ENVIRONMENTAL IMPACT OF AIRCRAFT ENGINES
D. Lentini, a.a. 2018/19
1. INTRODUCTION

- **TEXTBOOK:**

– **LECTURE NOTES 2018/19 (in Italian)**
– **PRESENTATION 2018/19 (in English)**
→ **dma.dima.uniroma1.it:8080/STAFF2/lentini.html (under *Lecture Notes*)**
→ **or site CAD Aerospaziale**

- **diego.lentini@uniroma1.it, tel. 0644585281**
- **REGISTER ON THE LIST**

LECTURES:	**Monday**	**11:00–12:00**	**hall 10**
	Tuesday	**08:30–10:00**	**hall 10**
	Friday	**08:30–10:00**	**hall 16**

OFFICE HOURS:	**Tuesday**	**14–16**	**Dip. Ing. Mecc. Aerosp. Area Propulsione (cloister)**
[check website]	**Friday**	**14–16**	

- **EXAM: <u>WRITTEN TEST</u> (QUESTIONS LISTED ON WEBSITE) + <u>DISCUSSION</u>**
- **<u>REVIEW</u>: AEROSPACE PROPULSION**

1.2 EMISSIONS

- **CHEMICAL:**
  - **POLLUTANTS: NO_x, SO_x, *soot*, CO, UHC (*Unburned HydroCarbons*)**
  - **CONTAMINANTS: CO_2, N_2O, H_2O**

  AVIATION SHARE OF GLOBAL FUEL CONSUMPTION ONLY 3,5% (THOUGH ON THE RISE), BUT... AIRCRAFTS FLY AT HIGH ALTITUDE

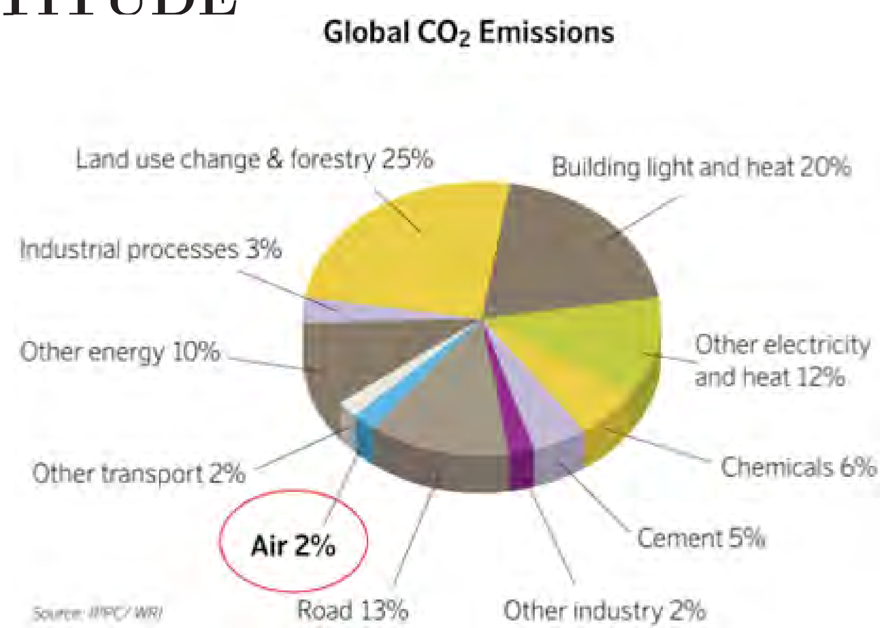


Figure 1: Contributors to CO_2 emissions.

- **NOISE:**
  - **FROM ENGINES**
  - **FROM AIRFRAME**
    (→ course title somewhat restrictive)

1.3 ALTITUDE DISTRIBUTION

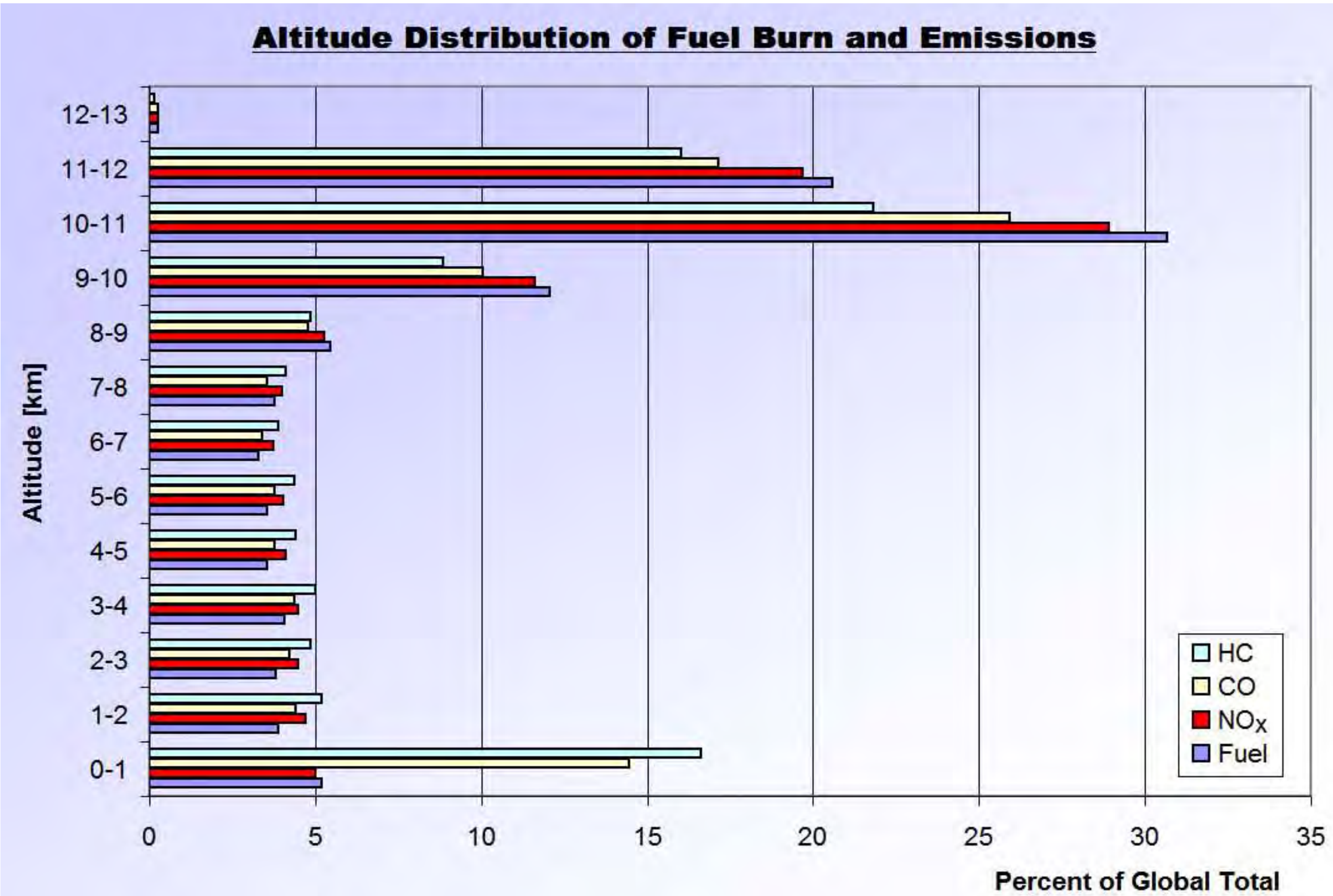
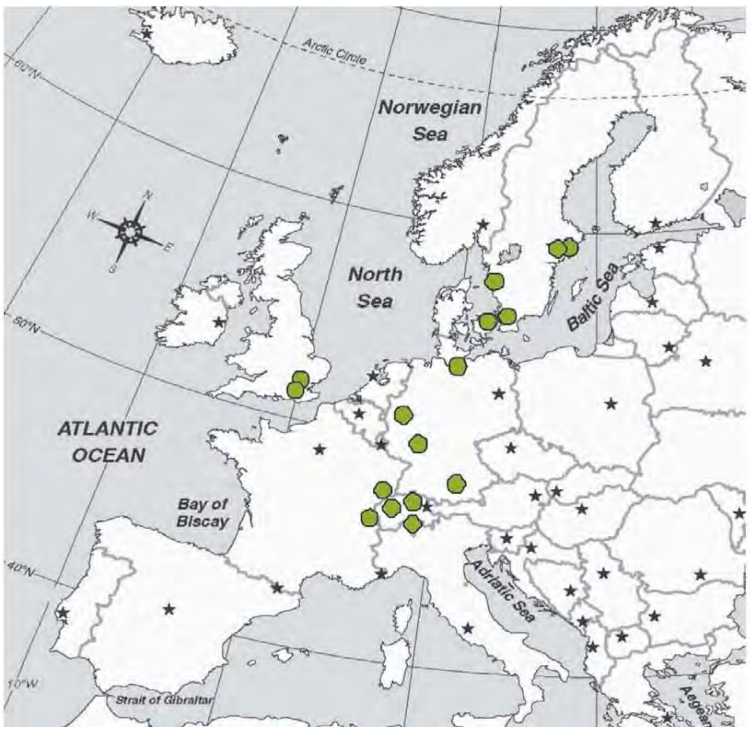


Figure 2: Altitude distribution of aircraft fuel burn and emissions.

1.4 EMISSION STANDARDS

1. **INITIALLY ENFORCED BY FAA IN USA (FAR), JAA IN EUROPE, THEN MERGED IN ANNEX 16 OF ICAO STANDARDS**
2. **FURTHER, LOCAL RESTRICTIONS**



3. **STANDARDS INCREASINGLY STRINGENT AS YEARS GO BY**
4. **ARE GAINING THE ROLE OF CONTROLLING FACTORS IN THE DEVELOPMENT OF NEW ENGINES AND AIRCRAFTS**
5. **ECONOMIC CONCERN TOO (e.g., AIRPORT NIGHT CURFEW, LOCAL TAXES)**

1.5 EXAMPLE: NOISE STANDARDS

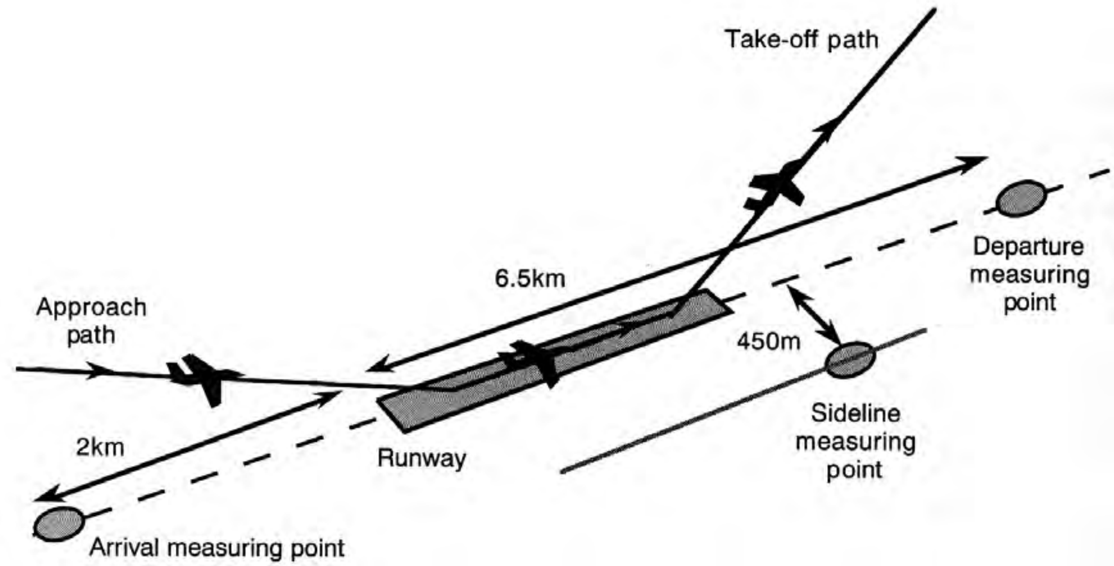


Figure 3: Standard positions for noise measurement.

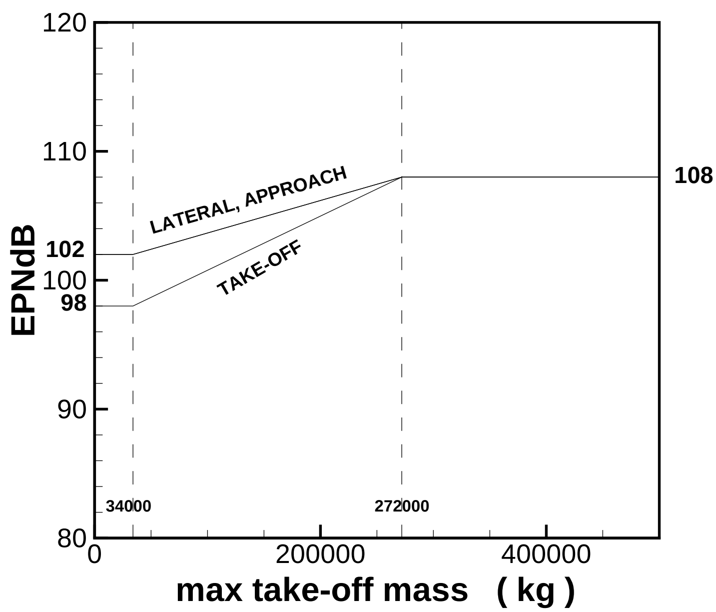
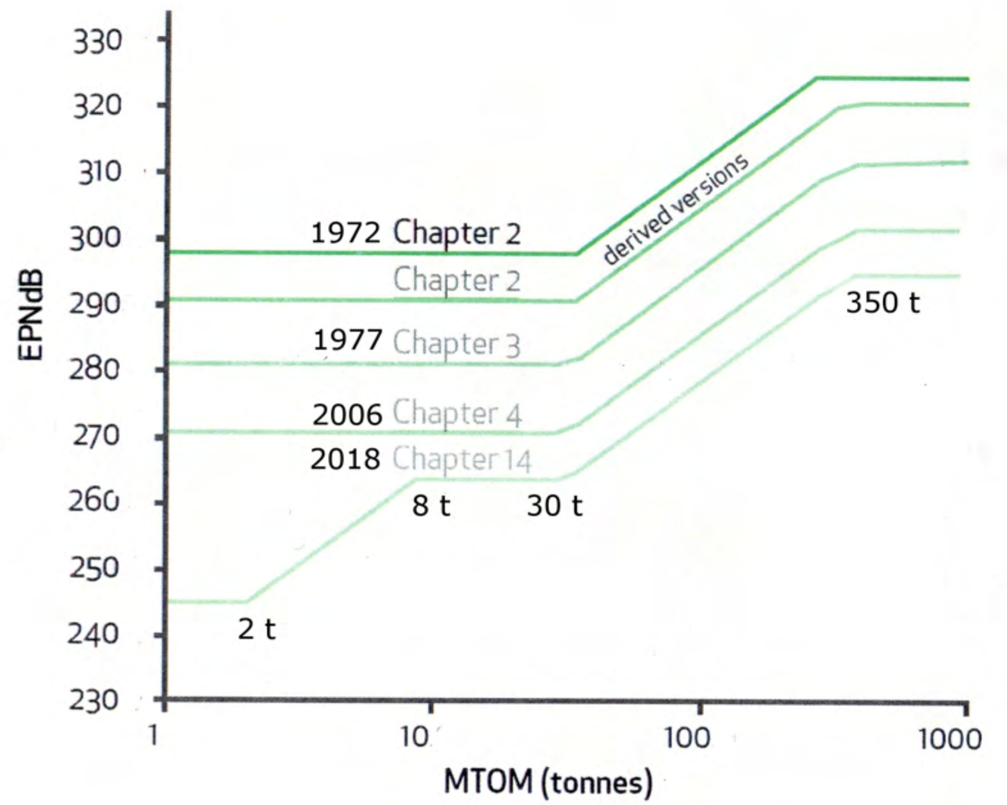


Figure 4: Noise limits, ICAO Annex 16, Chap. 3 (1977); Chap. 4 (2006): sum three contributions must be 10 dB lower than Chap. 3; Chap. 14 (2018): additional 7 dB lower than Chap. 4.

