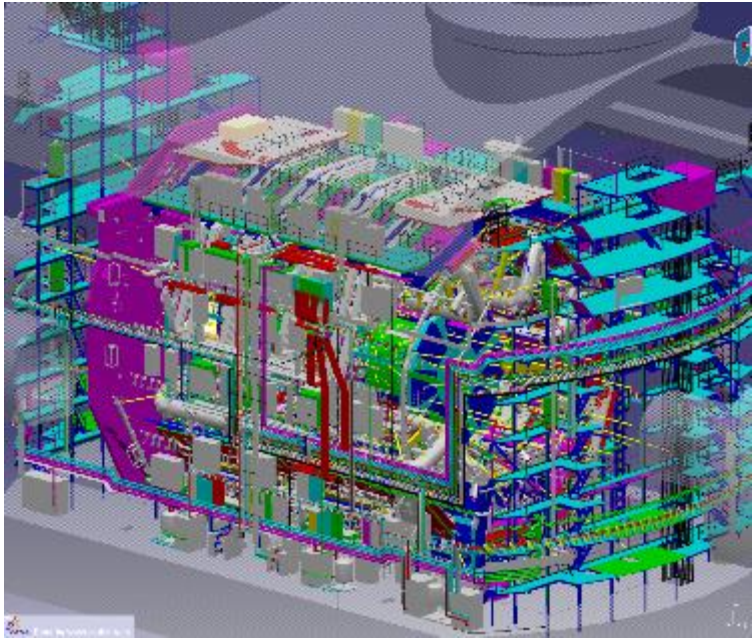
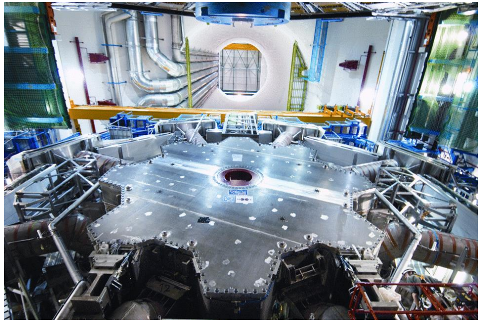


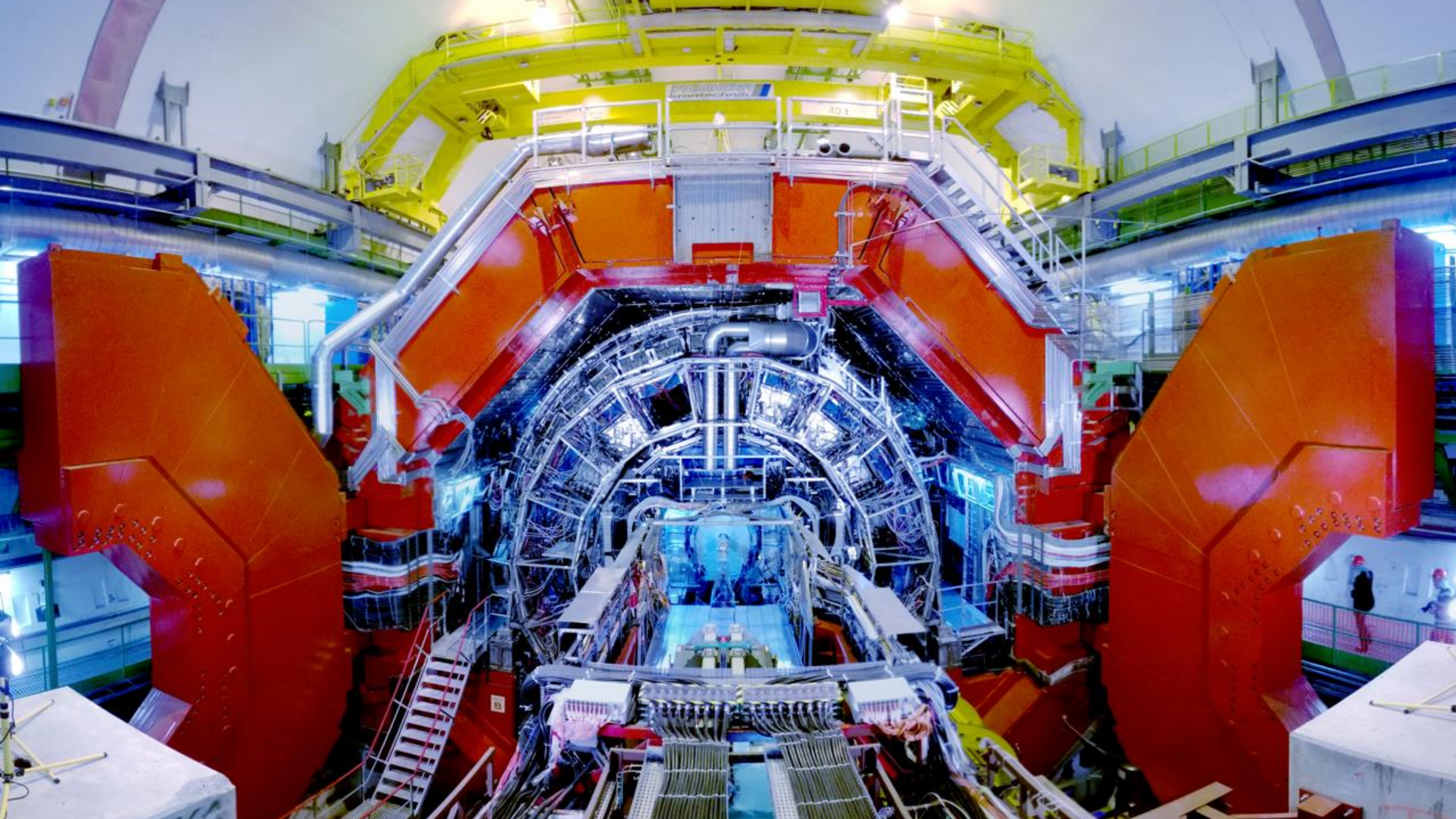


Inspired by Physics – Just How Big is Disruptive?

