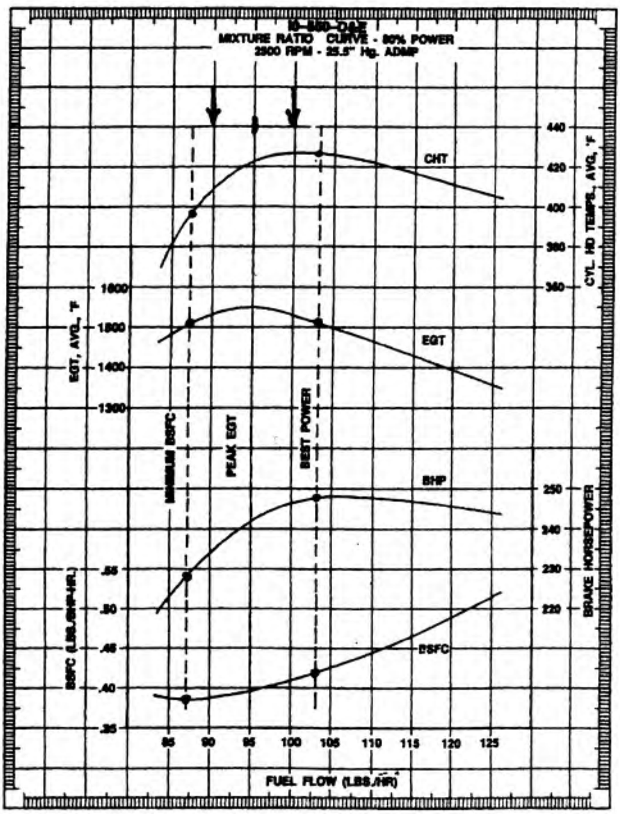


Figure 13-14. Mixture Ratio Curve 80% Power
IO-550-D&E

Leaning - Fuel Mixture Management

First, let me make very clear, that now we'll be dealing with a **modern, high performance, fuel injected engine, in the very best cases, even with Matched Injectors**, so we'll assume for the moment, that all cylinders are acting the same, (a very big assumption), also, **full EGT, and CHT sensors, and readouts**, so we'll **have a proper check of whether, or not, there is something close to mixture balanced cylinders, or not!** **Later**, we'll deal with our old 1940's, 50's carburetor engines.

Notice that at **Max Economy we're dealing with 227 H.P.**, say **~16:1 Max Economy Mixture, *not*** the **249 H.P. Max Power case, ~91%, ~9% less Power!** If we were low enough, we could open the throttle, get back up to 100%, but say we're at **high Altitude**, with **plane and engine power matched**, just as the book advises. **Our Engine reacts much like the curves!**

Should we try 50^0 F Lean of Peak?

Look, our **CHT is down from 428 F, to 395F, a lot better** for the **marginal Aluminum Cylinder Alloys, that crack when mistreated**, and the **EGT is at 1500 F^O, not a 1550 F^O+ max.**, the **same as 50 F^O rich of Peak, often recommended, LOP is potentially significantly better for the Cylinder Material, the same temp. for the valves, and their critical material!!!**

Here are the key things to see ---

Max Cylinder Temp is near Max Power! - Don't Fly There!

Max EGT is between Max Econ. and Max Power! a No No!

50° Rich of Peak, often recommended, Delicate Cylinders Worse!!!

Max Econ. cools Key Cylinder Head Temperatures to OK!

Max Economy has EGT Valve Temperatures back Lower!

Max Economy: 12.5/16, .78125, ~22% less Fuel Burn?, No!

Here we see .383 / .423, BSFC, Max Power, ~10% saving, Real World!!!

Now, that's the core of the story, BSFC about .385 / .41, = .939, about 6.6% better BSFC 50° lean of peak, vs. 50° rich of Peak EGT! An oxidizing atmosphere lean, seems OK. The key is balanced mixture, good instruments, *or not!!!* We get **less Power at Max Economy**, but that **just lets you fly optimum lower, on Shorter Flights, more choice, flexibility!**

So WHY would an Engine Manufacturer recommend 50° F Rich of Peak when it is clearly worst, bad for Cylinder Head Temperatures, no better for critical exhaust valves? Cracked Cylinders is a real, and prevalent problem.

Well, first, they know they are shipping Engines with Bad to Terrible Fuel Distribution!!! Simply, they don't want a bunch of Amateurs, with "bad to none" Instrumentation and Knowledge, mucking around, burning valves, because some of your valves, *unchecked* could easily be at max. EGT!!!!

The big Airline Round Radials, very symmetrical, fine distribution, finally, in the 50's, had excellent distribution, real scientific, careful monitoring, professional flying -- and pro pilots could often see, the yellow, blue, or white exhaust, have an absolutely valid visual check, learned at night!!!

Our flat 4's and 6's have bad distribution, unless, on rare later top engines, the manufacturer got serious about mix! I'm told the carbureated Lycomings with the Plenum feed Chamber in the mixture ducts are worst, many expensive injected engines worse than you'd hope, the reason the most expert pilots, with the critical advanced engines, often go for swapping injectors, professional balancing -- pro work!

Obviously, on any advanced, serious engine, with a serious, knowledgeable Pilot, you want first class EGT, and CHT sensing, and readout, easy, quite available today!! Wishing isn't good enough, it's not likely to work, likely harmful!

If you do the right thing, get yourself good instrumentation, learn this, "easy enough insight", you can, with just the knowledge herein, know where you are, run your engine intelligently, safely, based on good facts about EGT, and CHT, both important to safe, optimum Engine Operation!!! I'm tough here, no excuses, because if I weren't it would be irresponsible! Higher Altitude insight, next, is important!