1.6 HISTORICAL NOISE STANDARDS



1.7 NO_x (NITROGEN OXIDES) STANDARDS

- D_p grams POLLUTANT EMITTED PER LANDING TAKE–OFF (LTO) CYCLE
- F_{00} STATIC THRUST (kN)

$$\frac{D_p}{F_{00}} = \begin{cases} 16.72 + 1.408 \cdot OPR & \text{per} \quad OPR \leq 30 \\ -1.04 + 2 \cdot OPR & \text{per} \quad 30 < OPR \leq 82.6 \\ 32 + 1.6 \cdot OPR & \text{per} \quad OPR > 82.6 \end{cases}$$

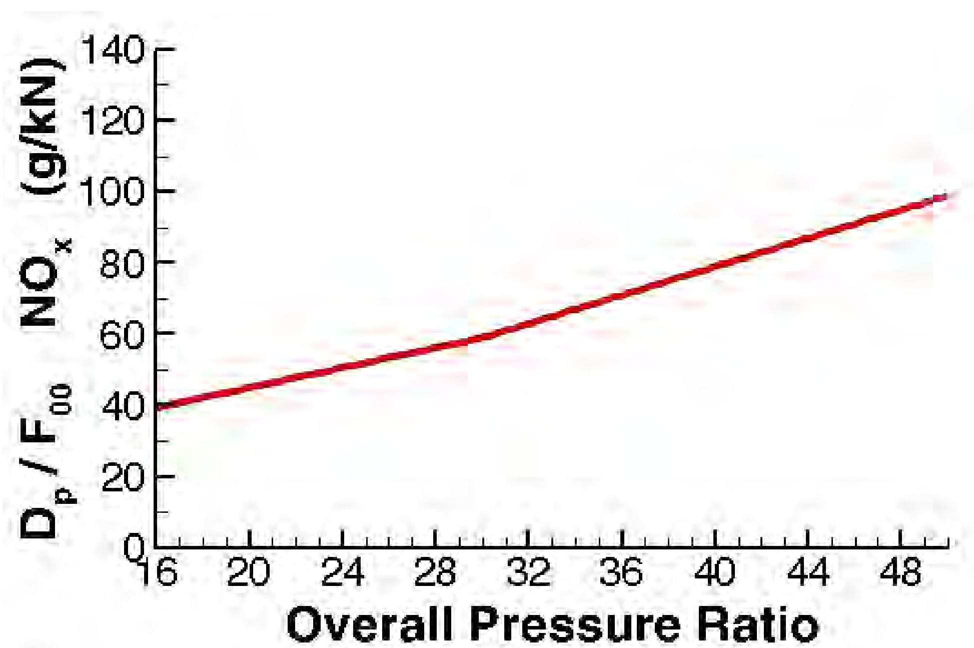


Figure 5: Limits on NO_x emissions per LTO cycle *vs.* OPR.

1.8 *TSFC* & NO_x EMISSIONS *vs. OPR*

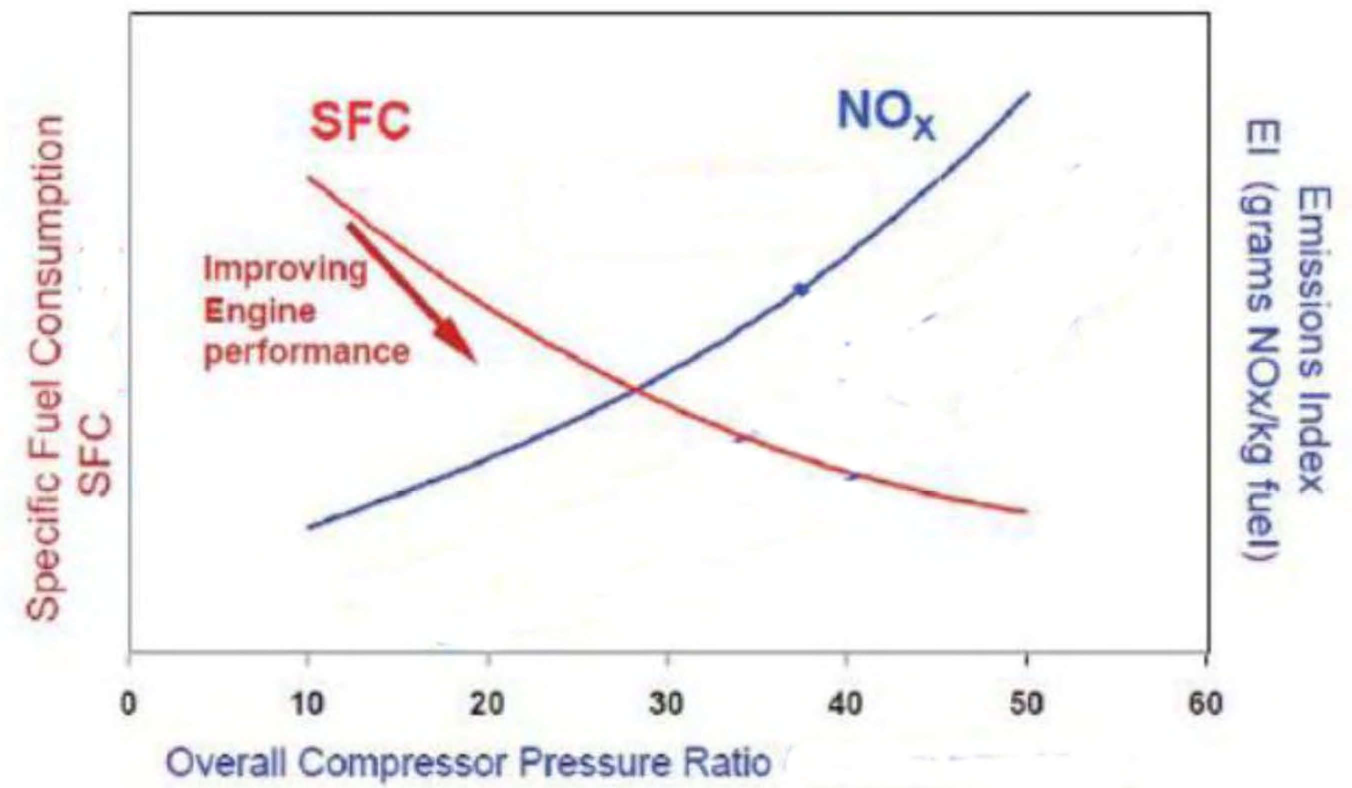


Figure 6: Andamenti del consumo specifico di spinta e dell'indice di emissione di NO_x, in funzione del rapporto di compressione globale OPR.

1.9 CORSIA
CARBON OFFSETTING and REDUCTION SCHEME for INTERNATIONAL AVIATION

- **TO BE INTRODUCED IN 2021**
- **DESPITE REDUCTION *TSFC*, AVIATION CO_2 EMISSIONS INCREASE DUE TO EXPANSION AIR TRAVEL ($\sim$ 5% per year)**
- **GOAL: STABILIZE AVIATION CO_2 EMISSION AT 2020 LEVEL BY *TRADING* EMISSION QUOTA**
- **'CAP AND TRADE' SYSTEM**
- **CURRENTLY $\sim$ 20 € per ton CO_2**

1.10 HISTORICAL TREND OF SPECIFIC CONSUMPTION

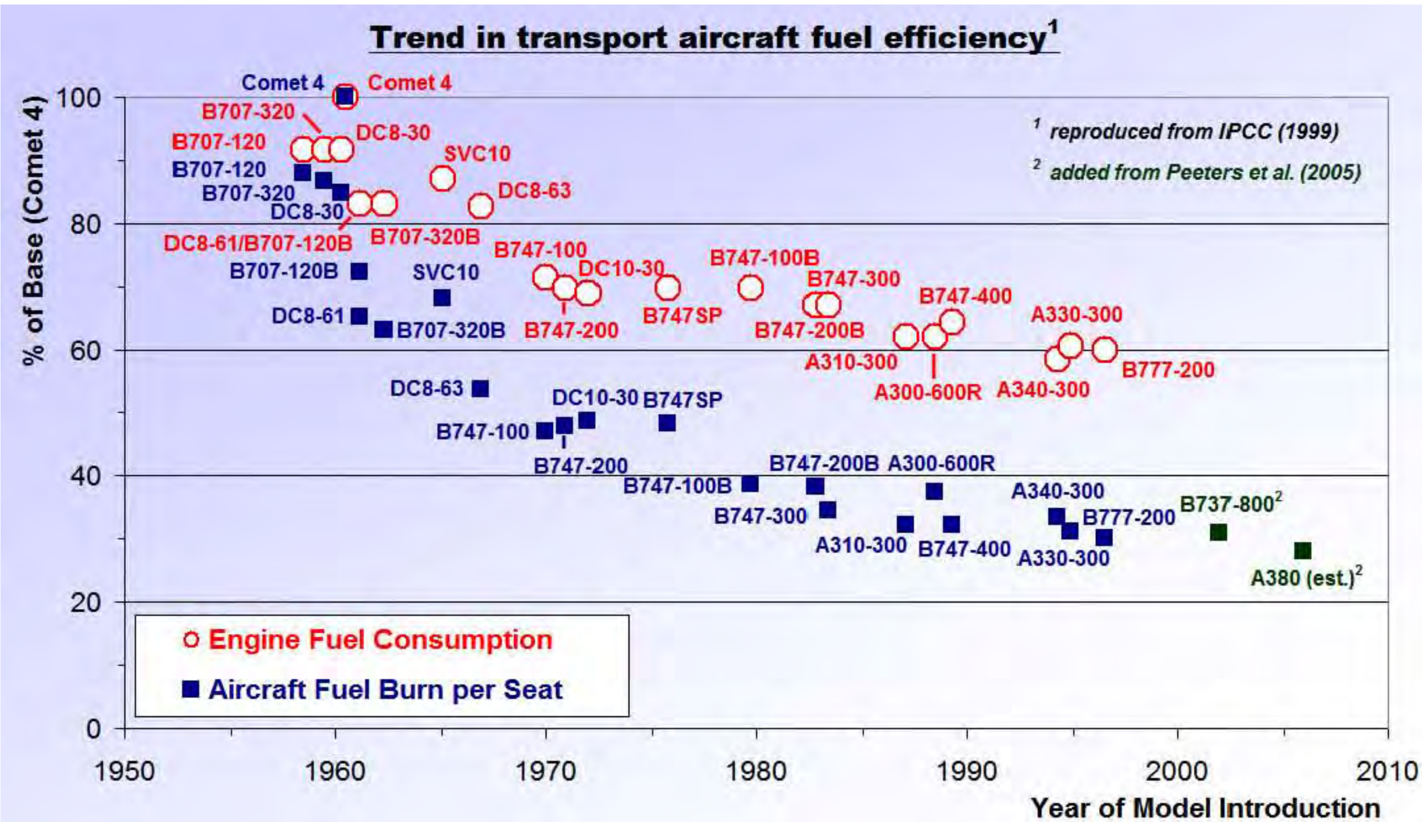


Figure 7: Historical trend of fuel consumption per unit thrust, and *per* pax–km.

1.11 HISTORICAL TREND OF ENERGY INTENSITY

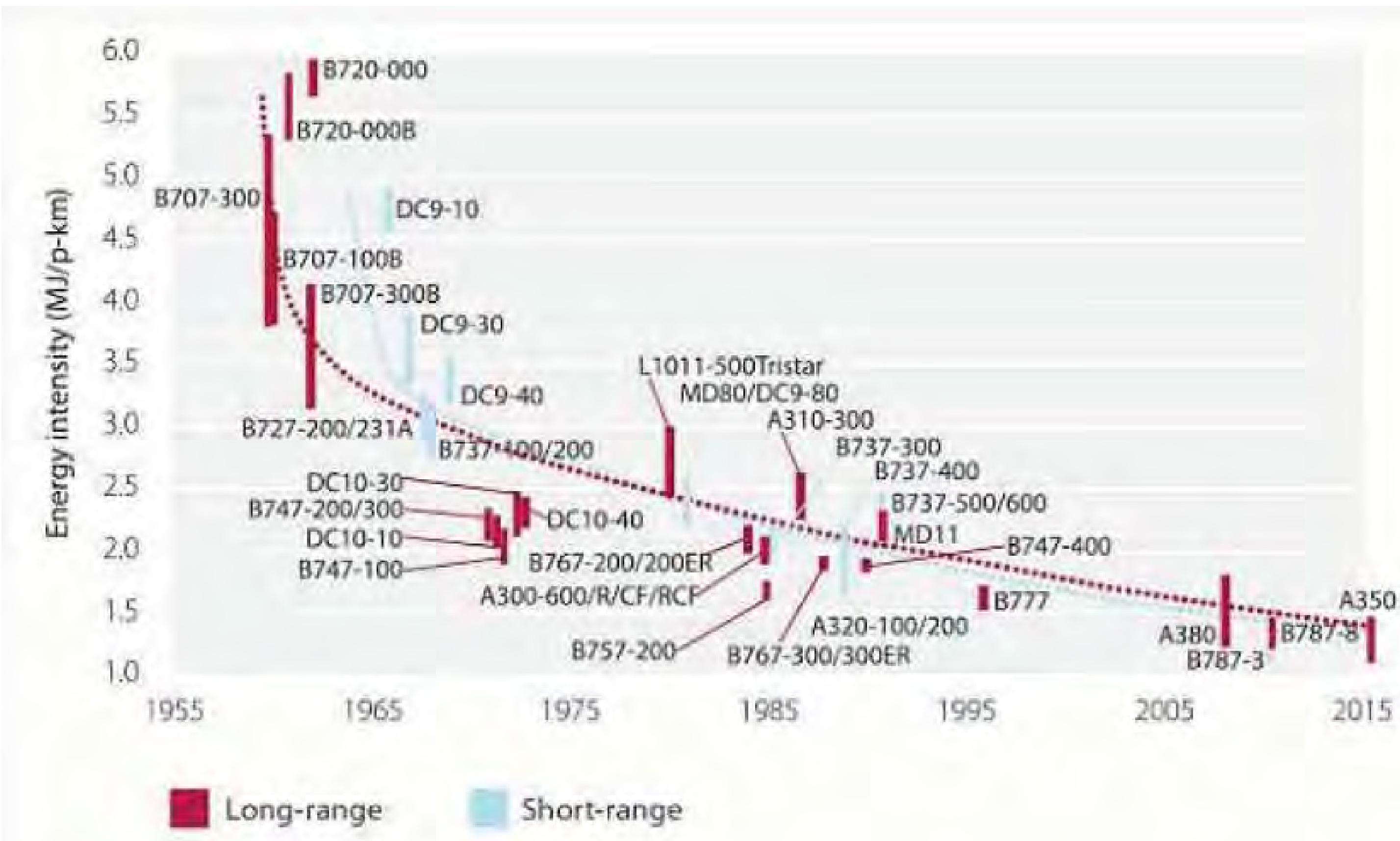


Figure 8: Historical trend of energy consumption per unit thrust, and *per* pax–km.