Design a Flying Jumbo Jet in Just One Hour

ESADE Executive Program, Markus Nordberg
November 15, 2017

Development & Innovation Unit (CERN)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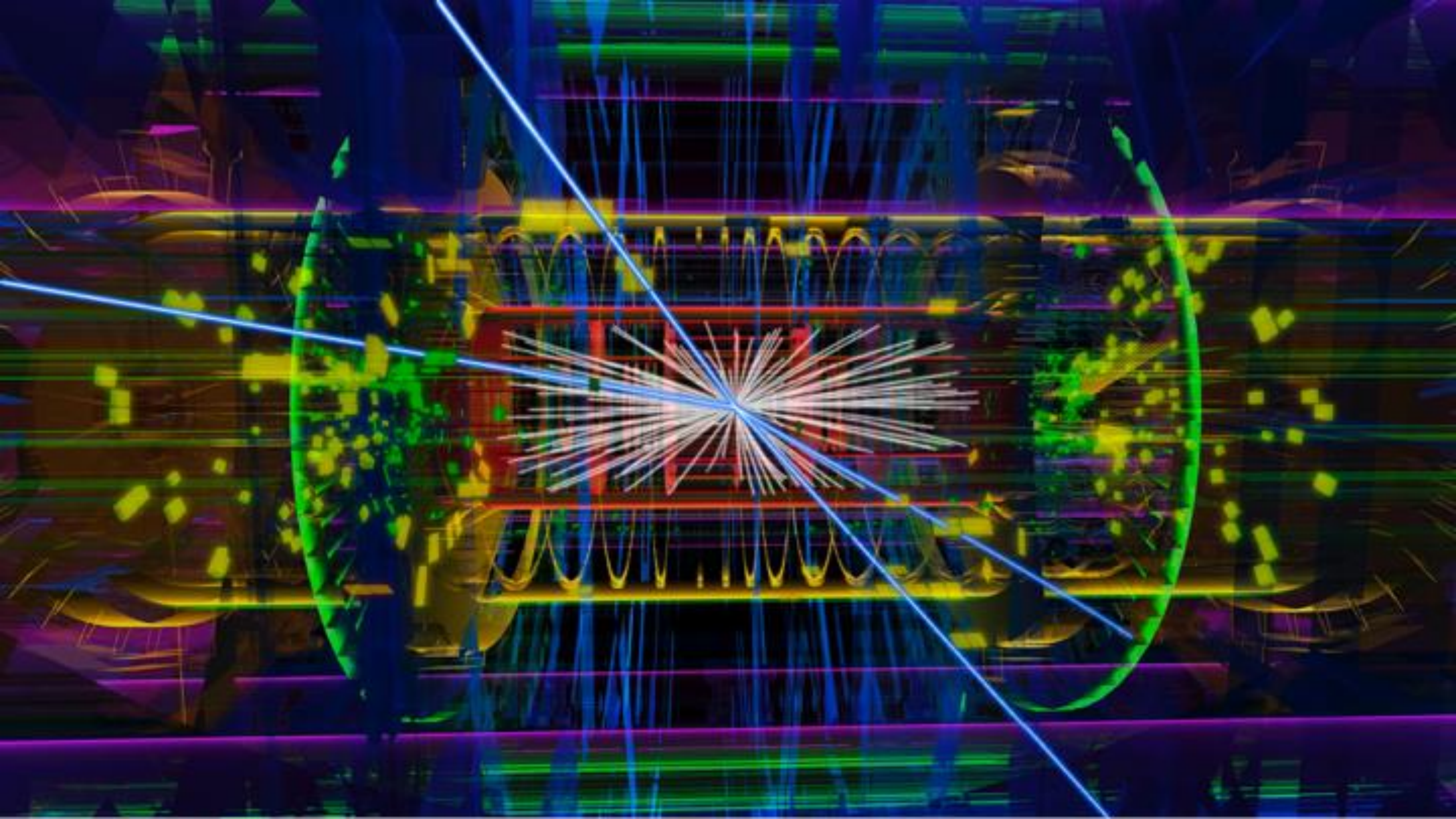
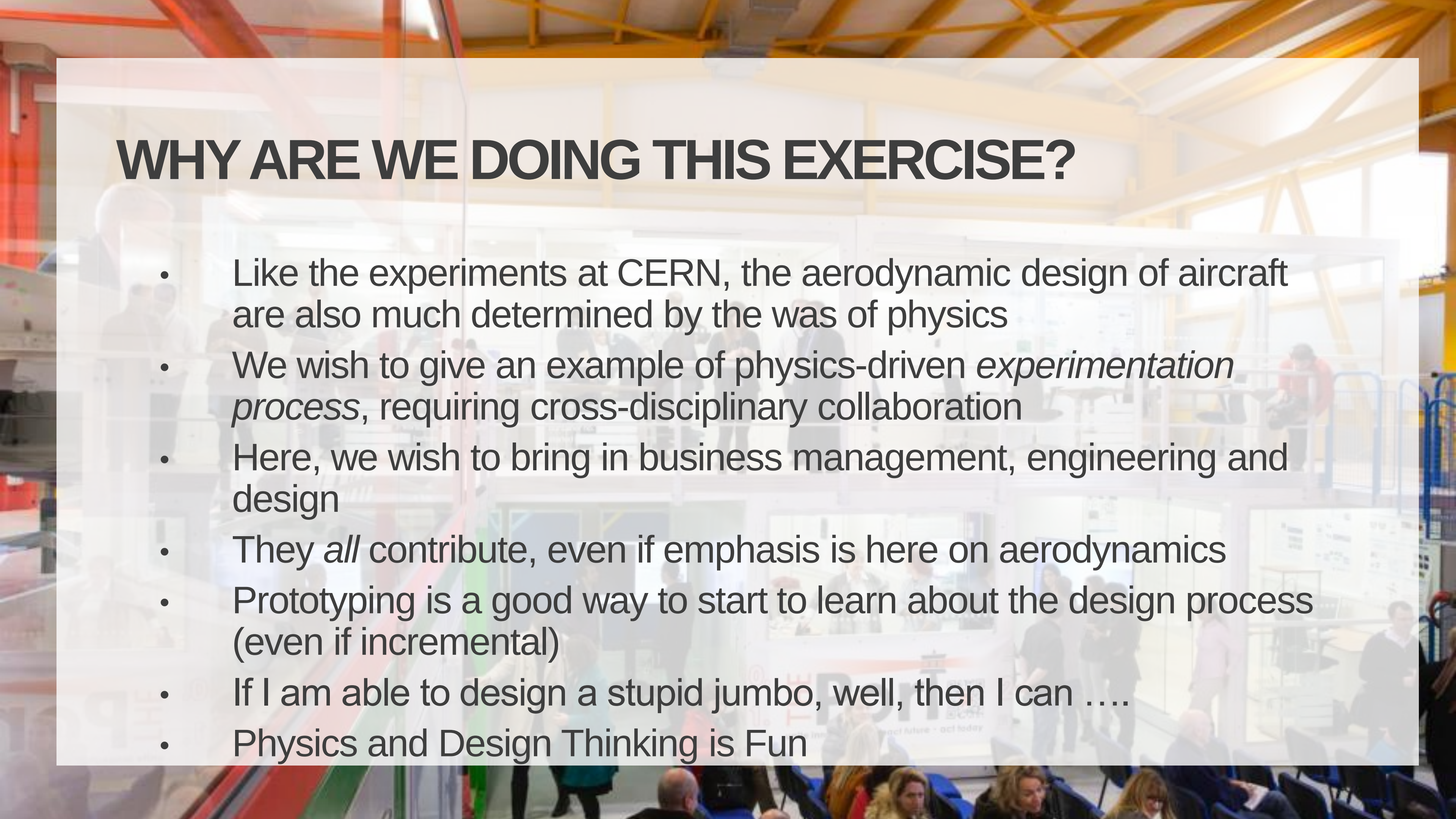
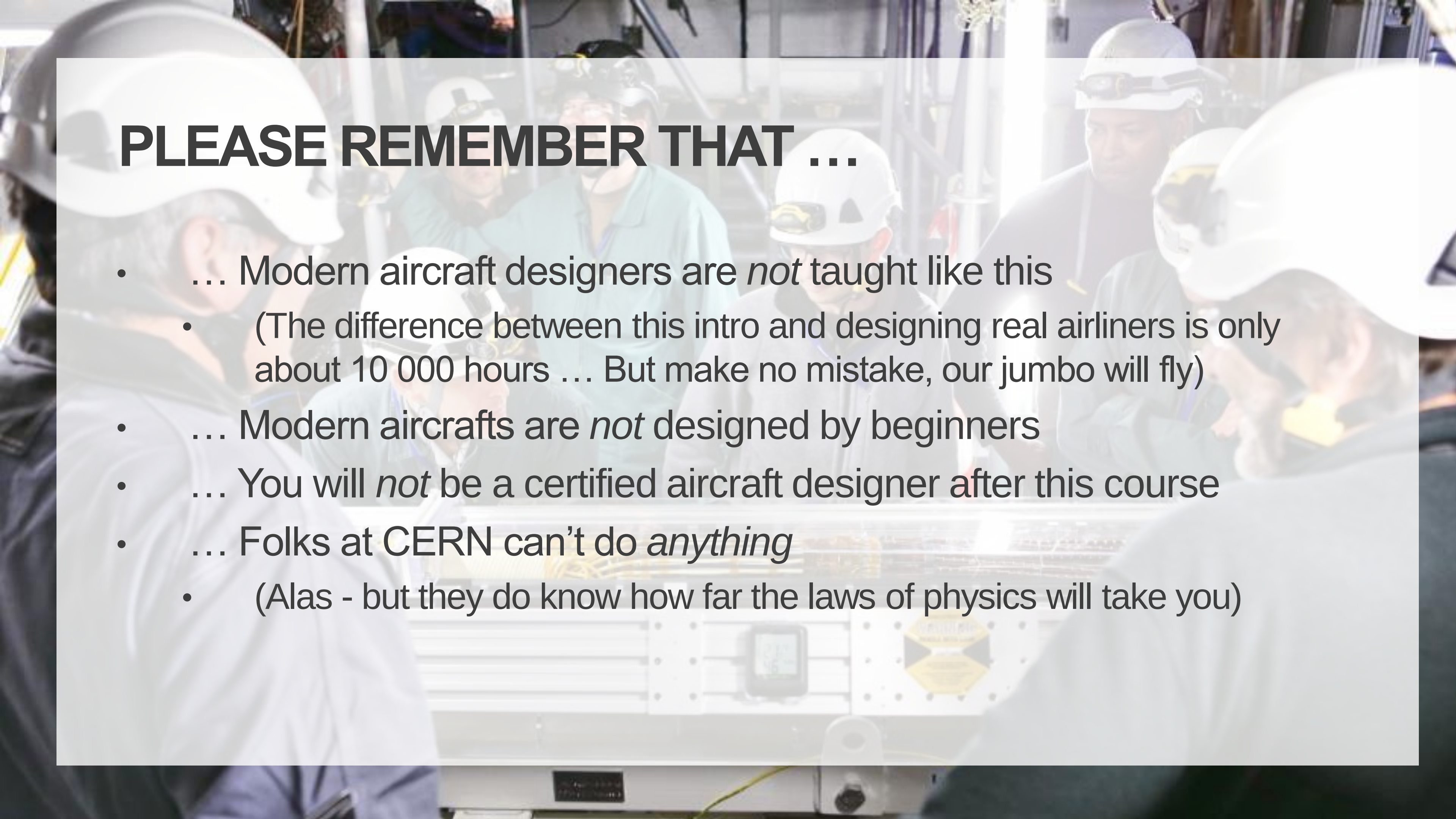




WHY ARE WE DOING THIS EXERCISE?

- Like the experiments at CERN, the aerodynamic design of aircraft are also much determined by the was of physics
- We wish to give an example of physics-driven *experimentation process*, requiring cross-disciplinary collaboration
- Here, we wish to bring in business management, engineering and design
- They *all* contribute, even if emphasis is here on aerodynamics
- Prototyping is a good way to start to learn about the design process (even if incremental)
- If I am able to design a stupid jumbo, well, then I can ….
- Physics and Design Thinking is Fun

PLEASE REMEMBER THAT …

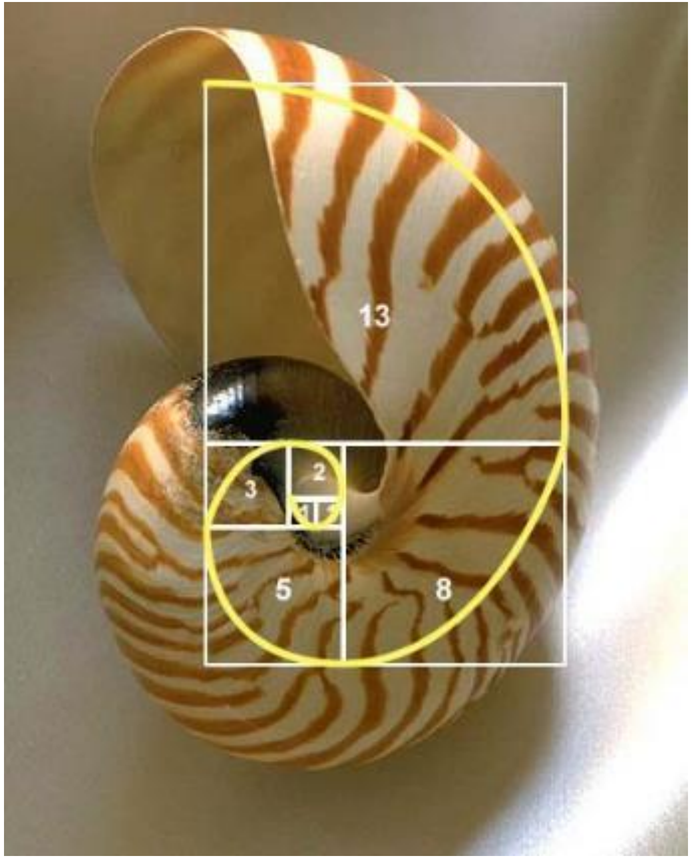


- … Modern aircraft designers are *not* taught like this
  - (The difference between this intro and designing real airliners is only about 10 000 hours … But make no mistake, our jumbo will fly)
- … Modern aircrafts are *not* designed by beginners
- … You will *not* be a certified aircraft designer after this course
- … Folks at CERN can’t do *anything*
  - (Alas - but they do know how far the laws of physics will take you)

WHO DESIGNED THIS?

OR THIS?