Flying at higher altitude, we have two countervailing factors! At Much Lower Power, we should, logically, have more leeway, margin, you might first think. *But*, we still try to adjust to the same mixtures, the same Temperatures, ***careful!***

Let me digress a little, a life of Flight. At Christmas 1950, the Korean War on, being in the Air National Guard, to play with B 26 Invaders, with the big kids, who fought WW II, knowing I'd be called into the Air Force at Wright Field, in Dayton, as an officer, looking for a Cessna 140 to fly home to see Milly on weekends, I found a near new, **2 1/2 year old $3400 Deluxe Luscombe 8E for $1225**. **A student**, with **no income, I bought it on faith!**

Life turned into a Whirl Wind, leading the Aircraft Laboratory Group on Mock up and Engineering Inspections, on all the new planes, with the top Industry, and Air Force People! I had a fantastic life, founded and ran companies, got Primary Flight Controls on Boeing Jets, my Spacecraft Controls in the Smithsonian, consulted, had a life most could only dream about. ***I sure didn't have time to have a plane* - *but I never let go***. Simple, reliable, rarely needed fixing, it was **my great escape when work got wild! I kept it as a Classic**, an Aerodynamic Test Vehicle, the Voyager, this book, Zero Thrust Glide Testing, a known 67% overall Propulsion Efficiency, η_p. **Lots more**, a 12:1 glide ratio, I do Zero Thrust or Idle powerless approaches, from 10,500', 2 miles, from 20 miles out, at ~70 MPH have 4 miles extra range, ***fly for 20 minutes with the engine essentially off***, **the Sierra wave, 18,000'**. The huge joke, last Christmas, 2006, 56 years, it cost **$21.88/ year!**

Money not a problem, safety ever more valued, only keeping it for fun, escape, **I hardly leaned, very conservative**, no need to push the envelope, flying just for fun, and to keep my hand in, **too busy to buy a Bonanza, and be more serious, my pro work great fun**, and **I always Overhauled the Engine Early. Guess what, it always had way too much Carbon Build up!!**

Flight was my hobby, since I was a kid, won the Model Senior National Championship Two of the 3 years I was there to compete. I decided I wanted to have a hand in the Engine Overhaul, know everything in there, Lean the Engine Properly, get intellectually serious, nail everything in these two books. A lifetime of pro insight, I should do no less! You can make that lifetime of Insight, fun, Work for You!

Over the years, I read everything good I could find, that seemed technically accurate, sensible, passed the horse sense test, a good rigorous technical look, vs. the **Graduate level Engine Design Course I took years ago! Truth, Facts, Physics don't change!**

Recently, boning up to check myself on all this, I found an excellent, concise article by **Peter Garrison**, a well respected, long experienced, Pilot, Designer, Builder, Melmoth I, and II, and respected, well proven author for AOPA Pilot, among others

Like many, Peter had bought all the instrumentation, studied, did the full Science Approach, over a long, long time. But, he **finally ended up more simply, using the old approach, lean to a bit of roughness**, that would be on the lean side of peak, **then richen a bit** to ***smooth enough*** operation, no misfires, no real roughness, (my words not his), and has no problems. I should immediately say that **Peter has GAMI Injectors, knows that his cylinders have well matched mixtures**, and the **full EGT, CHT instrumentation**. As he leans by sound, feel, he can glance over, **see exactly what his real EGT, CHT facts are, like a pro should. He has a 6 Cylinder Continental TSIO 360F, 200 H.P. Engine.** Just like the book, **he usually flys high, efficient, at 65% Power, or below**.

In the same vein, I fly high, typically at **10,500', wide open, 2300 RPM**, with **a higher pitch cruise prop**, **aggressively leaned**, but never rough, specifically at 49 HP, on a Sea Level 85 H.P. Engine, **57.65% Power**. With a pedestrian engine, nothing wonderful for valves, I've been doing that 1000 hours over 23 years, on my R&R Classic. When I look in with a borescope, there is ***no carbon buildup anymore***, everything looks just fine It's been to every corner of the country, many times over 56 years, transcontinental several times, first from Cleveland, from LA since 62. **It's right to be knowledgeable, careful, don't do dumb things, gamblers don't last, flying!**

It's proper to lean, not carbon up your engine, wrong not to!

Any aggressive Engine, I'd demand full instrumentation, exact insight, monitoring - ***on the most aggressive engines, balanced injection.*** **A wise Pilot, cautious, learns, has great fun, a long full life!**

Since we're trying to run at the same temperatures at Altitude, I'd be cautious to argue that flying high is easier on the specifics of Exhaust Valve Protection, but at Higher Altitude, at only 57% to 65% Power, one has the help of a much lower heat load, the chance for less challenged heat conduction through the metals. It's Hell in there, caution is good! Bottom line, I never lean really aggressively until I'm above 10,000', where I know I can't pull even 65% Power!

I fly High, WOT, low HP, Max IAS vs. Drag, then even faster TAS, at no additional Drag -- and Lean, just like the book says, at low HP, the Engine perfectly matching the plane's demand, without Throttling losses!

People misunderstand that I'm somehow flying slower, when, in fact, I'm always flying as fast as the plane will go, Wide Open at Altitude, where everything matches perfectly, loping along efficiently, cool, air conditioned where it may be 100F°+ down on the Western desert.

The day we all flew LA to McCall ID, for a fly in, I left two hours after everyone else, got there an hour before them, burned about 3/4 their gas, went non stop. The gang made two stops, sweat in 110 degree heat at Bishop, had big trouble climbing over the Mountains North of Bishop, hot. 2nd stop, one guy landed in a dust devil, ended up out in the weeds, shaken if OK.

A 747 takes off at ~170 MPH Heavy, only goes ~270 IAS, but at 40,000 feet thats 540 MPH. That's a good act to copy! The Game in Life is to just learn, Get Smart as You GO!!!