1.12 HISTORICAL TREND OF PERCEIVED NOISE

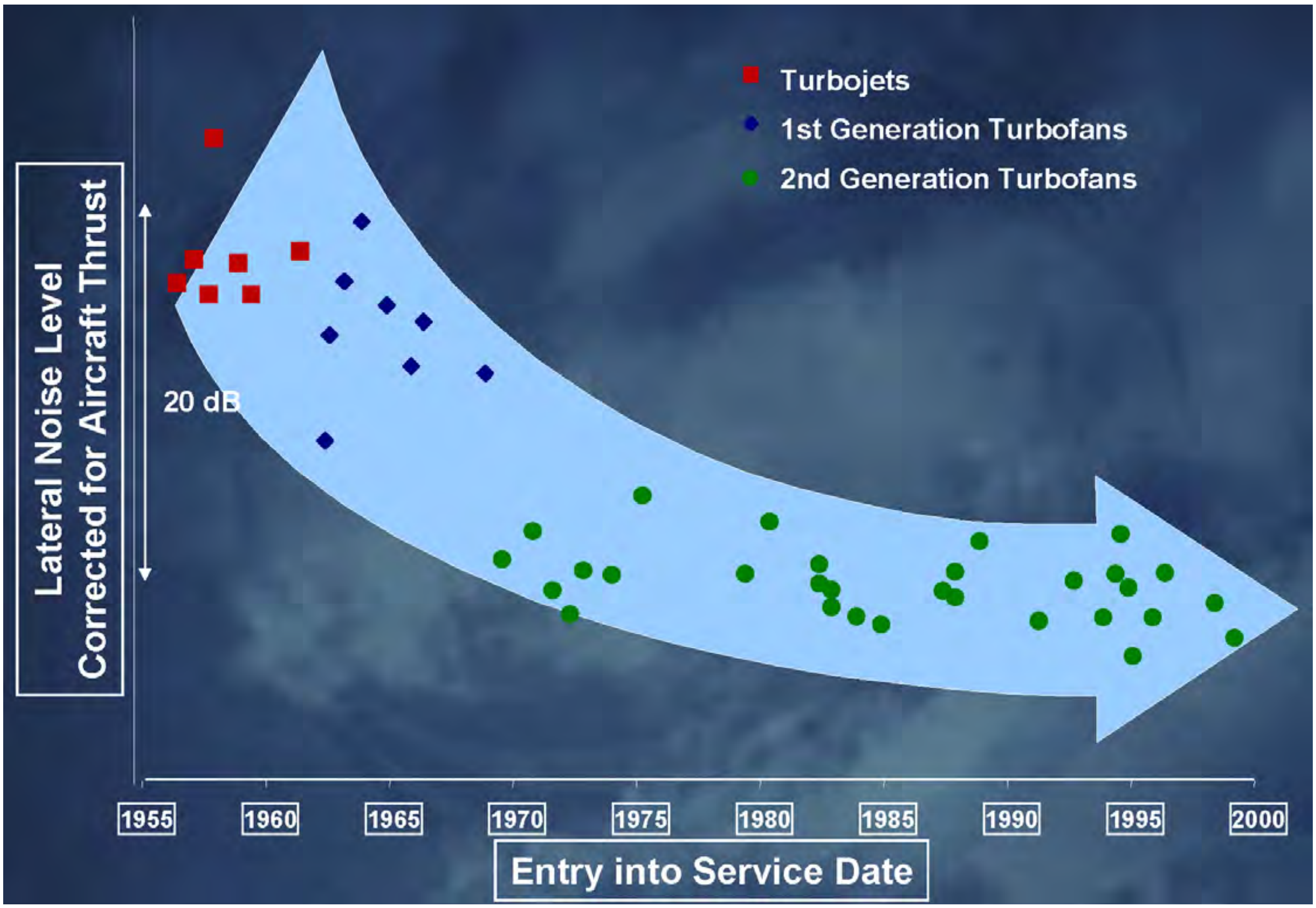


Figure 9: Historical trend of noise from commercial aircrafts, perceived on the ground.

1.13 NOISE EMISSIONS AND STANDARDS

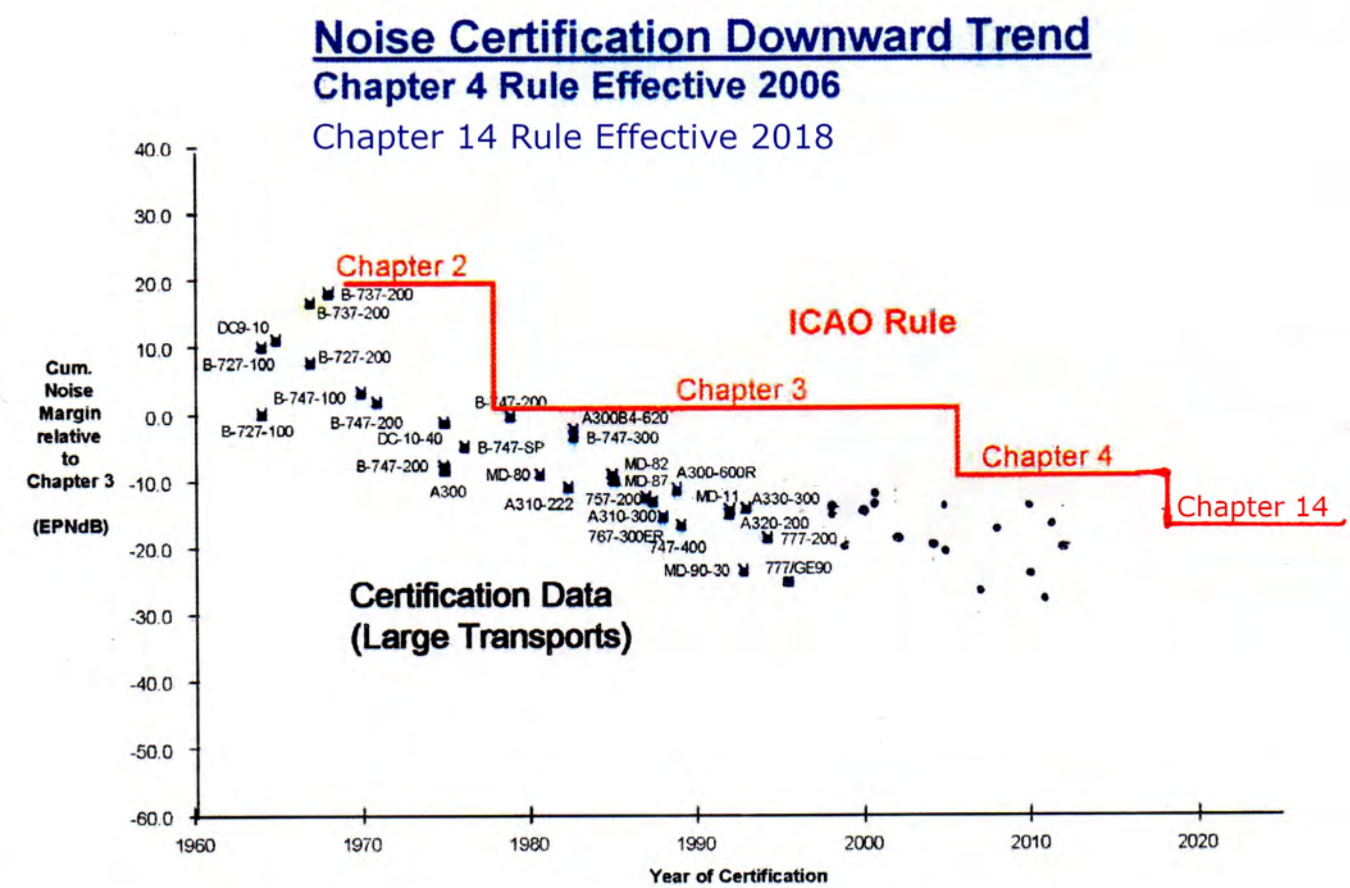


Figure 10: Noise emissions by commercial aircrafts, and ICAO standards in time.

1.14 NO_x EMISSIONS AND STANDARDS

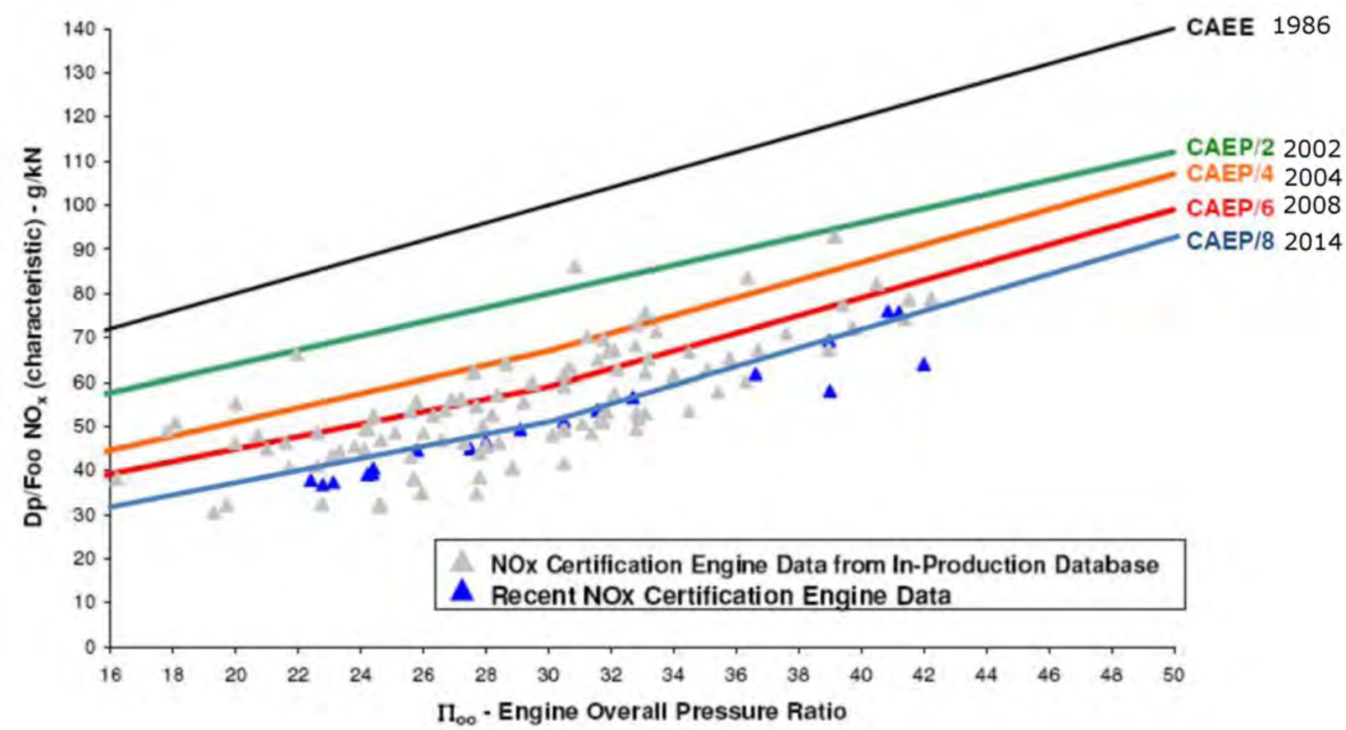


Figure 11: Emissioni di ossidi di azoto da aerei commerciali e normative ICAO nel tempo.

1.15 ACARE TARGETS '*VISION 2020*' (2001)

- ***Advisory Council for Aerospace Research in Europe***
  - * 50% REDUCTION CO_2
  - * 80% REDUCTION NO_x
  - * HALVE NOISE
  - * ELIMINATE NOISE DISTURBANCE AWAY FROM AIRPORTS
  - – SUBSTANTIALLY CUT OPERATING COSTS
  - – REDUCE ACCIDENT RATE BY A FACTOR 5
  - – DRASTICALLY REDUCE IMPACT OF HUMAN ERRORS
  - – ENSURE 99% FLIGHTS NOT DELAYED $>$ 15 min
  - – NEW STANDARDS QUALITY AND EFFICIENCY
  - – HALVE *TIME–TO–MARKET*
  - – IMPROVE SINERGIES BETWEEN MILITARY AND CIVIL RESEARCH
- FOR EMISSIONS, THESE GOALS IMPLY DOUBLING HISTORICAL IMPROVEMENT RATE

1.16 SIMILAR TARGETS

- **Global Aviation Sector (ICAO *et al.*)**
  - **IMPROVE CO_2 EFFICIENCY 1.5% PER YEAR UP TO 2020;**
  - **STABILIZE NET CO_2 EMISSIONS BY 2020;**
  - **REDUCE 50% NET CO_2 EMISSIONS BY 2050 (w.r.t. 2005)**

- **'CLEEN' TARGETS (USA):**

	N+1 (2015) CONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+2 (2020-25) UNCONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+3 (2030-35) ADVANCED CONCEPTS RELATIVE TO 2005
NOISE	-32 dB cum below Stage 4	-42 dB cum below Stage 4	-71 dB cum below Stage 4
LTO NOX EMISSIONS (BELOW CAEP 6)	-60%	-75%	better than -75%
AIRCRAFT FUEL BURN	-33%	-50%	better than -70%

1.17 EUROPEAN TARGETS 2050 *vs.* 2020

- **REFERRED TO YEAR 2000 TECHNOLOGY**

ITEM	2020 TARGET	2050 TARGET
CO_2 EMIS.	-50%	-75%
NO_x EMIS.	-80%	-90%
NOISE EMIS.	-50%	-65%
MATERIALS		FULLY RECYCLABLE

1.18 ACHIEVING THE GOALS EXAMPLE: CO_2

- **GOAL: 50% REDUCTION CO_2**
  - **20% FROM ENGINES (REDUCTION *TSFC*)**
  - **20% FROM AERODYNAMICS**
  - **10% FROM AIR TRAFFIC CONTROL**
  - **? WEIGHT REDUCTION → THRUST (MATERIALS, STRUCTURES)**
- **ACHIEVING SUCH GOALS ACCORDINGLY REQUIRES MULTIDISCIPLINARY R&D (*RESEARCH AND DEVELOPMENT*)**