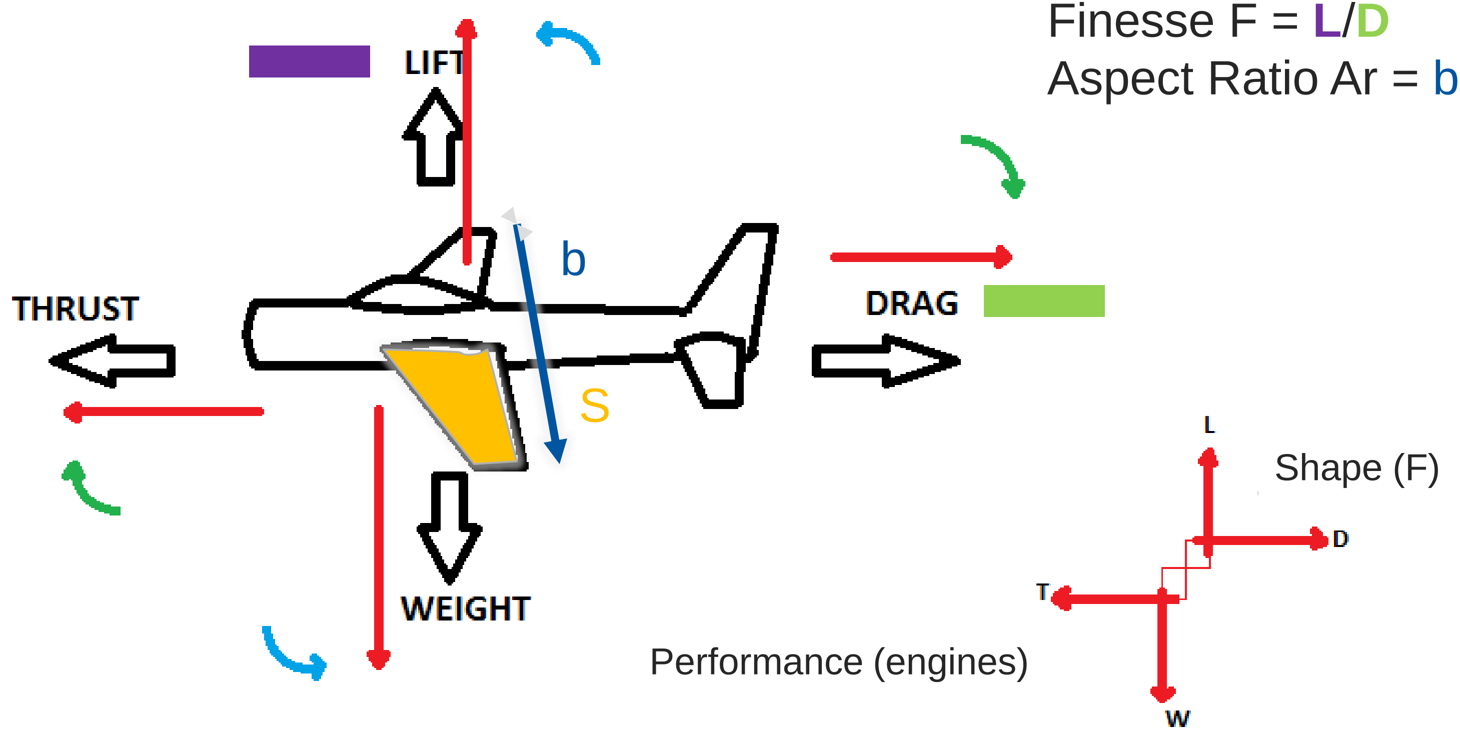
NATURE SEEMS TO KNOW ITS SHAPES WELL



ALL YOU NEED TODAY TO KNOW ABOUT FLYING

Finesse $F = L/D$

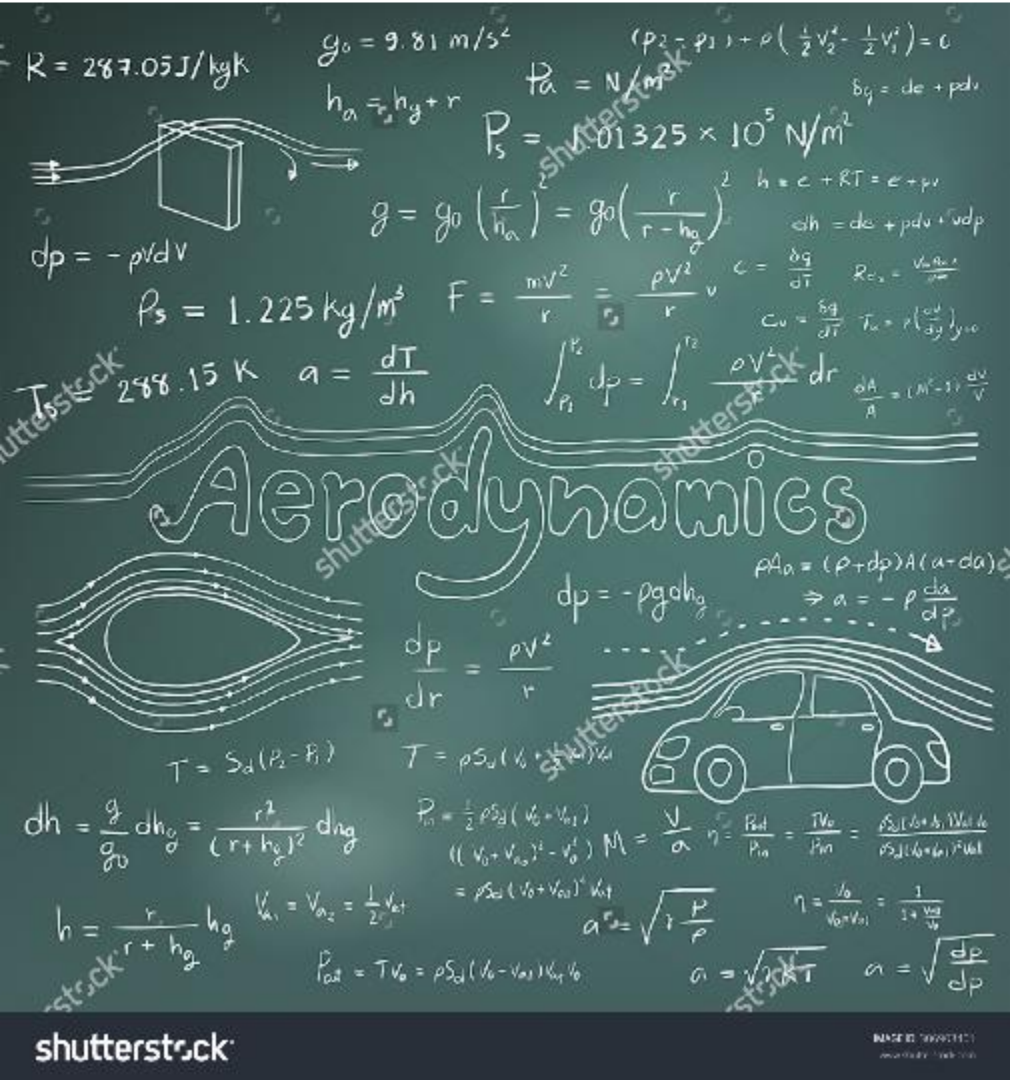
Aspect Ratio $Ar = b^2/S$



Shape (F)

Performance (engines)

codecogs



Well, Almost …

F = ma

or, in terms of pressure

(assuming air ~ fluid)

$W/S \sim 0.3 \times \sigma \times v^2$

Where:

W = weight of the object (N)

S = wing area (m²)

σ = density of air; 1.1 kg/m³ at sea level, 0.4 kg/m³ at 10 km altitude

v = (constant) cruising speed (m/s)

So at low altitudes

$W/S \sim 0.4 \times v^2$

How fast did Daedalus fly?

$$W/S \sim 0.4 \times v^2$$

(at low altitudes)

W = weight of the object (750N)
S = wing area ($2\ m^2$)
v = cruising speed (m/s) ~ 30 m/s = 110 km/h

Did my Uncle Alport's Opel *Really* Fly?

$W/S \sim 0.4 \times v^2$

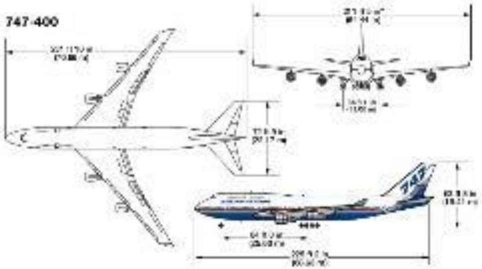
(at low altitudes)

W = weight of the object (8500N)

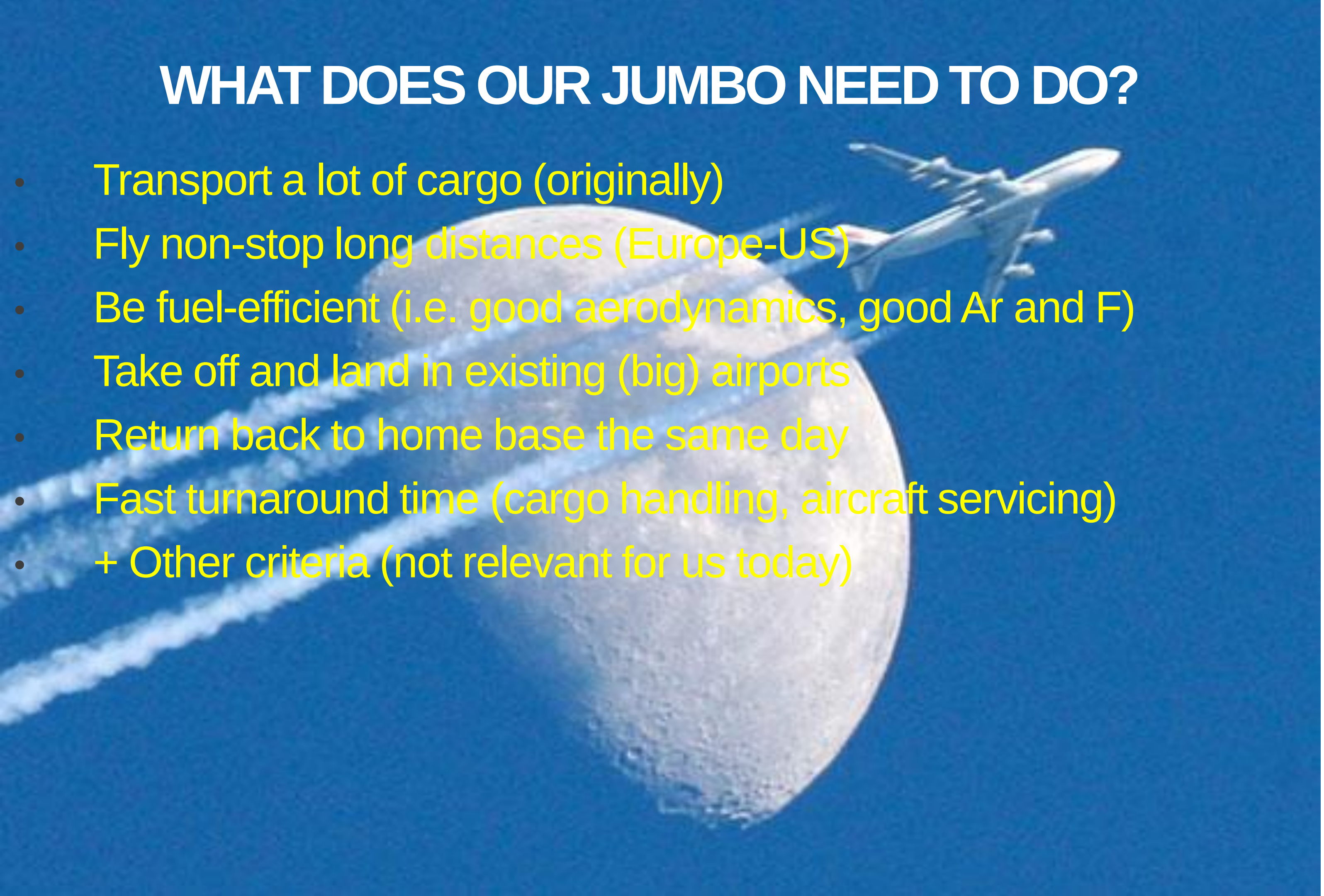
S = wing area (7 m²)

v = cruising speed (m/s) ~ 55 m/s = 200 km/h

LET US START



WHAT DOES OUR JUMBO NEED TO DO?