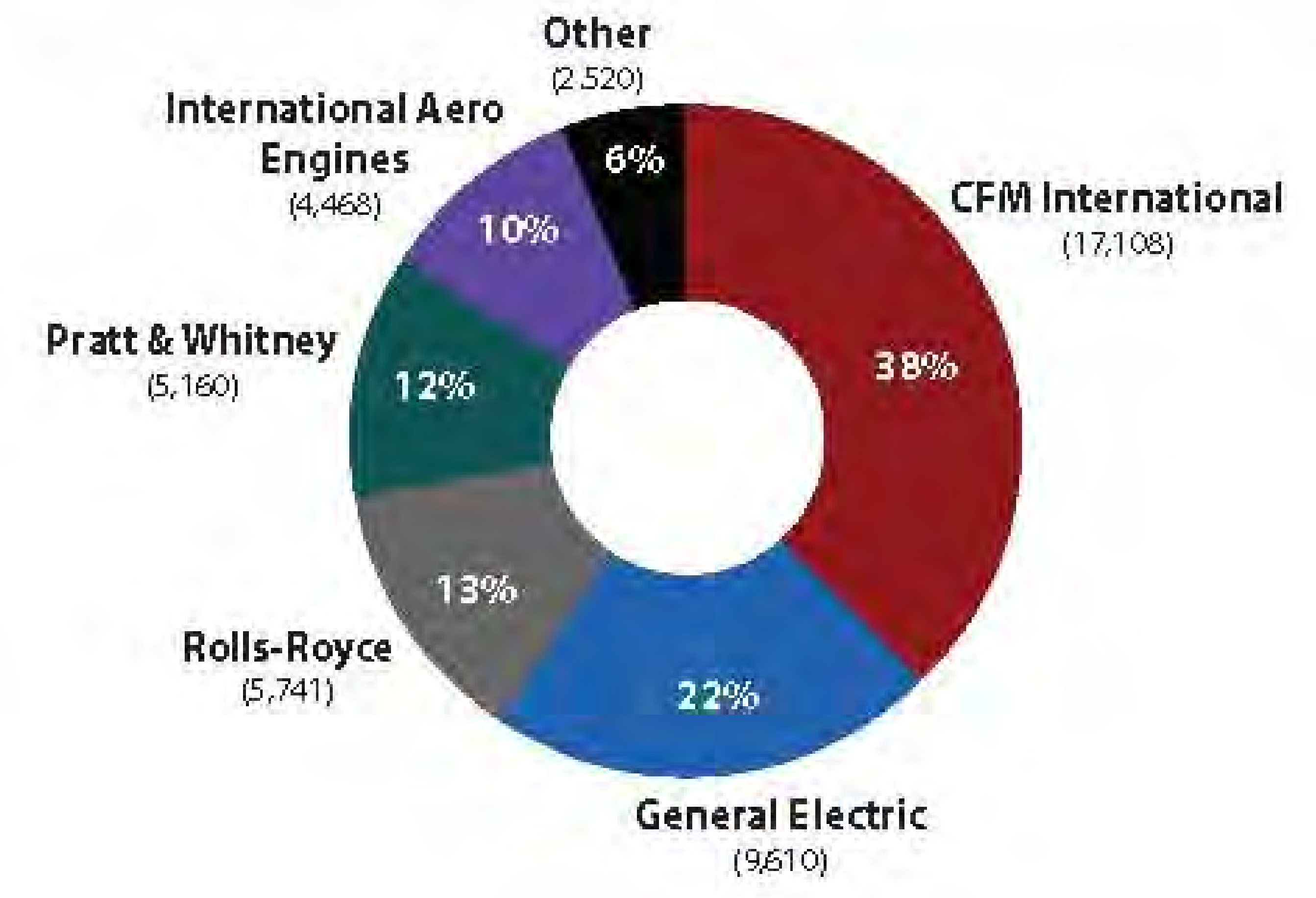
→ ONLY A FEW VERY LARGE COMPANIES (AIRCRAFT/ENGINES MAKERS) CAN SUCCEED

- **HOWEVER, AIR TRAFFIC IS EXPECTED TO TRIPLE BY 2020... (w.r.t. 2001)**

1.19 e.g., HEAVY, LONG–RANGE AIRCRAFT MANUFACTURES

LATE 50s TO MID–70s	NOWDAYS
BOEING	BOEING
DOUGLAS	
LOCKHEED	
CONVAIR	
VICKERS	AIRBUS
DE HAVILLAND	
ILYUSHIN	

1.20 COMMERCIAL AEROENGINES MARKET SHARE



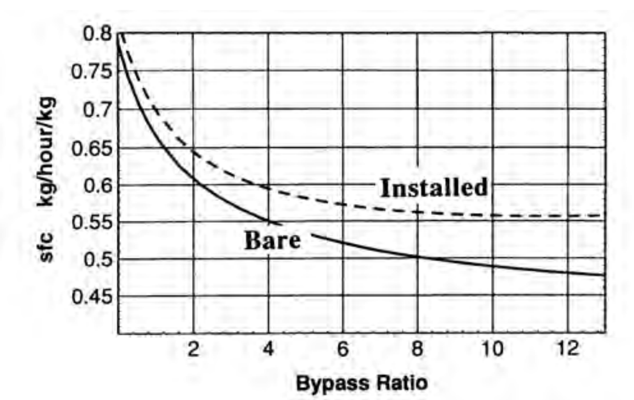
CFM	GENERAL ELECTRIC + SNECMA (FR)
INTERN AERO ENGS	PRATT & WHITNEY + MTU (GER) + JAPAN AERO ENG + (ROLLS–ROYCE)
ENGINE ALLIANCE	GENERAL ELECTRIC + PRATT & WHITNEY
GENERAL ELECTRIC	(USA)
ROLLS–ROYCE	(UK)
PRATT & WHITHEY	(USA)

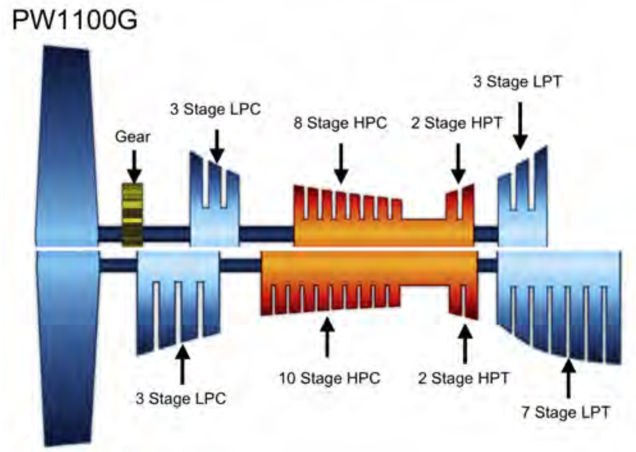
1.21 GUIDELINES FOR REDUCING FUEL CONSUMPTION per pax–km (THEN COSTS, EMISSIONS)

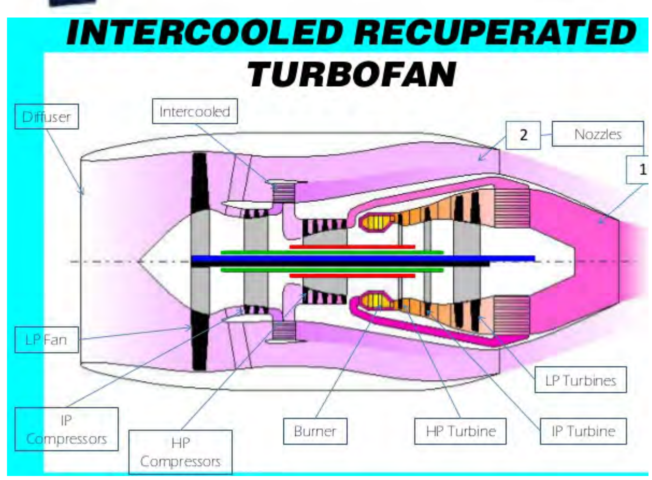
1. **REDUCING ENGINE $TSFC$**
2. **IMPROVING AERODYNAMIC EFFICIENCY L/D**
3. **AIR TRAFFIC MANAGEMENT**
4. **CONSTRUCTION AND MATERIALS**
5. **OTHER MINOR STEPS**

1.21.1 REDUCING ENGINE *TSFC*

- HIGHER *BPR*
- GEARED TURBOFAN (GTF) POSSIBLY UP TO *BPR* ∼ 20
- OPEN ROTOR or PROPFAN UP TO *BPR* ∼ 50 (NOISY)
- HIGHER CYCLE PRESSURE RATIO p_3/p_a (HEAVIER)
- INTERCOOLED/RECUPERATED ENGINES (HEAVY, BULKY → DRAG)

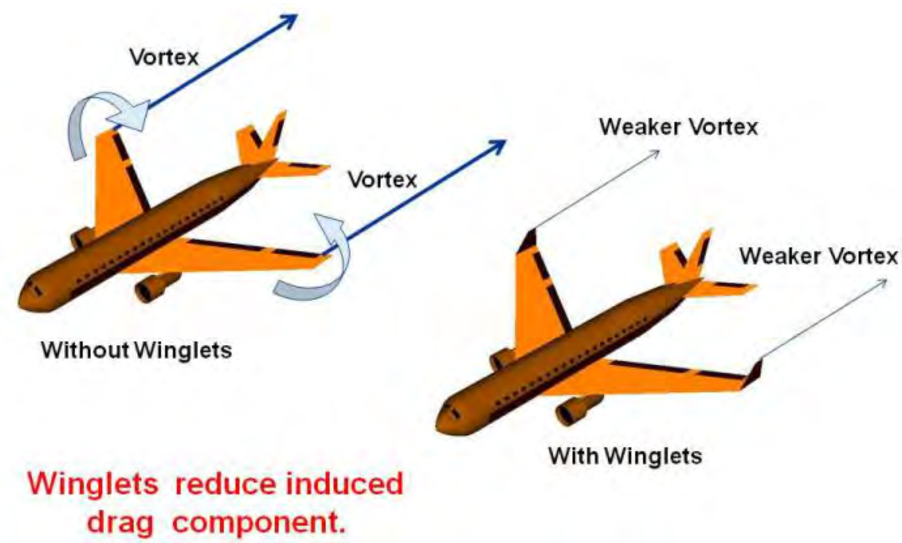






1.21.2 IMPROVING AERODYNAMIC EFFICIENCY L/D

- **WINGLETS**
- **BOUNDARY LAYER INGESTION**
- **BLENDED WING–BODY**



1.21.2' IMPROVING AERODYNAMIC EFFICIENCY L/D

- **SHARKLETS**
- **RAKED WINGTIPS**

REDUCING INDUCED DRAG

Airbus 350 sharklets

Boeing 787 raked wingtips

Mother Nature

1.21.3 AIR TRAFFIC MANAGEMENT

- **FLIGHT EFFICIENCY PLAN**
- **4–D (TIME–VARYING) AIRLANES (METEO, WINDS)**
- **STEP–CLIMB, CONTINUOUS CLIMB IN CRUISE**
- **CONTINUOUS DESCENT**

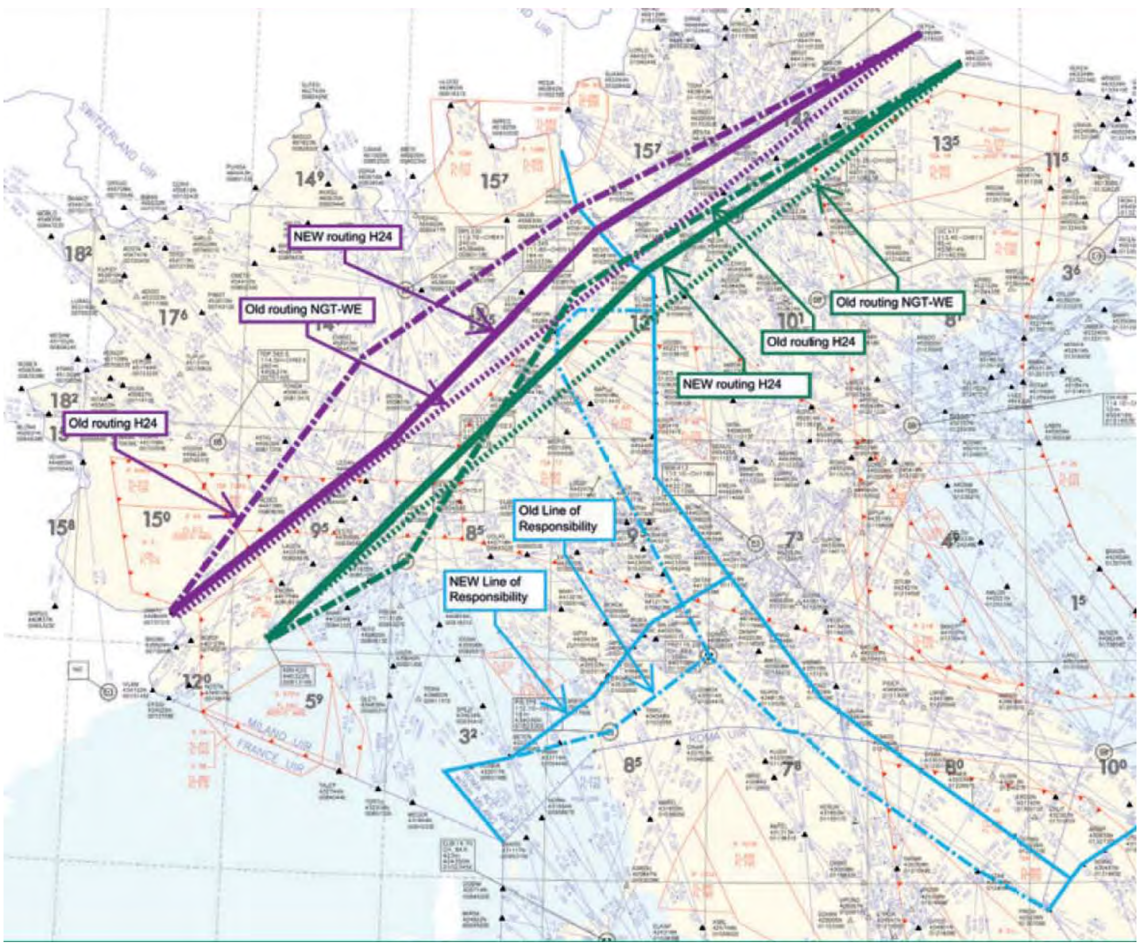
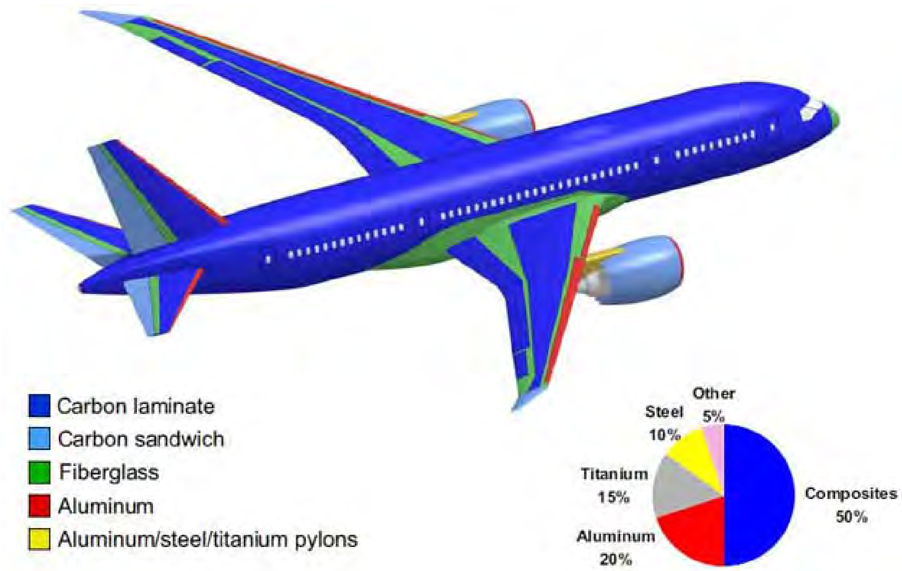


Figure 12: Old and new, shorter routes in Northern Italy.

1.21.4 CONSTRUCTION AND MATERIALS

- **COMPOSITES**
- **MULTIFUSELAGE, BWB CONFIGURATIONS**



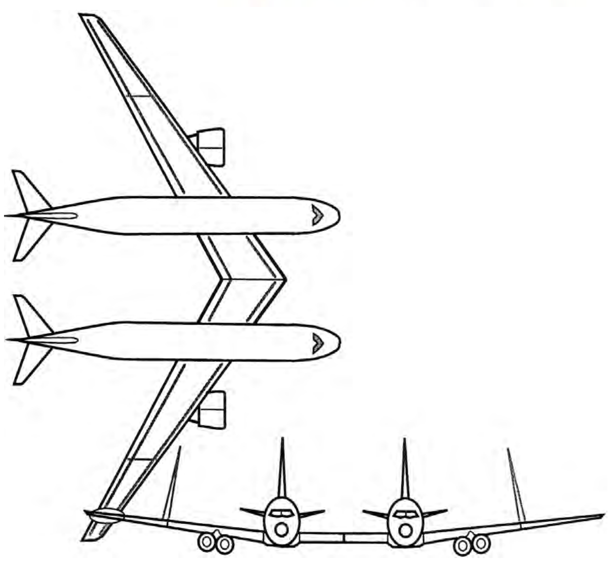


Figure 13: (Top) materials used in the Boeing 787, (left) multifuselage configuration, (right) blended wing–body configuration.

1.21.5 OTHER MINOR STEPS

• **ELECTRIC TAXIING**

1.22 OPTIMIZATION

- **ACHIEVING INDIVIDUAL EMISSION REDUCTION GOALS RELATIVELY EASY...**
- **BUT TROUBLE IS THAT THEY MUST ALL BE ACHIEVED SIMULTANEOUSLY**

$\rightarrow$ **OVERALL DESIGN OPTIMIZATION**

- **WHAT OPTIMIZE (DOC, RETURN ON INVESTEMENT...)? AND ON THE BASIS OF WHICH FUEL PRICE?**
- **OPTIMIZATION WITH CONSTRAINTS (NO. CONSTRAINTS CAN EXCEED NO. DESIGN VARIABLES)**

1.23 OPTIMIZING *INDIVIDUAL* ASPECTS

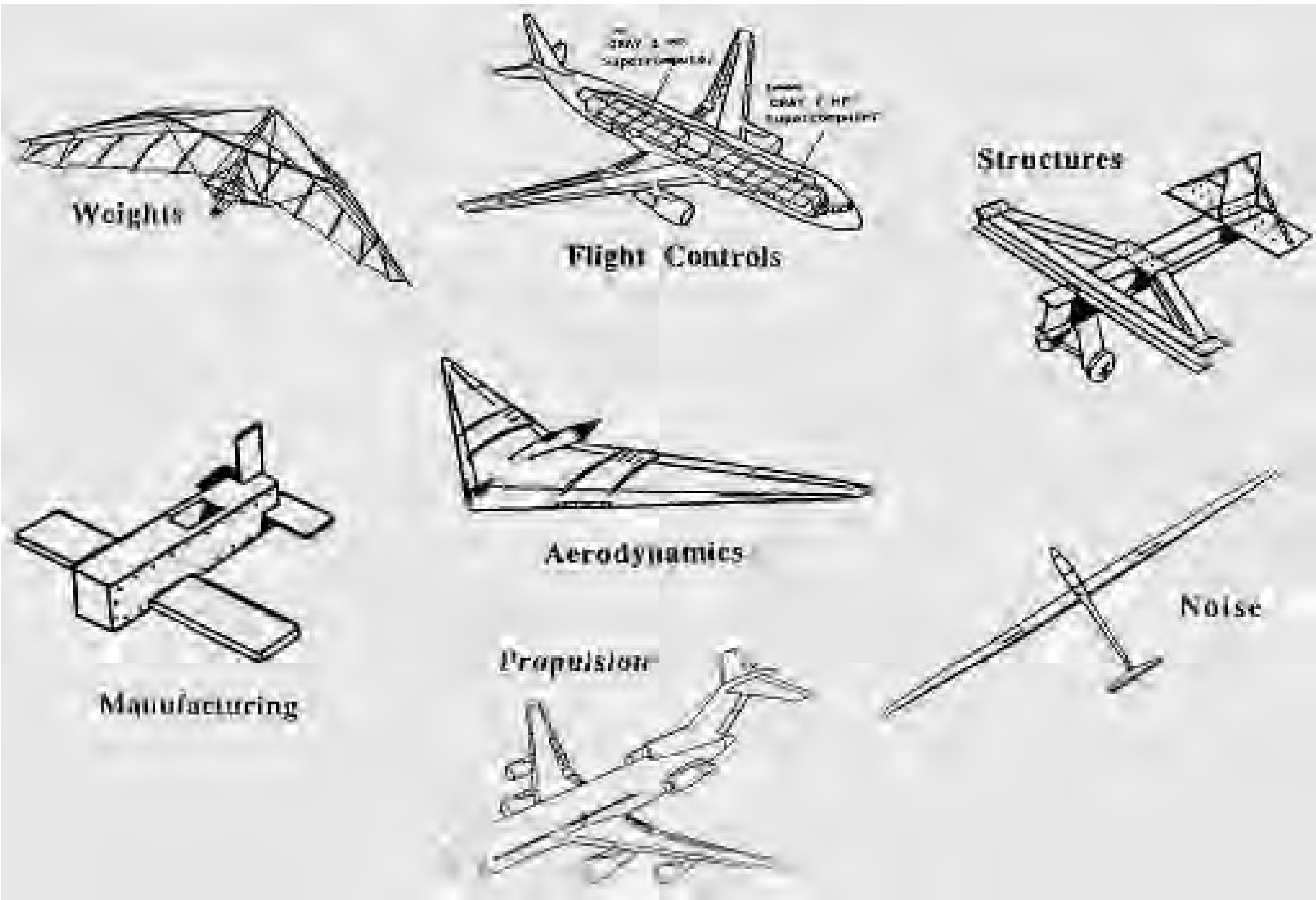
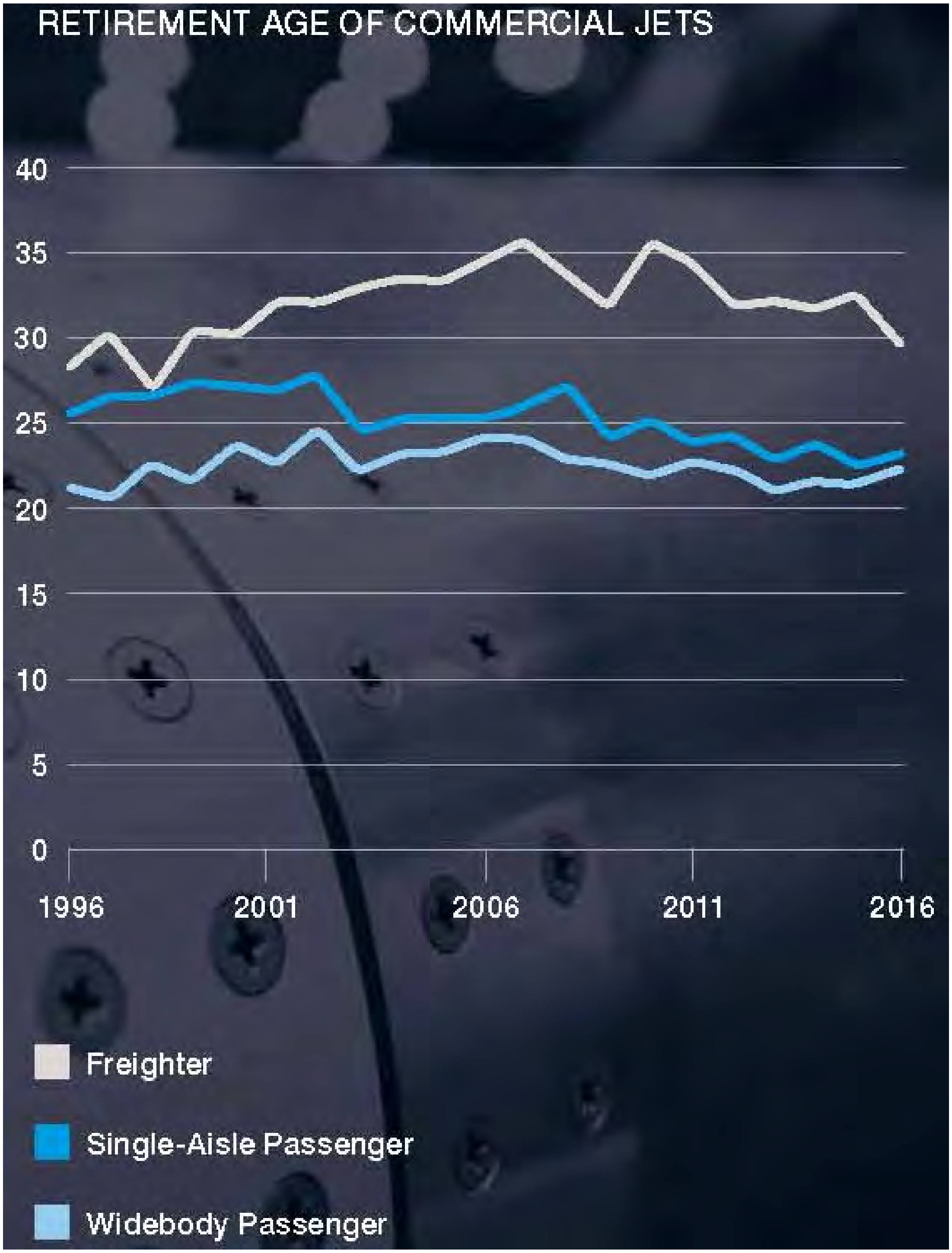


Figure 14: (Not to be taken too seriously)...

1.24 AVERAGE LIFE OF COMMERCIAL AIRCRAFT



1.25 POSSIBLE ANSWER: UNCONVENTIONAL CONFIGURATIONS

Figure 15: *Over the Wing Nacelle* configuration.

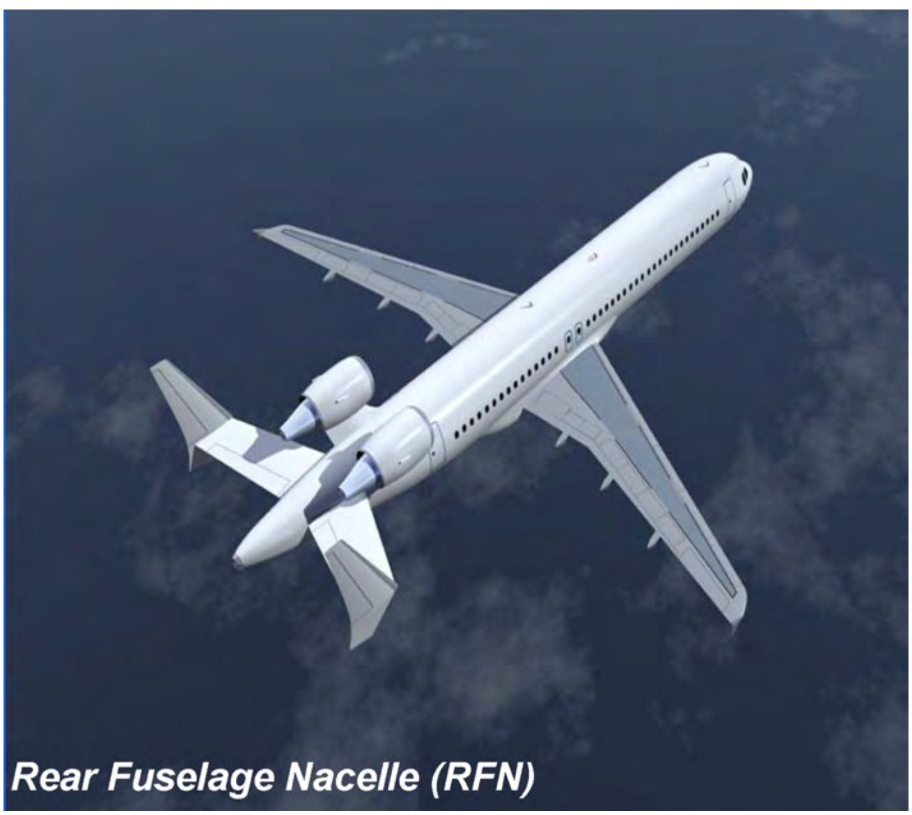
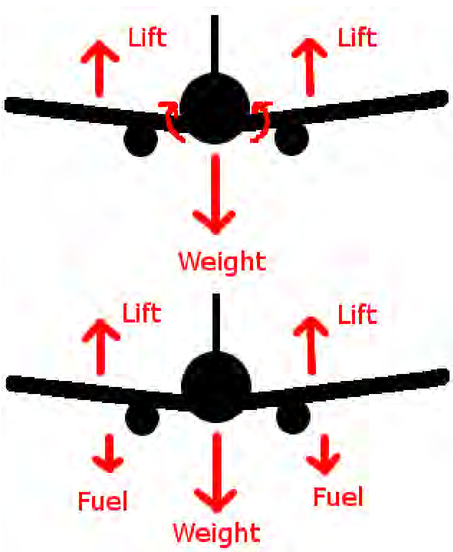


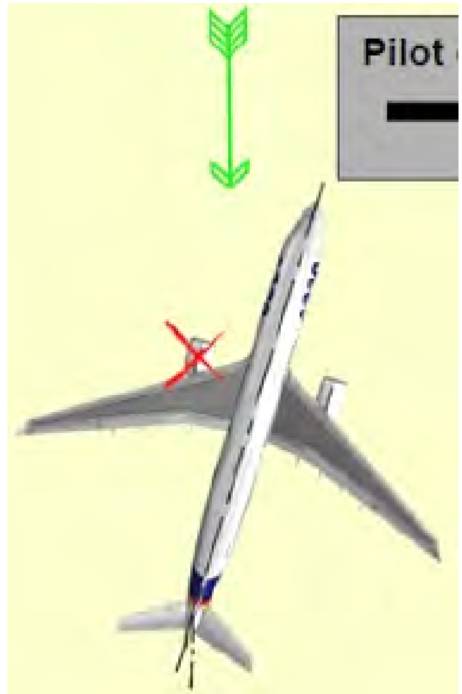
Figure 16: *Rear Fuselage Nacelle* configuration.