- Transport a lot of cargo (originally)
- Fly non-stop long distances (Europe-US)
- Be fuel-efficient (i.e. good aerodynamics, good Ar and F)
- Take off and land in existing (big) airports
- Return back to home base the same day
- Fast turnaround time (cargo handling, aircraft servicing)
- + Other criteria (not relevant for us today)

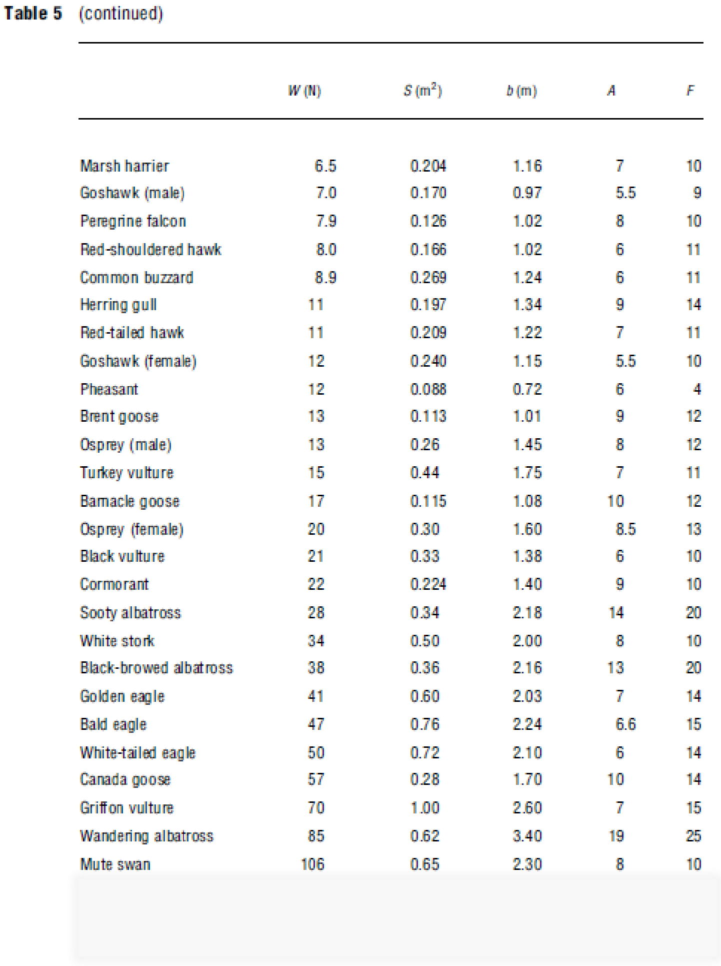


Table 5 (continued)

	W (N)	S (m^2)	b (m)	A	F
Marsh harrier	6.5	0.204	1.16	7	10
Goshawk (male)	7.0	0.170	0.97	5.5	9
Peregrine falcon	7.9	0.126	1.02	8	10
Red-shouldered hawk	8.0	0.166	1.02	6	11
Common buzzard	8.9	0.269	1.24	6	11
Herring gull	11	0.197	1.34	9	14
Red-tailed hawk	11	0.209	1.22	7	11
Goshawk (female)	12	0.240	1.15	5.5	10
Pheasant	12	0.088	0.72	6	4
Brent goose	13	0.113	1.01	9	12
Osprey (male)	13	0.26	1.45	8	12
Turkey vulture	15	0.44	1.75	7	11
Barnacle goose	17	0.115	1.08	10	12
Osprey (female)	20	0.30	1.60	8.5	13
Black vulture	21	0.33	1.38	6	10
Cormorant	22	0.224	1.40	9	10
Sooty albatross	28	0.34	2.18	14	20
White stork	34	0.50	2.00	8	10
Black-browed albatross	38	0.36	2.16	13	20
Golden eagle	41	0.60	2.03	7	14
Bald eagle	47	0.76	2.24	6.6	15
White-tailed eagle	50	0.72	2.10	6	14
Canada goose	57	0.28	1.70	10	14
Griffon vulture	70	1.00	2.60	7	15
Wandering albatross	85	0.62	3.40	19	25
Mute swan	106	0.65	2.30	8	10

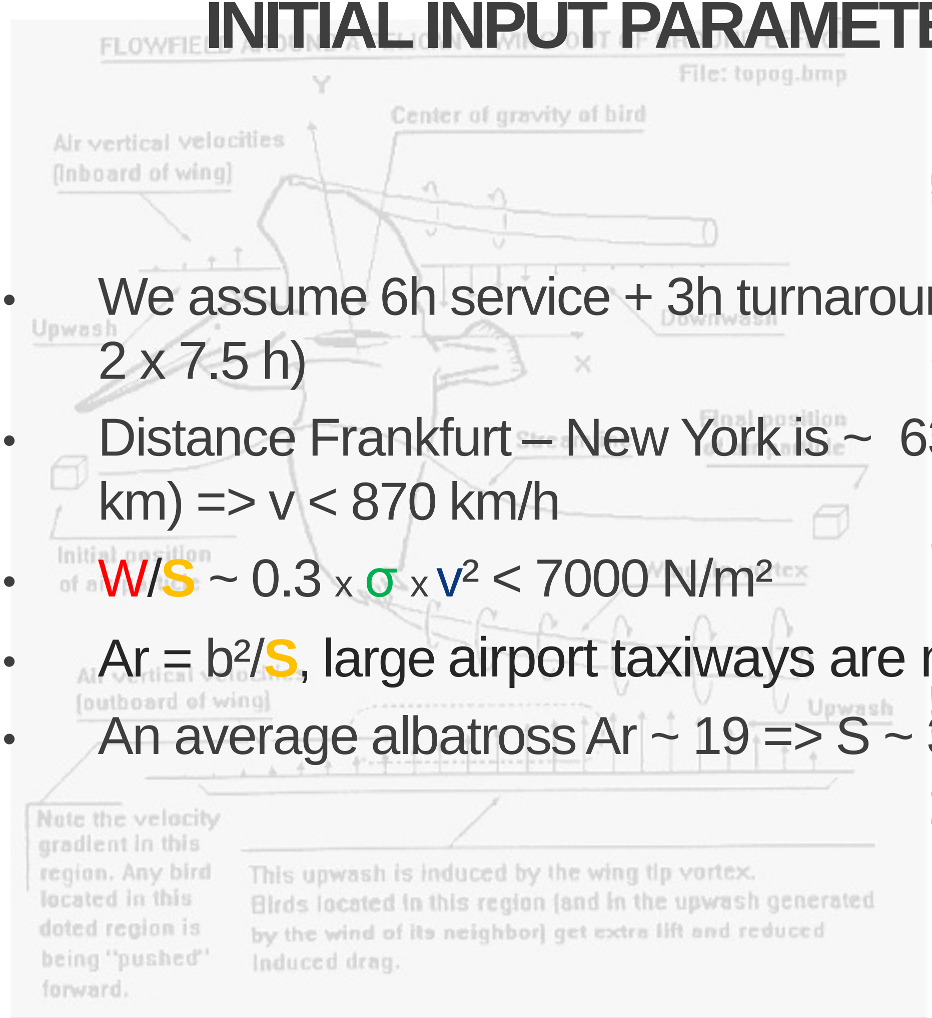
H. Tennekes (2009)

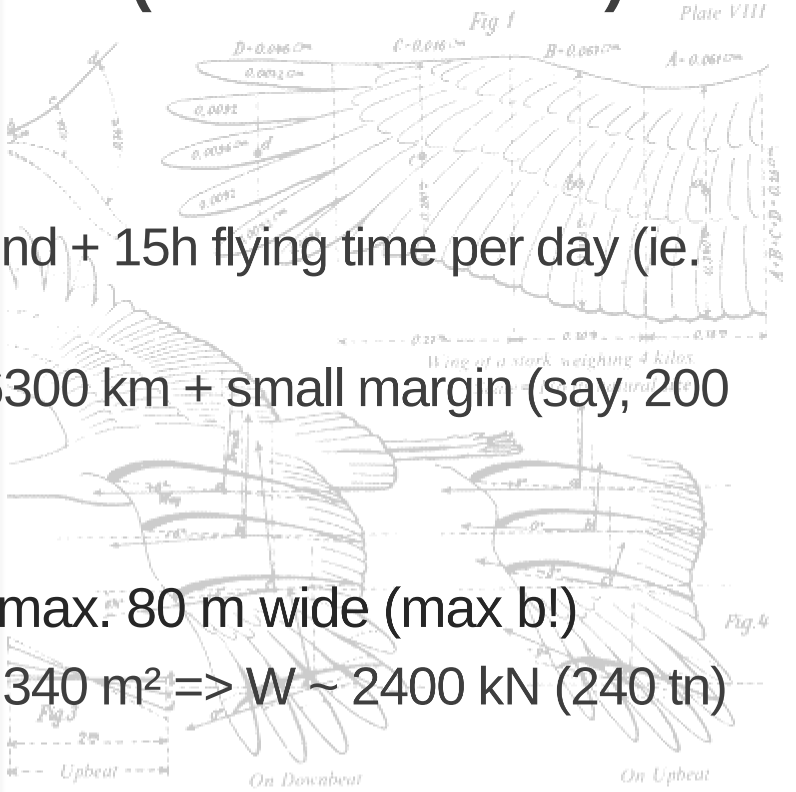
Let us Start with the Aerodynamics

Looking for inspiration from:

- heavy migrating birds
- high Aspect Ratio (Ar) and Finesse (F)

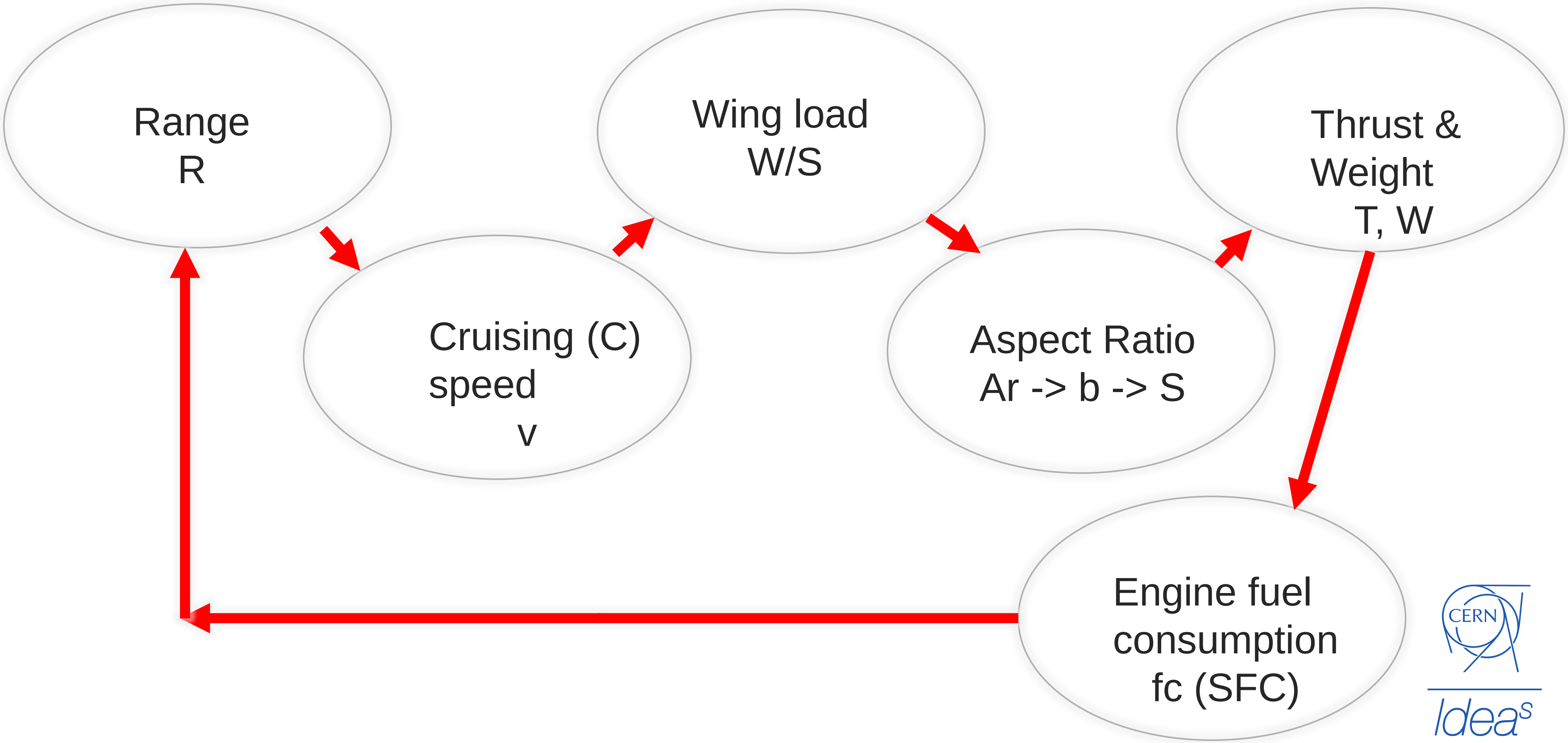
INITIAL INPUT PARAMETERS (ROUGH GUESS)