1.26 ENGINE LOCATION: PROS AND CONS

WING–MOUNTED (OWN or UWN)	REAR–MOUNTED
WING BENDING RELIEF	HIGHER GROUND CLEARANCE
FUSELAGE BEND. RELIEF	(ONLY OPTION A/C $<$ 50 pax)
→ LIGHTER	BETTER WING AERODYNAMICS
HIGHER CABIN NOISE	LONGER FUEL LINES
	CENTRE-of-GRAVITY MORE AFT
	→ LOWER TAIL ARM
	→ TIP–OVER
	LOWER YAW for ENGINE OUT
	→ SMALLER FINTAIL, RUDDER
	(LOWER WEIGHT/DRAG)
	→ SAFER EMERGENCY LANDING
	HOT DEBRIS in CRASH LANDING

1.27 WING–MOUNTED *vs.* REAR–MOUNTED





1.28 ...OR EVEN LESS CONVENTIONAL CONFIGURATIONS

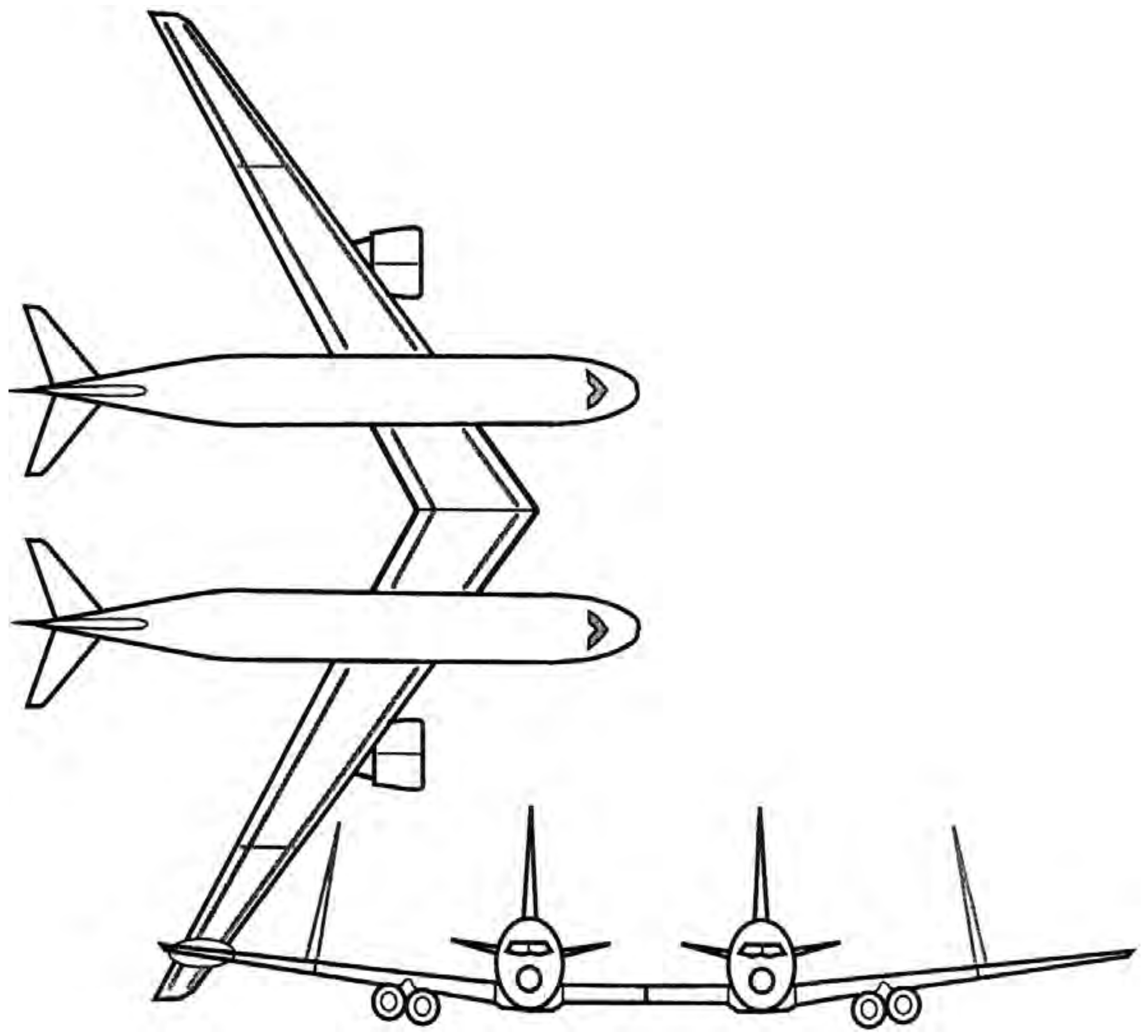


Figure 17: *Twin–fuselage* configuration.

1.29 RISK ASSOCIATED TO NEW CONFIGURATIONS

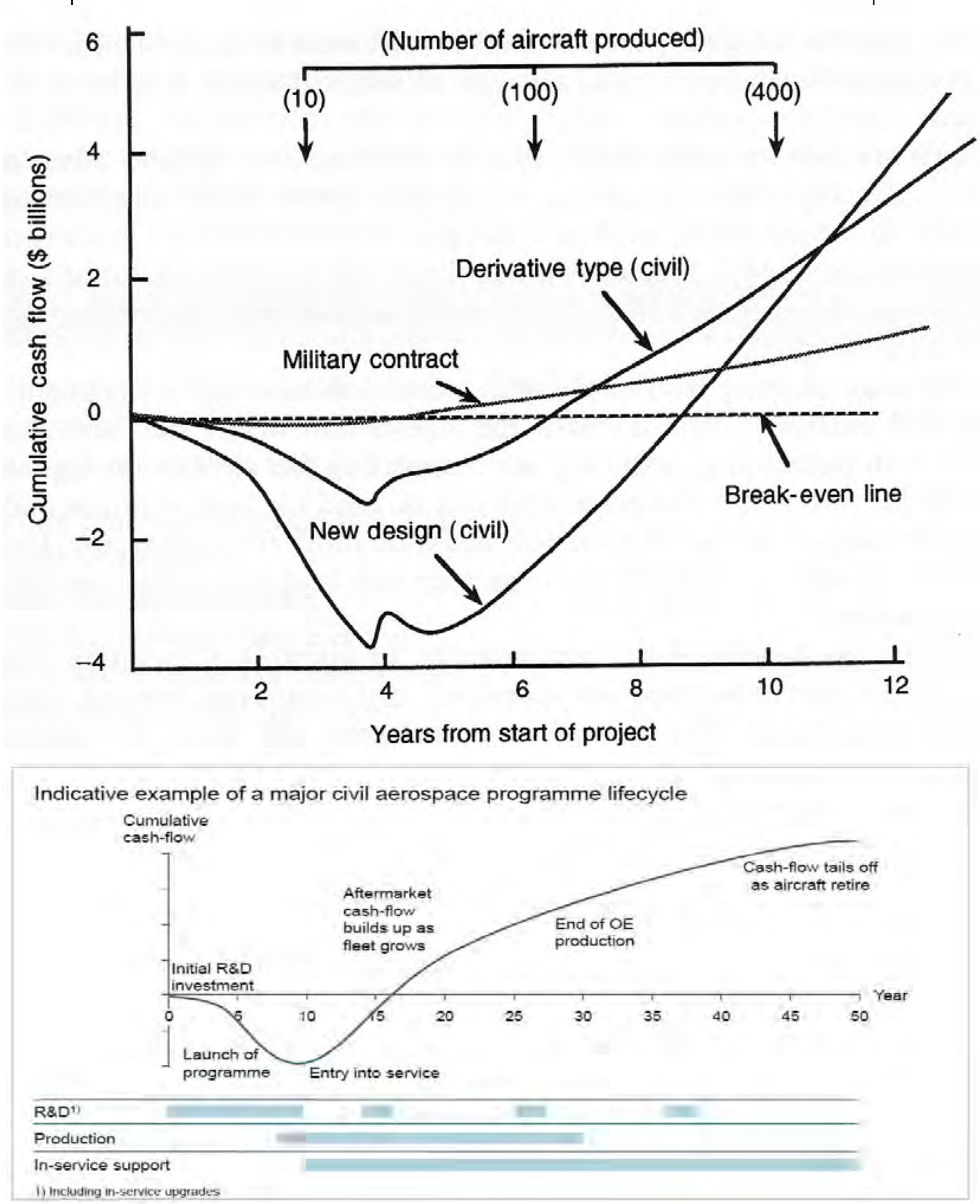


Figure 18: Time cash flow for the development a 150–seat aircraft (top), and for a large aircraft (bottom), both of conventional type.

- **AIRBUS 380 REQUIRED AN INVESTMENT $\sim$ 15 – 25 Geuro**

1.30 IN ORDER TO AVOID RISKS...

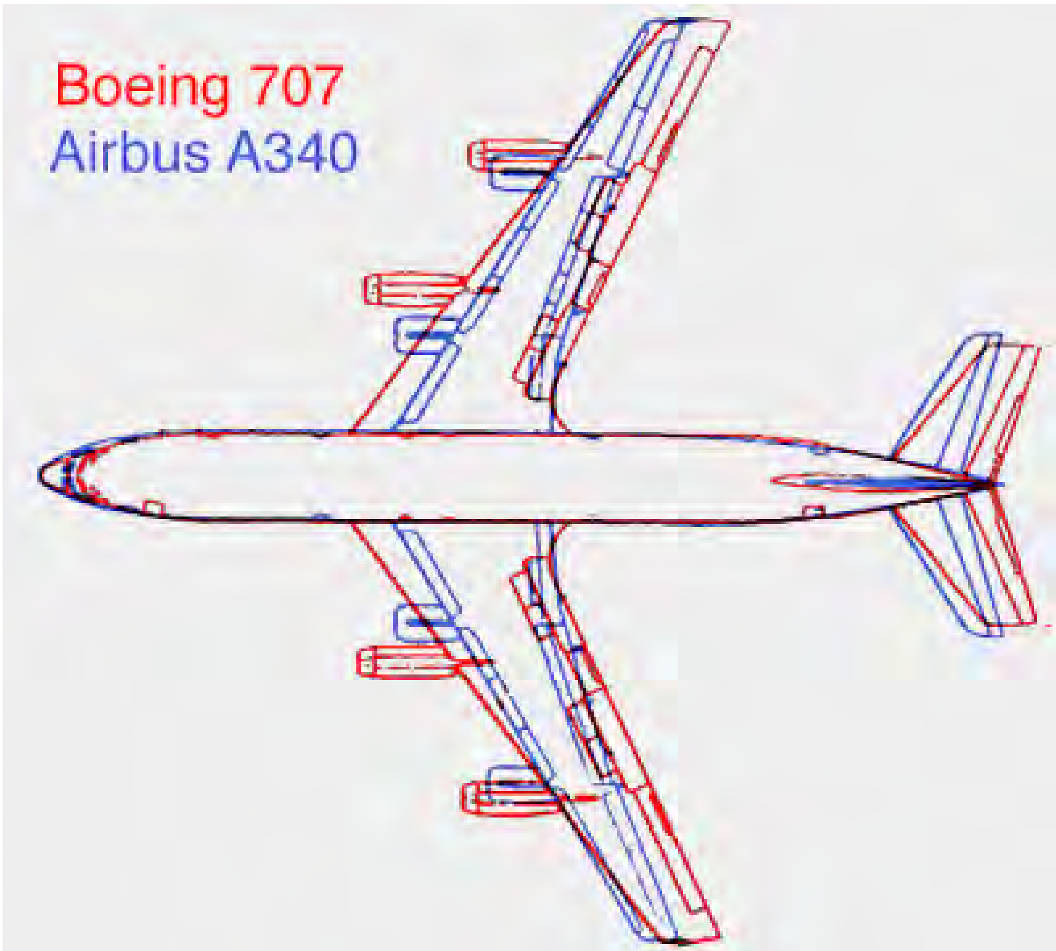
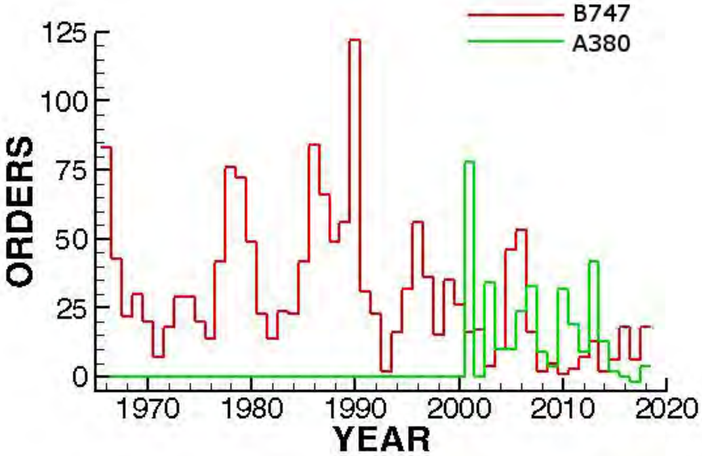
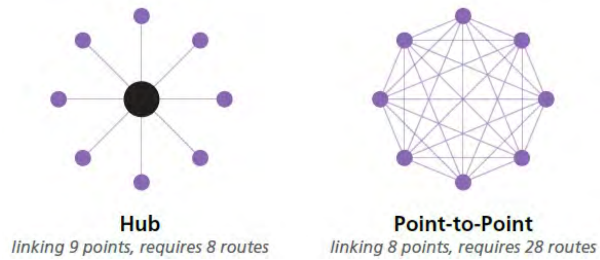


Figure 19: Comparison between the shapes of Boeing 707 and Airbus 340.

1.31 AIRBUS 380 PRODUCTION STOP





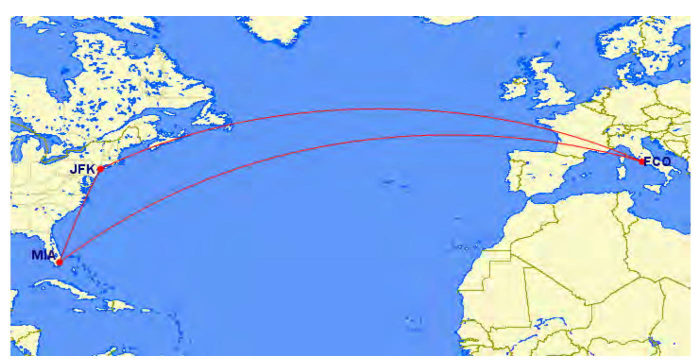
- **AIR TRAVEL EXPANDING ∼ 5% A YEAR**

→ FOSTERING POINT–TO–POINT PARADIGM

→ SMALLER CAPACITY AIRCRAFTS

A/C	SEATS
A380	525 – 853
B747	416 – 660
A330	257 – 406
B777	305 – 396
A350	325 – 366
B767	181 – 365

POINT–TO–POINT: PROS	CONS
NO NEED CONNECTIONS	MORE ROUTES
REDUCED TRAVEL TIME	LESS FREQUENT FLIGHTS
REDUCED FUEL CONSUMPTION	
REDUCED POLLUTION	
REDUCED RISK BAGGAGE LOSS	
LESS PRONE TO DELAYS	



1.32 ECONOMICAL IMPACT OF EMISSION REDUCTION

- **EMISSION REDUCTION OFTEN IMPLIES:**
  - **INCREASED SPECIFIC CONSUMPTION** $TSFC = \dot{m}_f / F$
  - **INCREASED ENGINE MASS** m_e
- **TAXES**

1.33 ECONOMICAL IMPACT OF INCREASED $TSFC$ (1)

		A340–500
	range (nm/km)	7050/13057
m_f/m_{TO}	fuel mass/m_{TO}	0,423
m_{pl}/m_{TO}	payload mass/m_{TO}	0,141