- We assume 6h service + 3h turnaround + 15h flying time per day (ie. 2 x 7.5 h)
- Distance Frankfurt – New York is ~ 6300 km + small margin (say, 200 km) => $v < 870$ km/h
- $W/S \sim 0.3 \times \sigma \times v^2 < 7000\ \mathrm{N/m^2}$
- $Ar = b^2/S$, large airport taxiways are max. 80 m wide (max b!)
- An average albatross $Ar \sim 19 \Rightarrow S \sim 340\ \mathrm{m^2} \Rightarrow W \sim 2400$ kN (240 tn)

DESIGN CYCLE



Range
R

Cruising (C)
speed
v

Wing load
W/S

Aspect Ratio
Ar -> b -> S

Thrust &
Weight
T, W

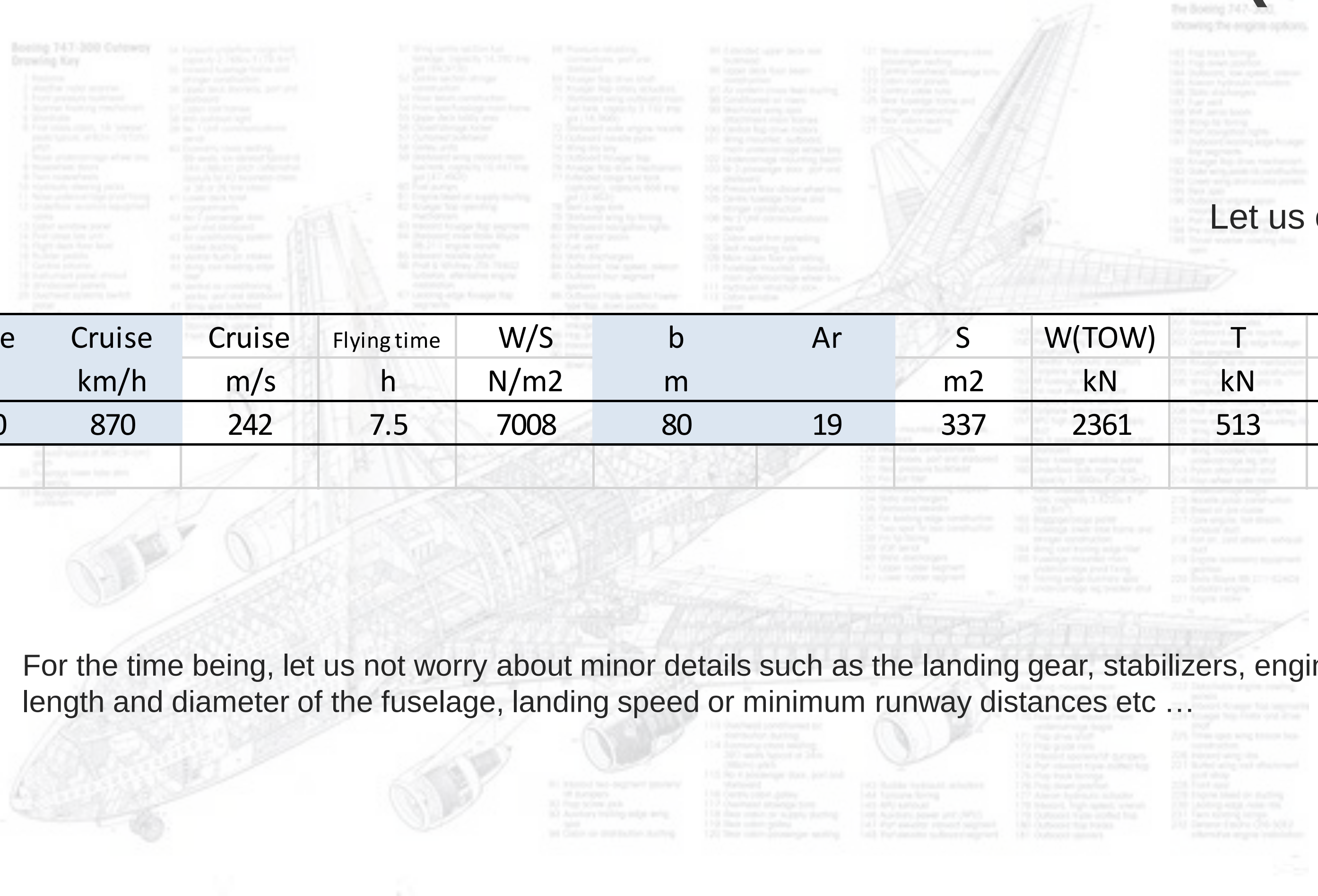
Engine fuel
consumption
fc (SFC)

PERFORMANCE OF CIVIL AIRCRAFTS IN 1960s

Aircraft	Length	b span	S area	TOW	W empty	Thrust	Range R	Cruise	Passangers		TOW/S	Ar	F	TOW/We	TOW/T	R/TOW	b/L	P/TOW	R/C	TOW-We	Fuel cons
	m	m	m2	tn	tn	kN	km	km/h	number of		N/m2								h	tn	tn/h
BAC 111	29	27	91	36	21	92	1340	880	89		3881	8	17	1.7	3.8	37.2	0.9	2.5	1.5	15	9.9
DC-9	32	27	87	41	22	62	1831	910	109		4623	8	17	1.9	6.5	44.7	0.8	2.7	2.0	19	9.4
F-28	27	24	76	29	17	88	2000	850	65		3743	8	17	1.7	3.2	69.0	0.9	2.2	2.4	12	5.1
Trident HS 121	35	27	126	49	30	138	2170	935	101		3815	6	14	1.6	3.5	44.3	0.8	2.1	2.3	19	8.2
Convair 990	43	37	209	112	51	284	5780	1000	149		5257	7	15	2.2	3.9	51.6	0.9	1.3	5.8	61	10.6
Boeing 720	41	40	234	101	47	212	6820	1000	149		4234	7	16	2.1	4.7	67.5	1.0	1.5	6.8	54	7.9
Boeing 707	44	40	283	112	50	200	6940	915	110		3882	6	14	2.2	5.5	62.0	0.9	1.0	7.6	62	8.2
DC-8	46	43	253	124	75	160	7530	870	140		4808	7	16	1.7	7.6	60.7	0.9	1.1	8.7	49	5.7
VC-10	48	45	265	152	63	402	9400	930	151		5627	8	17	2.4	3.7	61.8	0.9	1.0	10.1	89	8.8
IL 62M	53	43	280	165	72	432	10000	900	180		5781	7	15	2.3	3.7	60.6	0.8	1.1	11.1	93	8.4
										average	4565	7.0	16	2.0	4.6	55.9	0.9	1.6	5.8		8.2

Wikipedia

OUTPUT JUMBO PARAMETERS (1st CYCLE)

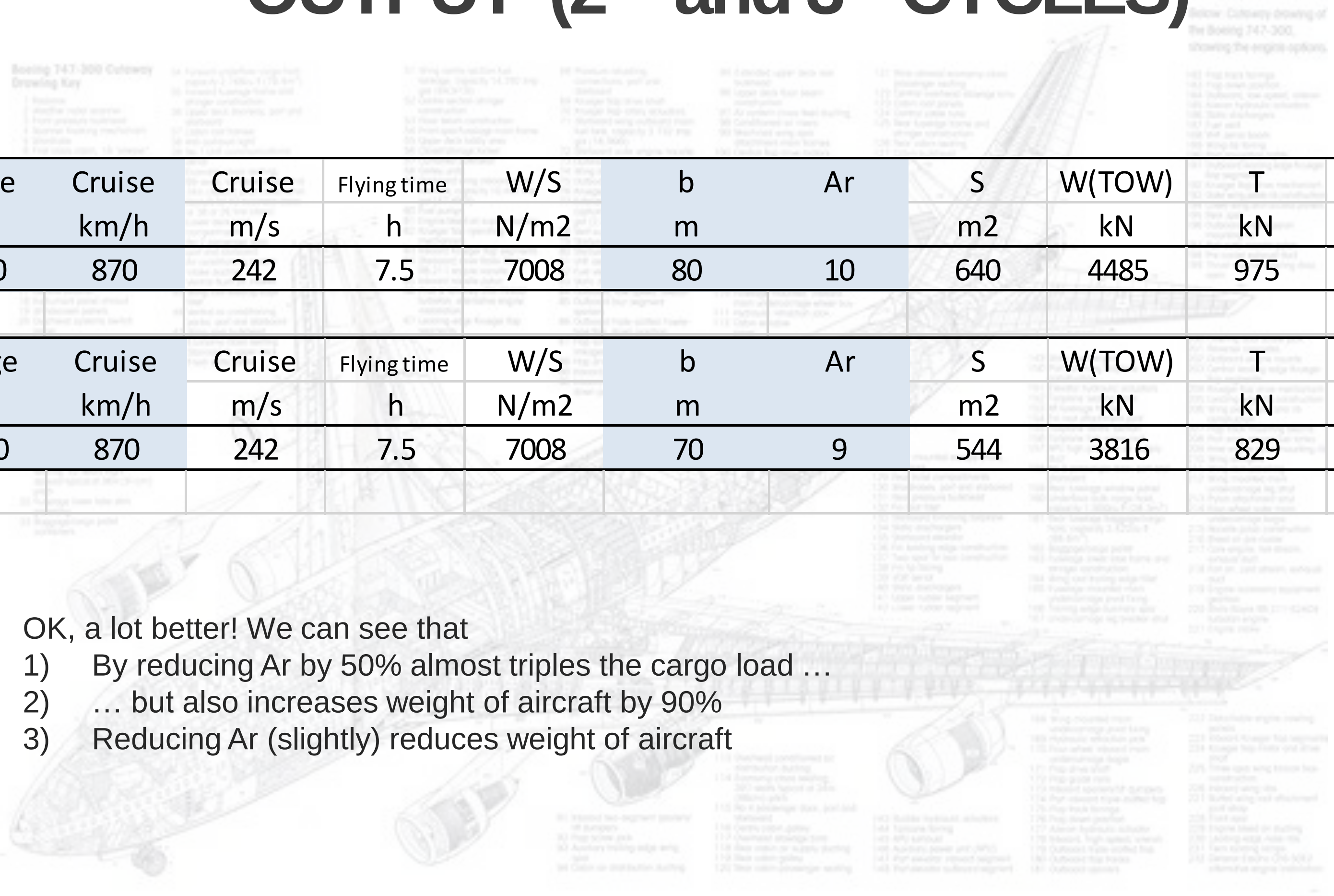


Let us optimize on Cargo

Range	Cruise	Cruise	Flying time	W/S	b	Ar	S	W(TOW)	T	Load	Min. fuel	Cargo
km	km/h	m/s	h	N/m2	m		m2	kN	kN	tn	tn	tn
6500	870	242	7.5	7008	80	19	337	2361	513	118	61	57
											ass. 8.2tn/h	