- **RELATIVE REDUCTION m_{pl} ($\simeq$ COST INCREASE) DUE TO RELATIVE INCREASE OF $TSFC$:**

* $\Delta m_{pl} = -\Delta m_f$

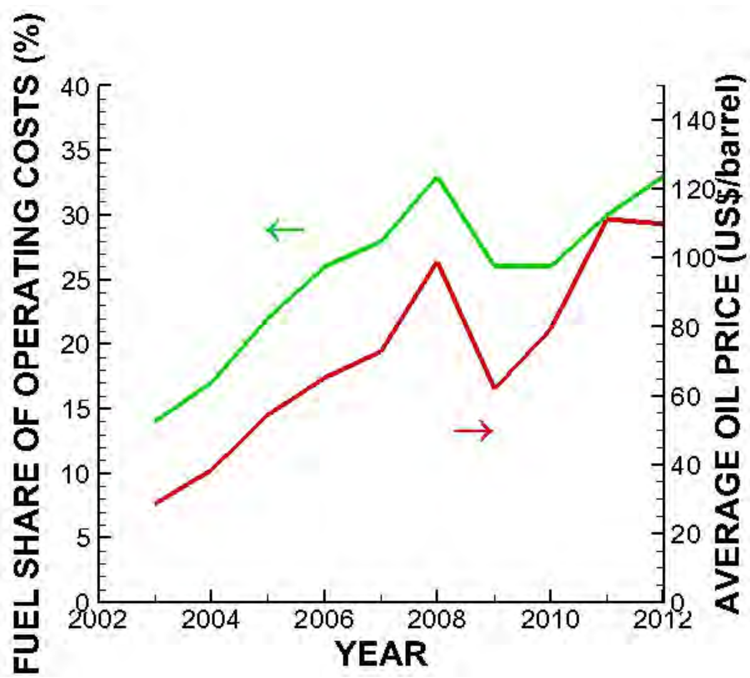
* $$\frac{\Delta m_{pl}}{m_{pl}} = -\frac{\Delta m_f}{m_f}\frac{m_f}{m_{pl}} = -\frac{\Delta m_f}{m_f}\frac{m_f/m_{TO}}{m_{pl}/m_{TO}}$$

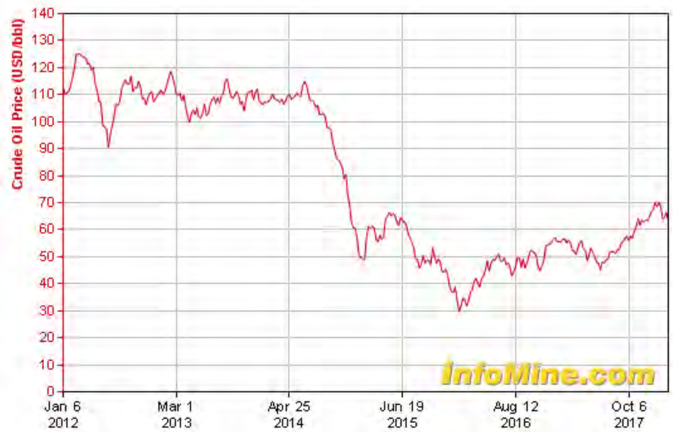
* **e.g., A340–500, $TSFC$ INCREASED BY 1%:**

$$\frac{\Delta m_{pl}}{m_{pl}} = -0,01\,\frac{0,423}{0,141} = -3\%$$

- **PLUS COST EXTRA FUEL**

1.34 ECONOMICAL IMPACT OF INCREASED $TSFC$ (2)

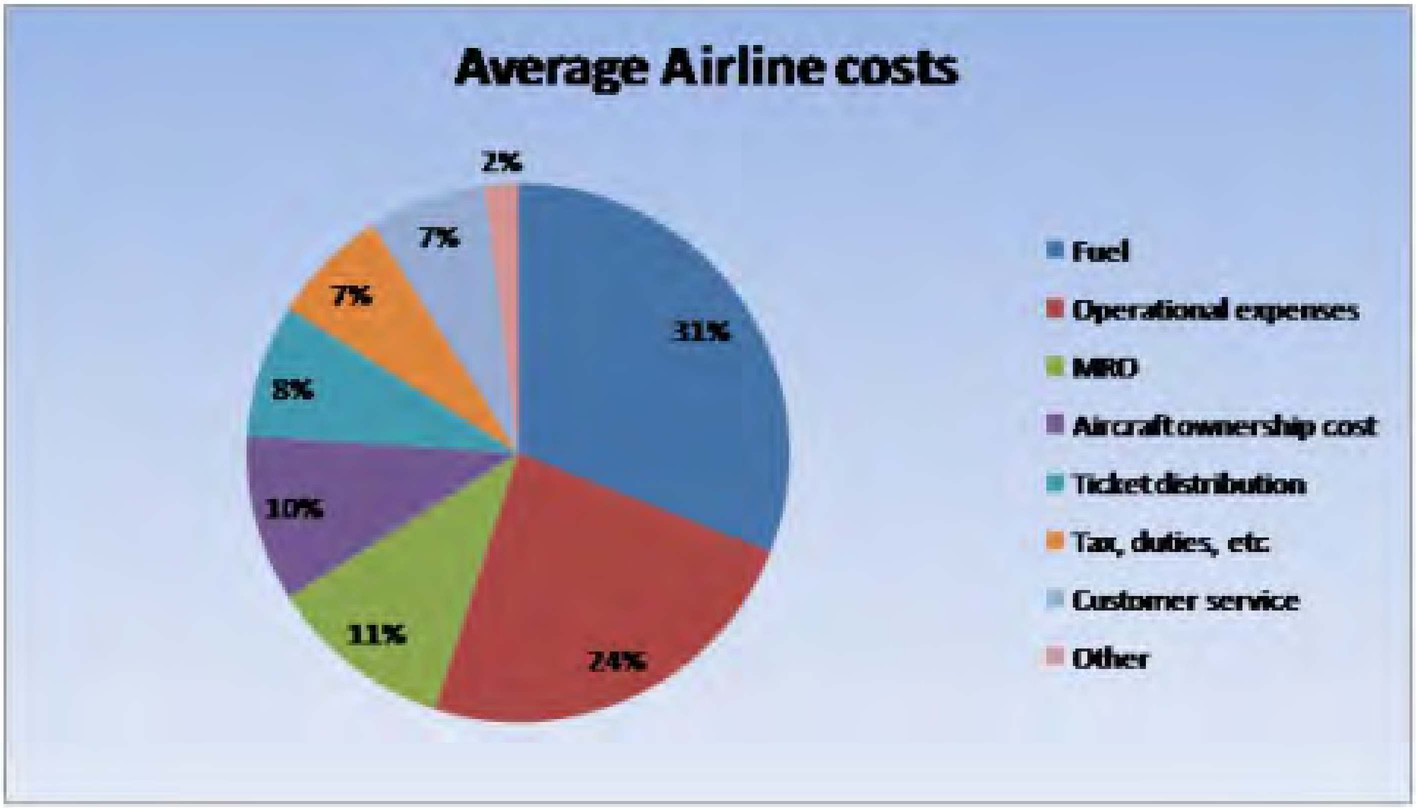




- **FUEL SHARE OF OPERATING COSTS CURRENTLY AROUND 23.5%**
- **1% INCREASE FUEL BURN ≃ 0,235% INCREASE OPERATING COSTS**
- **RELATIVE INCREASE OPERATING COST PER UNIT PAYLOAD MASS ≃ 3,3 %**

$$\frac{1,00235}{1 - 0,03} \simeq 1,033 \qquad (1)$$

1.35 BREAKDOWN OF AIRLINE COSTS



- ***MRO*** **MAINTENANCE RELATED OPERATIONS**
- **(INDICATIVE)**

1.36 ECONOMICAL IMPACT OF INCREASED ENGINE MASS

		A340–500
m_{pl}/m_{TO}	payload mass/m_{TO}	0,141
$F/(g_0\, m_{TO})$	A/C thrust/weight ratio, take–off	0,2634
(F/W)	engine thrust/weight ratio	5,1

- **RELATIVE REDUCTION m_{pl} ($\simeq$ COST INCREASE) DUE TO RELATIVE INCREASE ENGINE MASS m_e:**

* $\Delta m_{pl} = -\Delta m_e$
* $$\frac{\Delta m_{pl}}{m_{pl}} = -\frac{\Delta m_e}{m_e}\frac{m_e}{m_{pl}} = -\frac{\Delta m_e}{m_e}\frac{F}{g_0\,(F/W)}\frac{1}{m_{pl}} =$$

$$-\frac{\Delta m_e}{m_e}\frac{\dfrac{F}{g_0\, m_{TO}}}{(F/W)}\frac{m_{TO}}{m_{pl}}$$

* **e.g., A340–500, m_e INCREASED BY 1%**

$$\frac{\Delta m_{pl}}{m_{pl}} = -0,01\,\frac{0,2634}{5,1}\,\frac{1}{0,141} = -0,366\%$$

* **WITHOUT ACCOUNTING FOR ADDITIONAL STRUCTURAL/FUEL MASS ASSOCIATED WITH INCREASED m_e (e.g., PYLONS,...)**

→ **POSSIBLY 3 TIMES AS LARGE ($\simeq$ 1,1%)**

1.37 COURSE PROGRAMME (1/2)

1. **INTRODUCTION**
2. **POLLUTANTS AND CONTAMINANTS**
   - **DIRECT EFFECTS**
   - **GLOBAL WARMING (GREENHOUSE EFFECT)**
   - **DEPLETION OF STRATOSPHERIC OZONE LAYER**
3. **COMBUSTION CHAMBER:**
   - **BASIC ASPECTS: DIFFUSERS, INJECTORS, COOLING**
   - **FUNDAMENTALS OF COMBUSTION**
   - **COMBUSTION EFFICIENCY**
   - **FUELS**
4. **POLLUTANT FORMATION/EMISSION CONTROL:**
   - **CONTROL STRATEGIES**
   - **PRIMARY AND SECONDARY PARTICULATE, VOC (+ Lab)**
   - **SO_x**
   - **NO_x**
   - **CO, UHC**

1.38 COURSE PROGRAMME (2/2)

5 ELEMENTS OF ACOUSTICS:

- **ACOUSTIC QUANTITIES**
- **WAVE EQ.**
- **SOUND MEASUREMENT**
- **ATTENUATION**

6 NOISE EMISSIONS:

- **ACTIONS AGAINST NOISE**
- **COMPONENTS OF NOISE:**
  - **PROPULSIVE**
  - **NON–PROPULSIVE**

7 EMISSIONS BY SUPERSONIC AIRCRAFTS

8 UNCONVENTIONAL CONFIGURATIONS

2.1 POLLUTANTS AND CONTAMINANTS

- **AGENTS:**
  - **POLLUTANTS (DIRECT EFFECT ON HEALTH)**
  - **CONTAMINANTS (CAN ALTER CLIMATE)**
- **POLLUTANTS:**
  - **PRIMARY**
  - **SECONDARY**
- **SCALES:**
  - **LOCAL**
  - **REGIONAL**
  - **GLOBAL**

2.2 INTERRELATION EMISSIONS/ATMOSPHERE/EFFECTS

- **EMISSION SOURCES**

→ **ATMOSPHERE:**

  - **TRANSPORT**
  - **DILUTION**
  - **SECONDARY REACTIONS**
  - **REMOVAL BY NATURAL MECHANISMS**

→ **RECEPTORS** → **EFFECTS**

2.3 MEASUREMENT CRITERIA FOR THE CONCENTRATION OF GASEOUS POLLUTANTS

- **CONCENTRATIONS:**
  - **MOLAR FRACTION (=VOLUME)** $X_i = n_i/n$
  - **ppm (parts per 10^6), ppb (parts per 10^9), ppt (parts per 10^{12})**
  - **SOMETIMES INDICATED AS ppmv (VOLUME), .**
  - **OFTEN REFERRED TO DRY MIXTURE (dry basis) ppmvd**
  - **MOLAR MASS (OR MOLECULAR WEIGHT) OF A MIXTURE OF *N* CHEMICAL SPECIES**

    $$\mathcal{M} = \sum_{i=1}^{N} X_i \mathcal{M}_i$$

  - **MASS FRACTIONS** $Y_i = m_i/m$ **CAN BE RECOVERED AS** $Y_i = X_i \mathcal{M}_i/\mathcal{M}$
- **CONCENTRATIONS OF LIQUIDS AND SOLIDS ALWAYS EXPRESSED IN MASS TERMS**
- **FOR SOLID/LIQUID/GASEOUS POLLUTANTS IN ATMOSPHERE, ALSO CONCENTRATION IN MASS PER UNIT VOLUME** $c_i = m_i/V$ **(μg/m^3)**

2.4 EMISSION INDICES

- **$EINO_x$ = g NO_x EMITTED PER kg FUEL BURNED**
- **$EISO_x$ = g SO_x EMITTED PER kg FUEL BURNED**
- **EICO = g CO EMITTED PER kg FUEL BURNED**
- **EIUHC = g UHC EMITTED PER kg FUEL BURNED**
- **EIPM = g PM (*Particulate Matter = soot*) EMITTED PER kg FUEL BURNED**

2.5 TYPICAL VALUES OF EMISSION INDICES

- **VALUES *AVERAGED* OVER THE WHOLE WORLD AIR FLEET:**
  $EINO_x = 13{,}2\ g/kg_f$, $EICO = 3{,}25\ g/kg_f$, $EIUHC = 0{,}4\ g/kg_f$, $EIPM = 0{,}025\ g/kg_f$
- **FOR A GIVEN ENGINE, THEY DEPEND ON OPERATING CONDITIONS, e.g., CFM56–5C3:**

MODE	POWER SETTING (%F_{oo})	TIME mins	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg)		
				HC	CO	NO_x
TAKE-OFF	100	0.7	1.373	0.008	0.98	34.7
CLIMB OUT	85	2.2	1.131	0.008	0.82	27.1
APPROACH	30	4.0	0.370	0.074	1.57	10.4
IDLE	7	26.0	0.1203	5.35	32.6	4.26

2.6 EMISSIONS PER LTO CYCLE (LANDING/TAKE–OFF)

- **EMISSIONS PER LTO CYCLE, e.g., NO_x (n NO. ENGINES, e.g., 2):**

$$m_{\mathrm{NO_x,LTO}} = n \cdot \sum_{i=1}^{4} \Delta t_i \, \dot{m}_{f,i} \, EINO_{\mathrm{x,i}} \, / \, 1000$$

MODE	POWER SETTING (%F_{oo})	TIME mins	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg)		
				HC	CO	NO_x
TAKE-OFF	100	0.7	1.373	0.008	0.98	34.7
CLIMB OUT	85	2.2	1.131	0.008	0.82	27.1
APPROACH	30	4.0	0.370	0.074	1.57	10.4
IDLE	7	26.0	0.1203	5.35	32.6	4.26

	TAKE OFF	CLIMB	APPR.	IDLE	TOTAL
UHC	0,001	0,002	0,013	2,008	2,025
CO	0,113	0,244	0,779	12,236	12,873
NO_x	4,002	8,092	1,847	1,599	15,540

2.7 UNITS OF MEASUREMENT

- **SI (SYSTÈME INTERNATIONAL) UNITS:**
  - **LENGTH m, MASS kg, TIME s, TEMPERATURE K, KILOMOLE kmol**
  - $T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273{,}15$
  - **ENERGY JOULE J (1 kWh = 3,6 MJ; 1 cal = 4,186 J; 1 kcal = 1 Cal = 4186 J; 1 BTU = 1055 J)**
  - **POWER WATT W (1 CV = 735,5 W; 1 HP = 746 W; 1 BTU/h = 0,293 W)**
  - **PRESSURE PASCAL Pa (1 atm = 101325 Pa)**
- **MULTIPLES/SUBMULTIPLES:**
  - kilo (k) = 10^3, mega (M) = 10^6, giga (G) = 10^9, tera (T) = 10^{12}, peta (P) = 10^{15}, exa (E) = 10^{18}, zetta (Z) = 10^{21}, yotta (Y) = 10^{24}
  - milli (m) = 10^{-3}, micro (μ) = 10^{-6}, nano (n) = 10^{-9}, pico (p) = 10^{-12}, femto (f) = 10^{-15}, atto (a) = 10^{-18}, zepto (z) = 10^{-21}, yocto (y) = 10^{-24}