For the time being, let us not worry about minor details such as the landing gear, stabilizers, engine nacelles, or the length and diameter of the fuselage, landing speed or minimum runway distances etc …

OUTPUT (2nd and 3rd CYCLES)



Range	Cruise	Cruise	Flying time	W/S	b	Ar	S	W(TOW)	T	Load	Min. fuel	Cargo
km	km/h	m/s	h	N/m2	m		m2	kN	kN	tn	tn	tn
6500	870	242	7.5	7008	80	10	640	4485	975	224	61	163
											ass. 8.2tn/h	

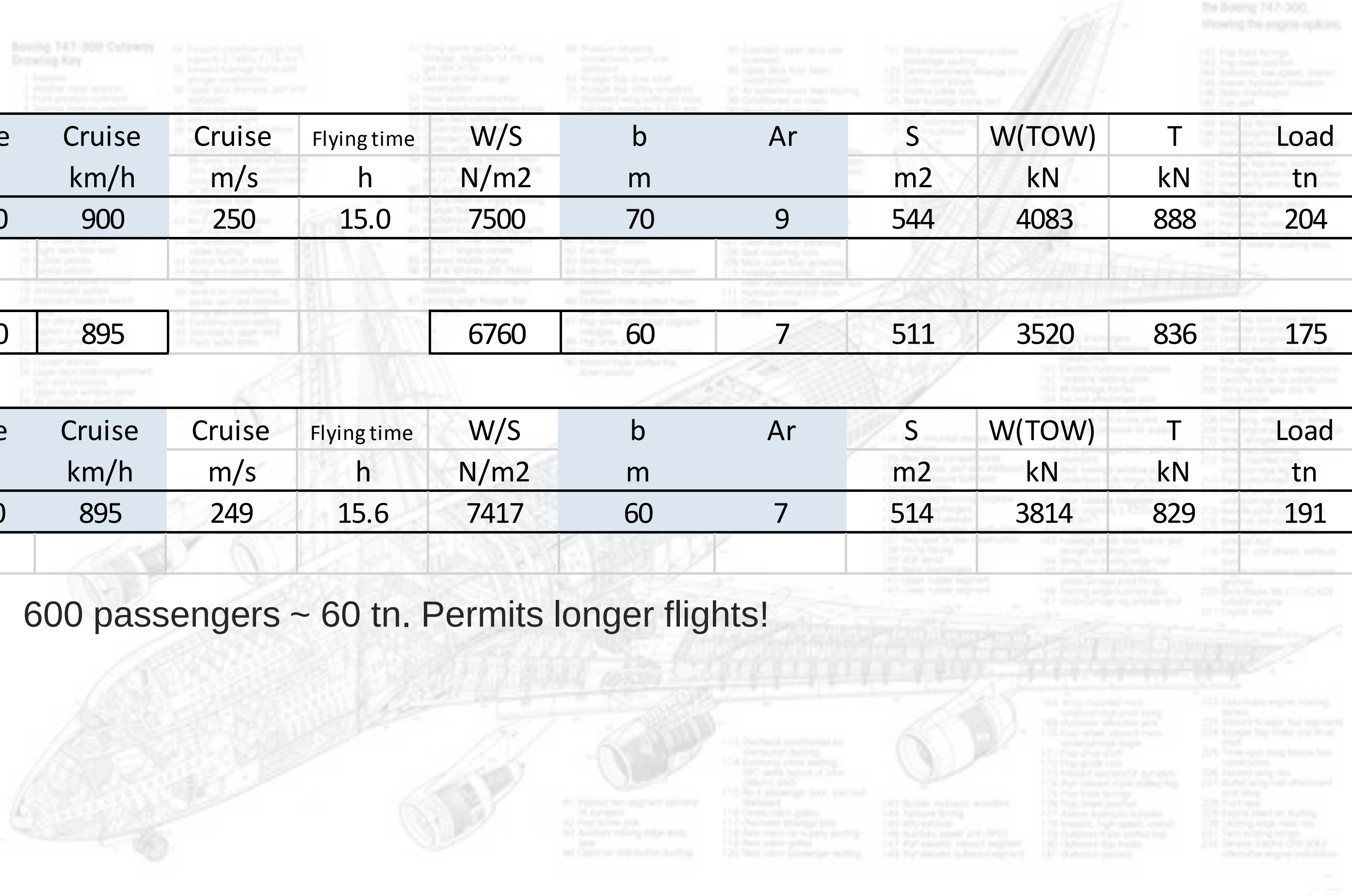
Range	Cruise	Cruise	Flying time	W/S	b	Ar	S	W(TOW)	T	Load	Min. fuel	Cargo
km	km/h	m/s	h	N/m2	m		m2	kN	kN	tn	tn	tn
6500	870	242	7.5	7008	70	9	544	3816	829	191	61	130
											ass. 8.2tn/h	

OK, a lot better! We can see that

1) By reducing Ar by 50% almost triples the cargo load …
2) … but also increases weight of aircraft by 90%
3) Reducing Ar (slightly) reduces weight of aircraft

SO CONGRATULATIONS …

… BUT WHAT IF WE FLY PEOPLE TOO?

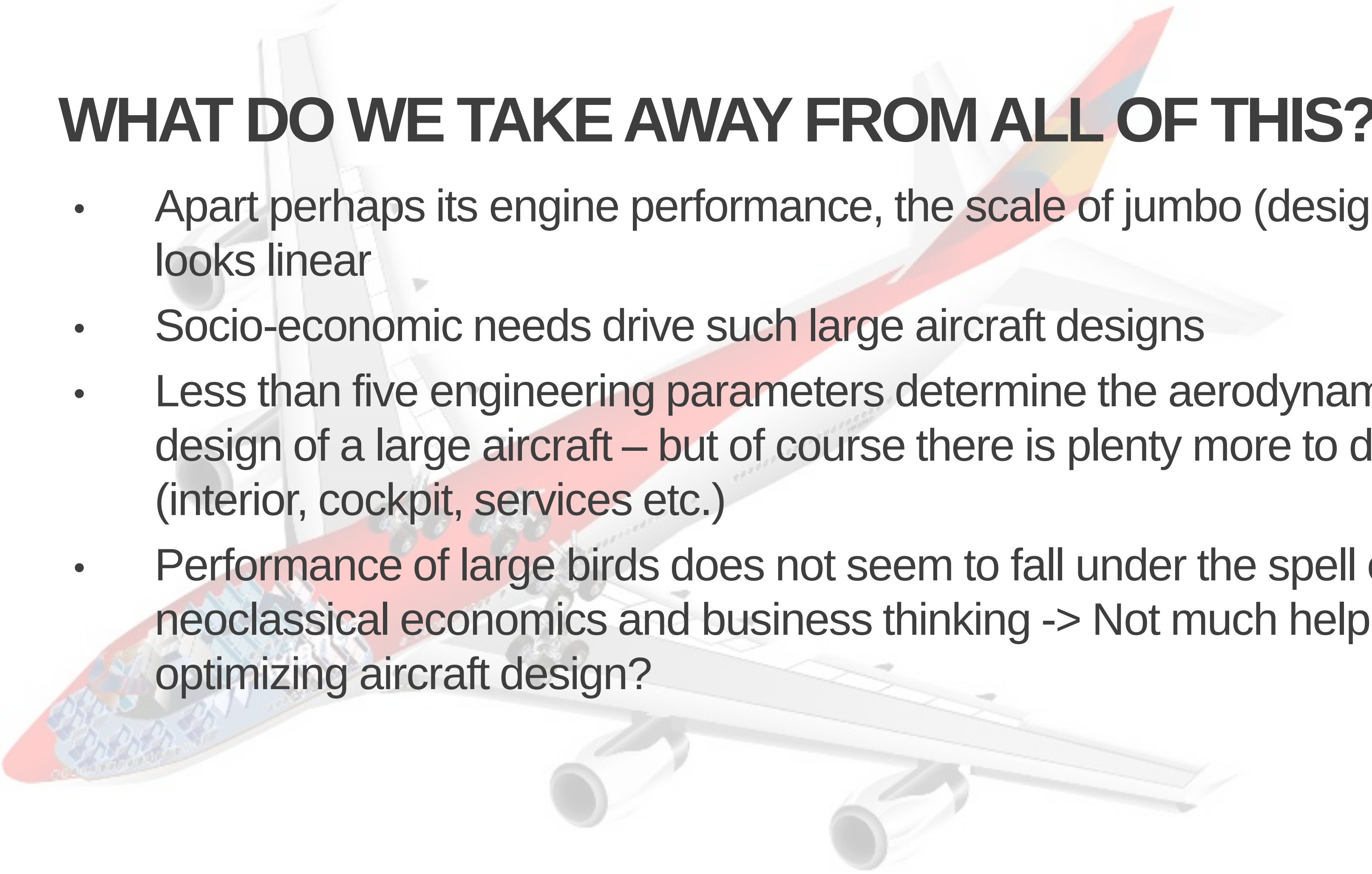


Range	Cruise	Cruise	Flying time	W/S	b	Ar	S	W(TOW)	T	Load	Min. fuel	Cargo	Passang.
km	km/h	m/s	h	N/m2	m		m2	kN	kN	tn	tn	tn	tn
13500	900	250	15.0	7500	70	9	544	4083	888	204	123	21	60
											ass. 8.2tn/h		
14000	895			6760	60	7	511	3520	836	175			39

Range	Cruise	Cruise	Flying time	W/S	b	Ar	S	W(TOW)	T	Load	Min. fuel	Cargo	Passang.
km	km/h	m/s	h	N/m2	m		m2	kN	kN	tn	tn	tn	tn
14000	895	249	15.6	7417	60	7	514	3814	829	191	128	23	39
											ass. 8.2tn/h		

600 passengers ~ 60 tn. Permits longer flights!

WHAT DO WE TAKE AWAY FROM ALL OF THIS?



- Apart perhaps its engine performance, the scale of jumbo (design) looks linear
- Socio-economic needs drive such large aircraft designs
- Less than five engineering parameters determine the aerodynamic design of a large aircraft – but of course there is plenty more to design (interior, cockpit, services etc.)
- Performance of large birds does not seem to fall under the spell of neoclassical economics and business thinking -> Not much help in optimizing aircraft design?

THANK YOU

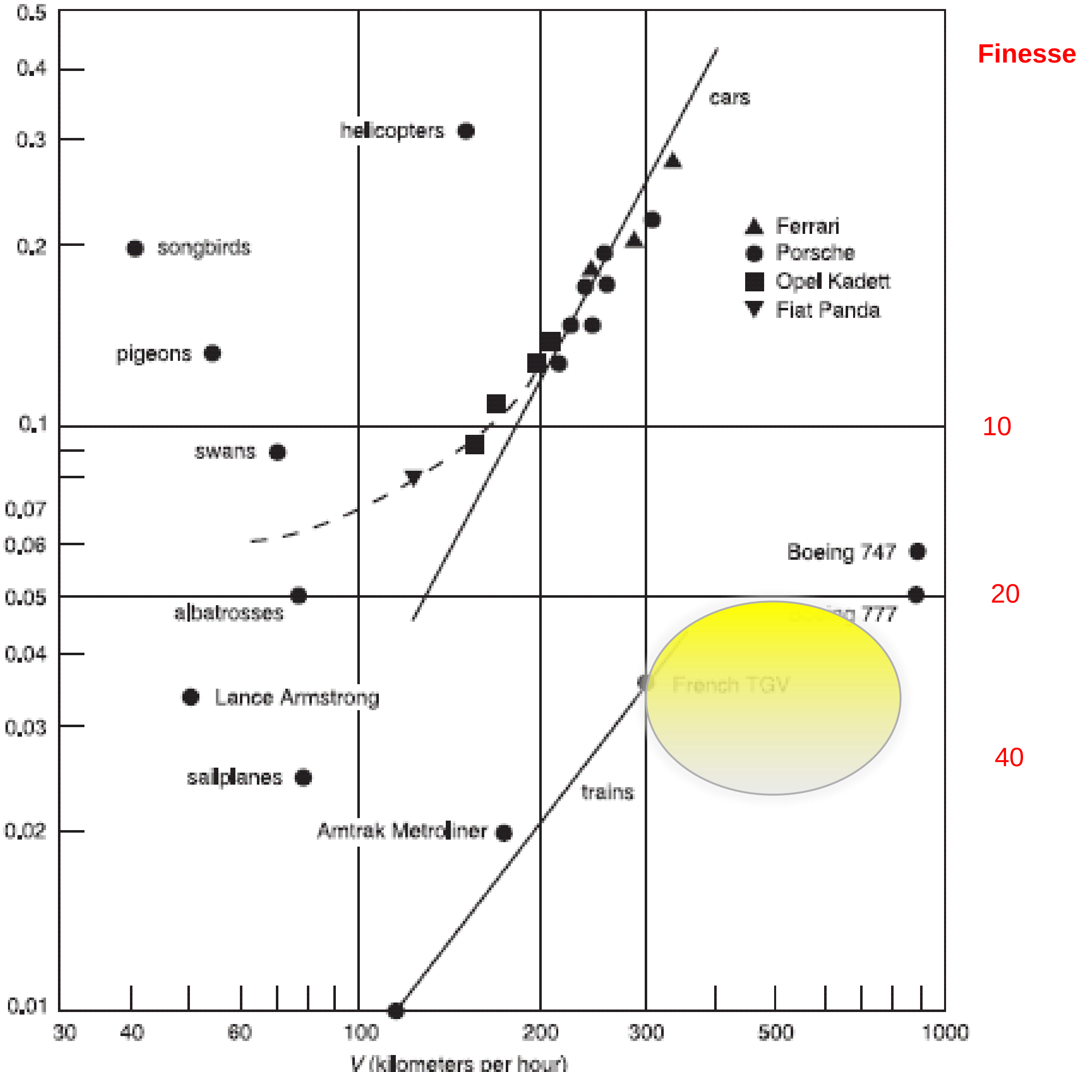
Questions? Comments?

Contact information:

Email: markus.nordberg@cern.ch

Skype: phone-markus

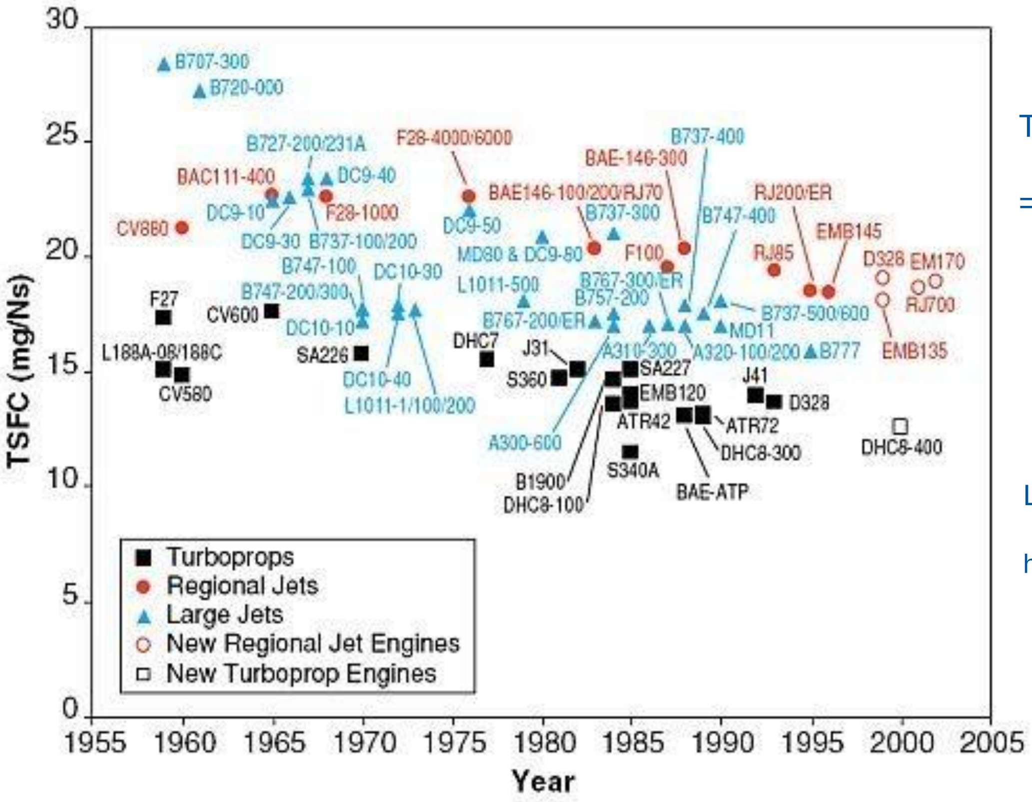
ASSIGNMENT



Please design a passenger aircraft that fulfills the following needs:

- Highly economical to fly (F higher than 20)
- Cruising speed less than current large jets (but above TGV)
- Can land and take off from existing airports or fields
- Integral element of a new, compelling business model
- Its appearance is perceived as unique or distinctive in the market

EVOLUTION OF JET ENGINE (FUEL CONSUMPTION)



Source MIT: Raffi Babikian, Stephen P. Lukachko and Ian A. Waitz

Figure 3: Improvements in TSFC for different aircraft types at cruise.

To obtain fuel consumption in tn/h,

= (TSFC x Thrust (kN) x 3600)/100’000

List of engines

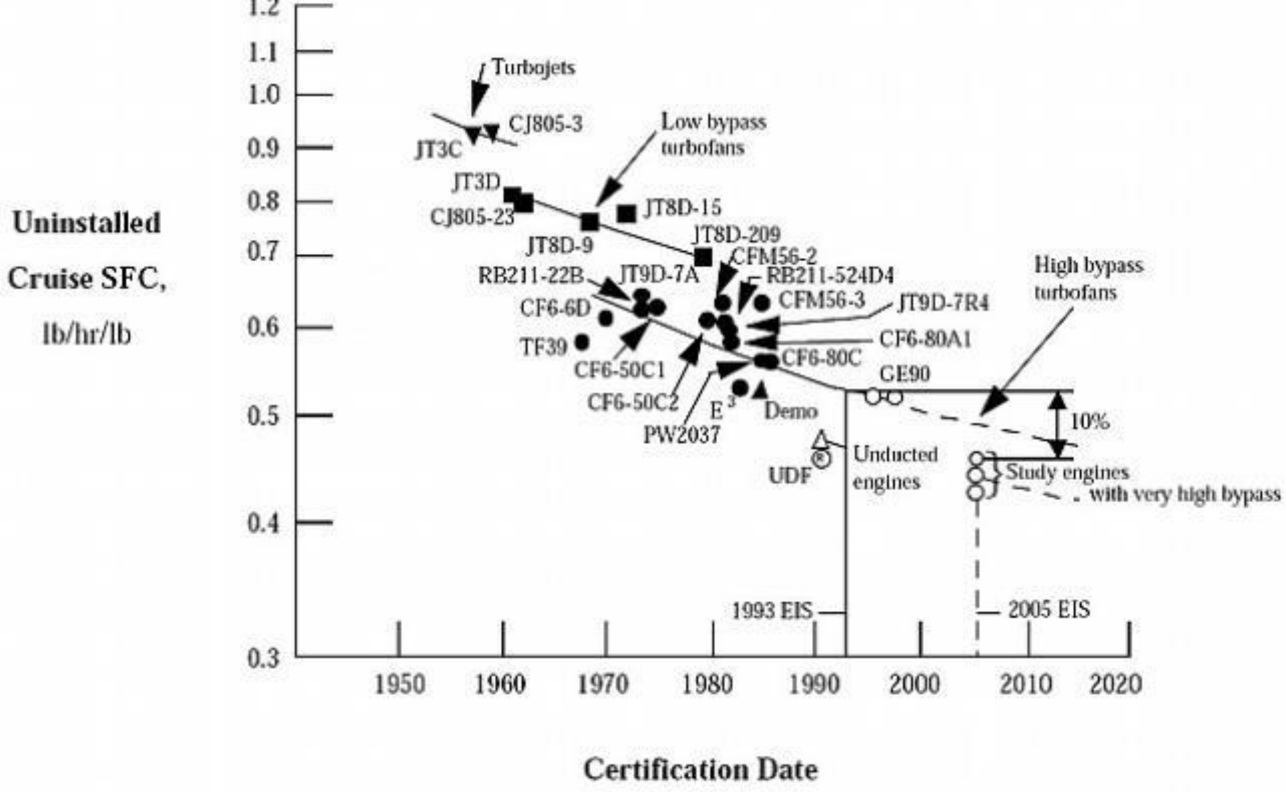
https://en.wikipedia.org/wiki/List_of_aircraft_engines

PPRuNe Forum

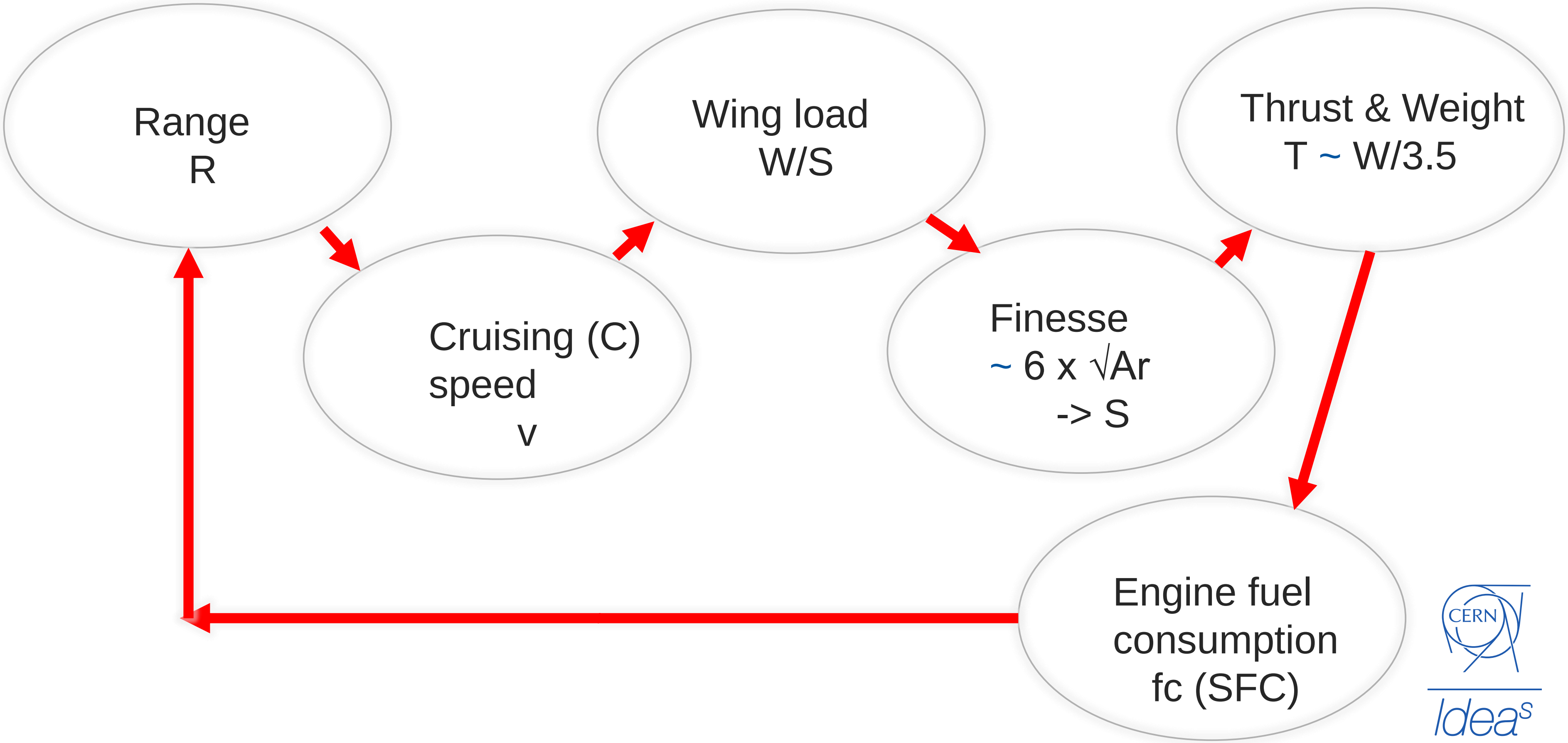
State-of-the-Art Subsonic Engine SFC

35,000 ft., 0.8M, Standard Day

To obtain fuel consumption in mg/Ns, multiply by 28



DESIGN CYCLE



Range
R

Cruising (C)
speed
v

Wing load
W/S

Finesse
~ 6 x √Ar
-> S

Thrust & Weight
T ~ W/3.5

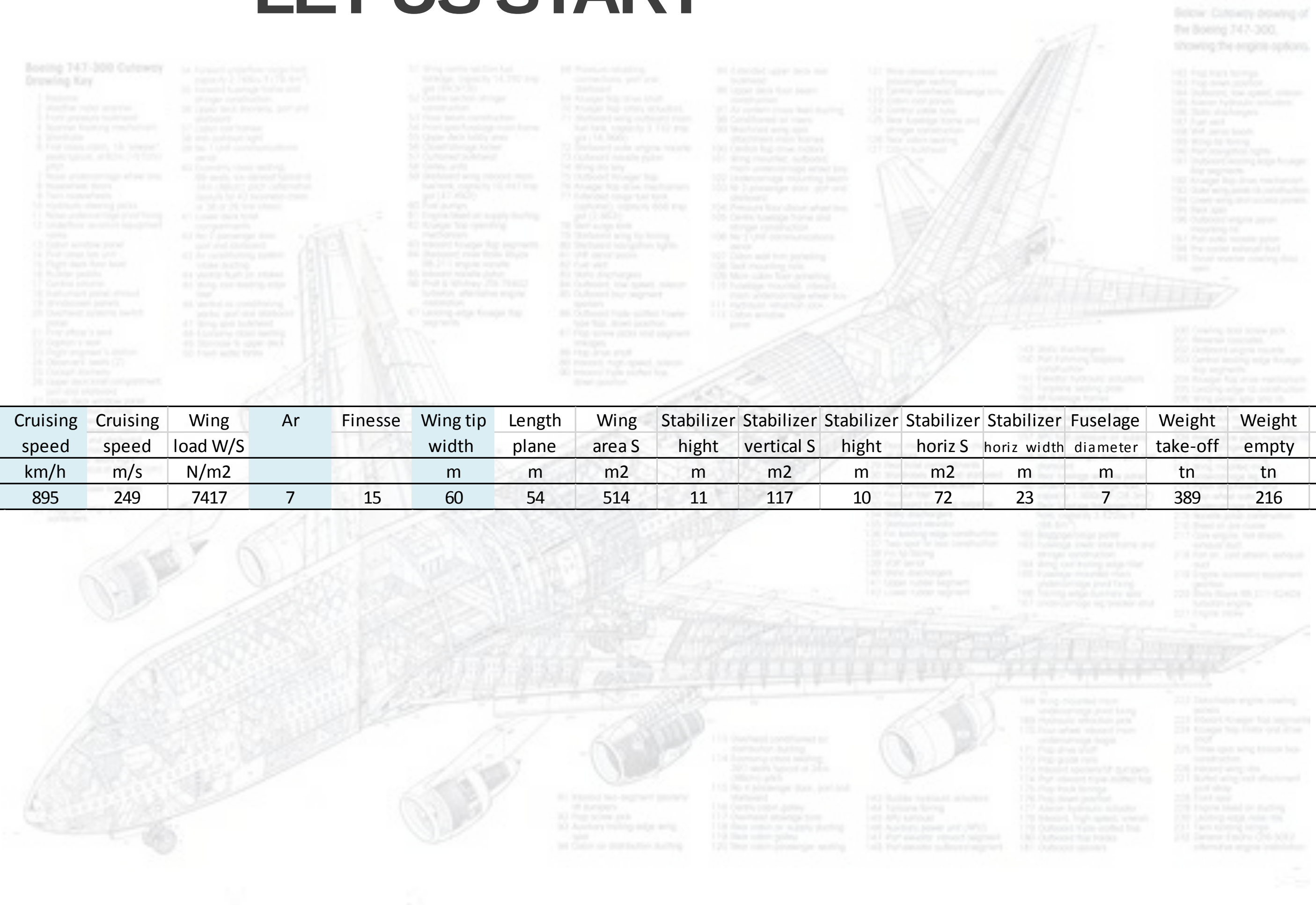
Engine fuel
consumption
fc (SFC)

DESIGN PARAMETERS OF MODERN CIVIL JETS

	W			S	b	F=L/D	sb		T		height	r		
Aircraft	**TOW**	**Empty**	**Seats s**	**Wing area**	**Wing span**	**Finesse**	**Sweepback**	**Length**	**Thrust**	**Fuselage**	**Fuselage**	**Runway**	**Vmax**	**Range**
	tons	tons		m2	m		degrees	m	kN	ratio	diameter	m	m/s	km
												MTOW	FL350	
Airbus 380-800	560	277	550	845	80	16	32.5	80	1424	1.17	8.4	2950	283	15700
Boeing 747-8	440	215	470	570	69	16	37.5	76	1185	1.2	7.8	3100	274	14200
Boeing 747-400	395	250	421	524	65	16	37.5	71	1008	1.2	7.8	3100	274	14000
Airbus 340-600	368	178	380	439	63		30	75	997	1.0	5.6	3100	254	14300
Boeing 747-200	352	178	387	511	60	16	25	71	836	1.07	7.8	3100	274	14000
Boeing 777-300ER	351	168	365	435	65	20	31.6	65	1026	1.0	6.2	3000	264	14600
Airbus 350-1000	308	220	400	460	65		32	74	861	1.02	6.1	2500	263	14800
Boeing 777-200ER	297	145	305	428	61		32	64	834	1.00	6.2	2800	263	14600
Airbus 350-900	265	192	314	443	64		32	74	775	1.02	6.1	2500	263	14500
MD DC-10-30	260	110	285	368	50	18	35	52	680	1.0	6.0	2800	273	10500
Boeing 787-9	245	181	250	370	60	20	32.3	63	610	1.03	6.0	2900	265	15700
Boeing 767-300	172	86	224	283	48		31.5	55	516	1.08	5.4	2500	254	7800
Concorde	185	100	100	358	26	7	70	62	679	1.15	3.3	3600	605	7200
Boeing 707-320B	151	90	190	283	44	19	35	47	326	1.05	3.8	3200	281	6900
Boeing 757-300	124	65	260	181	38	12	25	54	381	1.0	3.9	2300	237	6600
Space Shuttle	80	NA	8	250	24	5		37	7000			2100	NA	NA
Boeing 737-900	85	45	180	125	35	15	25	42	243	1.07	4.0	2500	243	4300
Airbus 320	74	43	150	123	34	17	25	38	235	1.05	4.1	2100	242	5900
Boeing 737-700	70	45	140	125	34	15	25	42	233	1.07	4.0	2500	243	4300
MD DC-9-50	55	28	130	93	28	17		41	142	1.09	3.6	2100	249	3300
Boeing 737-200	52	32	110	91	28	16	25	31	167	1.07	4.0	2000	243	4300
Fokker 100	43	24	107	93	28		17	36	131	1.0	3.3	1600	236	3100
Avro RJ100	42	24	110	77	26		15	29	124	1.0	3.5	1200	213	2900
Bombardier CL600	24		50	55	21		25	21	80			2000	242	5900
Embraer ERJ145	21	18	50	51	20		23	30	65	1.0	2.3	1030	236	2800

Wikipedia

LET US START



Range	Cruising speed	Cruising speed	Wing load W/S	Ar	Finesse	Wing tip width	Length plane	Wing area S	Stabilizer hight	Stabilizer vertical S	Stabilizer hight	Stabilizer horiz S	Stabilizer horiz width	Fuselage diameter	Weight take-off	Weight empty	Thrust total	Passeng. seats	Load for fuel&cargo	Minimum cargo	Max. fuel consumpt
km	km/h	m/s	N/m2			m	m	m2	m	m2	m	m2	m	m	tn	tn	N		tn	tn	tn/hr
14000	895	249	7417	7	15	60	54	514	11	117	10	72	23	7	389	216	1090	390	350	140	14

BE INSPIRED BY NATURE AND PHYSICS…

… BUT LET’s NOT GET TOO CARRIED AWAY


N746UW


Nils Holgerson Lines
AIRBUS


A390


A380
AIRBUS
A380
FreakingNews.com