2.8 MAIN ATMOSPHERIC POLLUTANTS AND CONTAMINANTS

- **PARTICULATE**
- **VOLATILE ORGANIC COMPOUNDS (*VOC*) AND UHC (*UNBURNED HYDROCARBONS*)**
- **OZONE O_3 (AT GROUND LEVEL)**
- **SULFUR OXIDES SO_x**
- **NITROGEN OXIDES NO_x**
- **CARBON MONOXIDE**
- **LEAD Pb, ARSENIC As**
- **...**

- **CARBON DIOXIDE CO_2**
- **METHANE CH_4**
- **NITROUS OXIDE N_2O**
- **(WATER H_2O)**

2.9.1 EFFECTS OF ATMOSPHERIC POLLUTANTS

- **EFFECTS ON HUMANS**
- **EFFECTS ON ANIMALS**
- **EFFECTS ON PLANTS**
- **EFFECTS ON MATERIALS**
- **EFFECTS ON THE ENVIRONMENT**

2.9.2 EFFECTS ON HUMANS

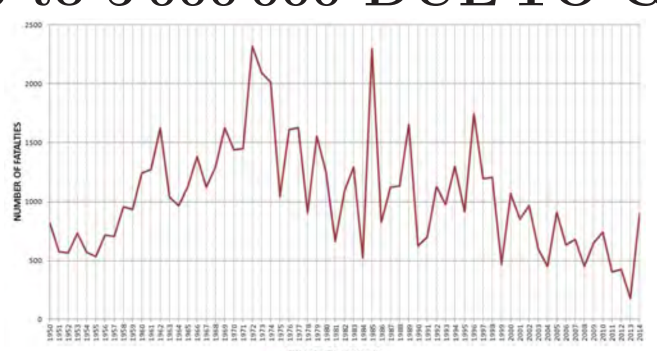
- **EVALUATED FROM:**
  - **EPIDEMIOLOGICAL STUDIES**
  - **STUDIES ON ANIMALS**
  - **EXPERIMENTS ON VOLUNTEERS**
  - **CELL CULTURE *IN VITRO* AND *IN VIVO***
- **POSSIBLE PRESENCE OF A *THRESHOLD***
- **GLOBAL ESTIMATE:**

  ~ 8 000 PREMATURE DEATHS PER YEAR DUE TO A/C EMISSIONS
- **TO BE COMPARED TO:**

  ~ 470000 DUE TO GROUND–LEVEL OZONE

  ~ 2 100 000 DUE TO PARTICULATE

  ~ 300 000 to 5 000 000 DUE TO GLOBAL WARMING
- **AND...**



2.9.3 EFFECTS ON ANIMALS

- **PARTLY SIMILAR TO THOSE ON HUMANS**
- **EFFECT OF UV RADIATION ON PLANKTON**

2.9.4 EFFECTS ON PLANTS

- **EXAMPLE: EFFECT SO_2 ON ALFALFA**
- **EFFECT NO_2 ↓**

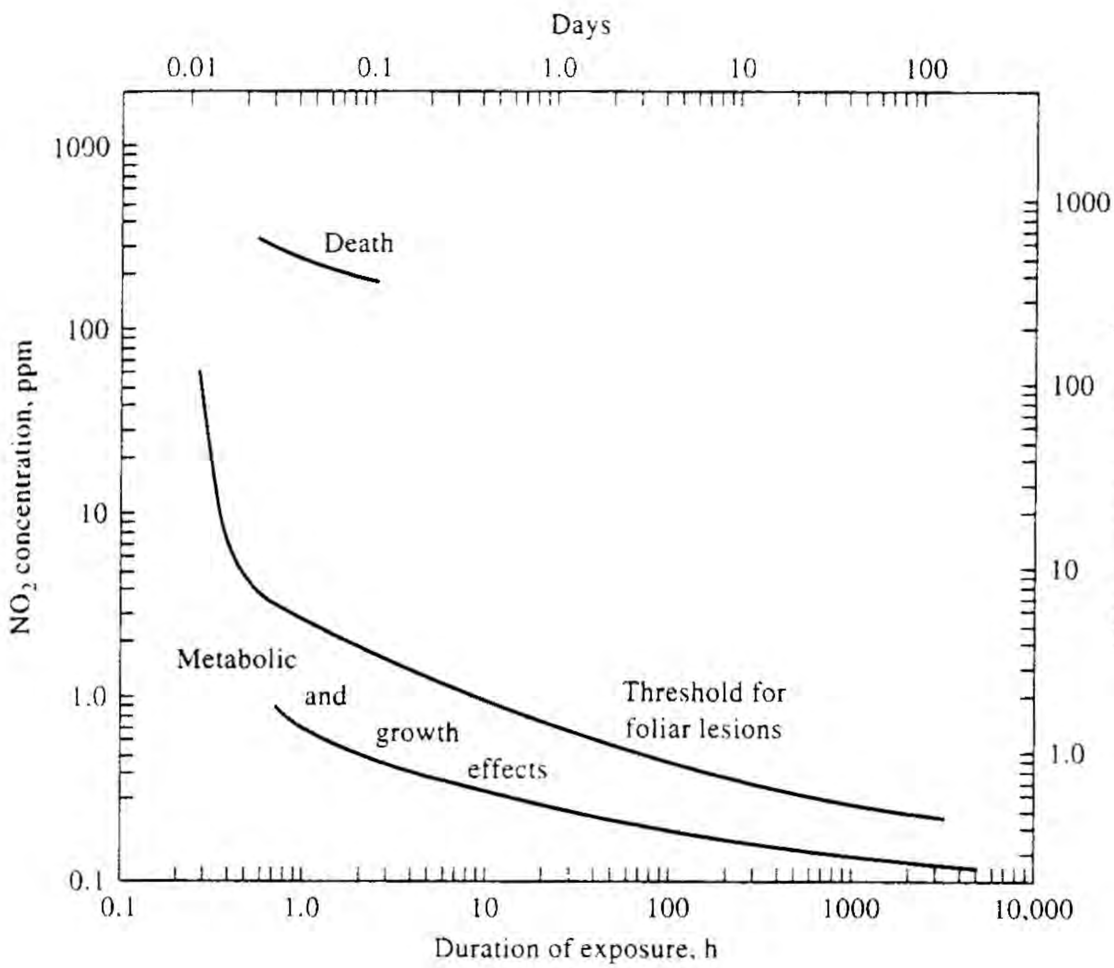


Figure 20: Threshold curves for the manifestation of effects on plants, as a function of NO_2 concentration and duration of exposure.

2.9.5 EFFECTS ON MATERIALS

- **EFFECT O_3 ON TYRES**
- **EFFECT SO_2 ON STEEL**

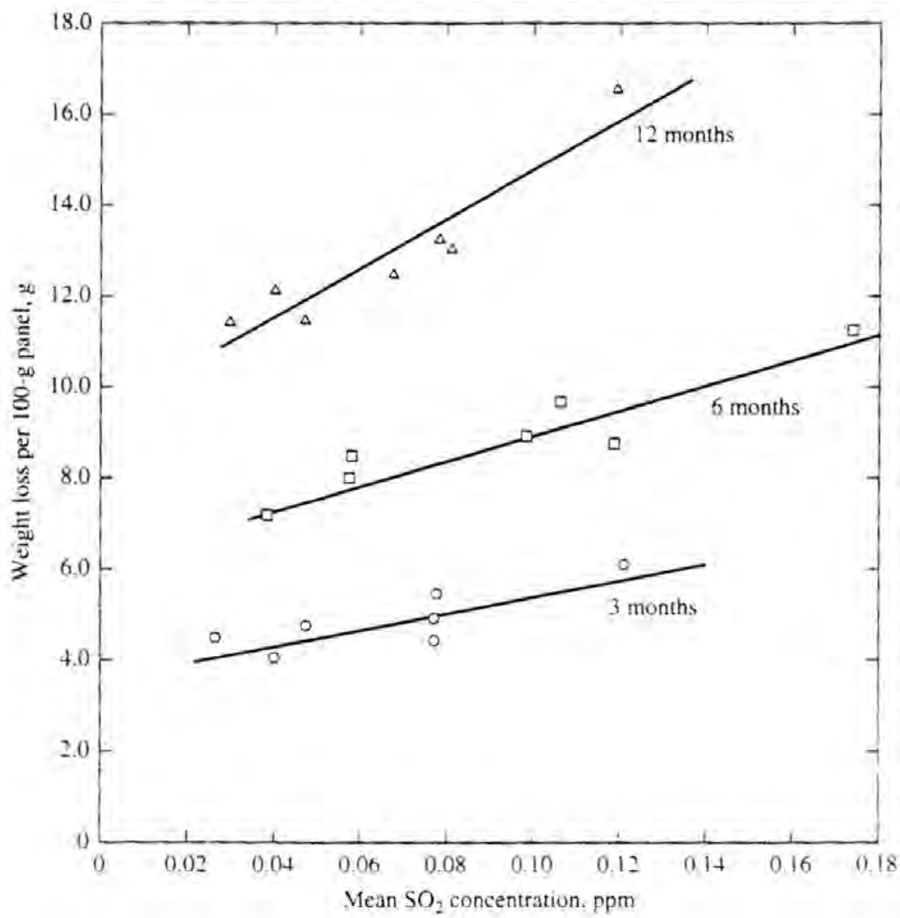


Figure 21: Weight loss of a steel panel as a function of SO_2 concentration, with duration of exposure as a parameter.

2.9.6 EFFECTS ON THE ENVIRONMENT

- **SMOG (VISIBILITY)**
- **ACID RAINS**
- **GLOBAL WARMING (GREENHOUSE EFFECT)**
- **DEPLETION OF OZONE LAYER**

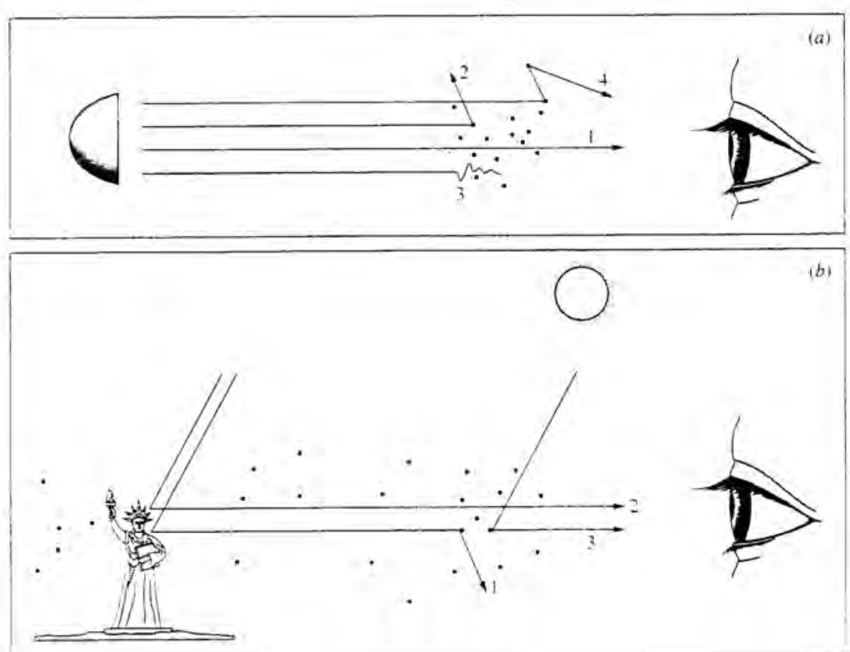


Figure 22: Interaction of photons with particles suspended in the atmosphere.

2.9.7 EFFECTS OF PARTICULATE

- **PRIMARY (RELEASED BY COMBUSTION) AND SECONDARY (FORMED IN ATMOSPHERE DUE TO VOC, UHC, NO_x, SO_x)**
- **FINE PARTICLES CAN REACH DEEPLY INTO THE LUNGS**
- **LONDON DECEMBER 1952, ABOUT 4000 DEAD**
- **100 $\mu g/m^3$ INCREASE PARTICULATE CONCENTRN $\rightarrow$ 6% INCREASE MORTALITY**
- **ALZHEIMER? (POSSIBLY 21% OF ALL CASES)**
- **VISIBILITY, GLOBAL WARMING**

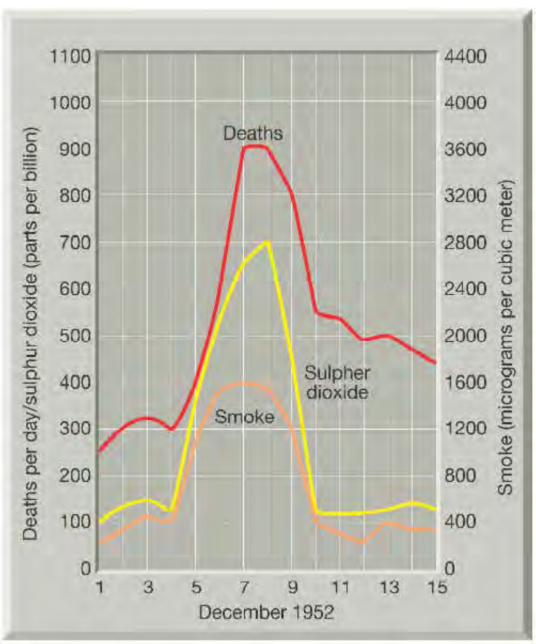


Figure 23: Daily mortality rate and particulate/SO_2 concentration for the pollution incident in London in December 1952.

2.9.8 EFFECTS OF SO_x

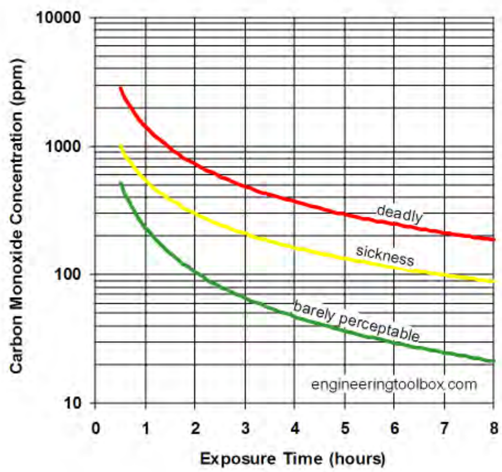
- **ACID RAINS (LARGEST CONTRIBUTOR)**
- **IRRITANT**
- **EFFECTS ON CULTIVATIONS**
- **PROMOTES FORMATION OF SECONDARY PARTICULATE**
- **COUNTERACTS GLOBAL WARMING**

2.9.9 EFFECTS OF NO_x

- **ACID RAINS (25 – 30% OF TOTAL)**
- **NO_2 RESPIRATORY IRRITANT ($\sim$ 1 ppb IN UNPOLLUTED AIR)**
- **EFFECTS ON CULTIVATIONS**
- **PROMOTES FORMATION OF SECONDARY PARTICULATE**
- **PROMOTES FORMATION OF GROUND–LEVEL O_3 IN THE PRESENCE OF HC, IRRITANT**
- **PROMOTES DESTRUCTION OF STRATOSPHERIC O_3 (BUT CFCs MUCH MORE HARMFUL)**
- **N_2O POWERFUL GREENHOUSE GAS**

2.9.10 EFFECTS OF CO

- **VERY STRONG AFFINITY FOR HEMOGLOBIN (220 TIMES > OXYGEN), FORMING CARBOXY-HEMOGLOBIN COHb**
- **CAN ALREADY BE FATAL FOR $X_{CO} = 0{,}02\%$**
- **CURRENTLY $X_{CO} = 120$ ppb N HEMISPHERE, 50 – 60 ppb S (SHORT MEAN LIFE, 0.2 a)**



% Hb CONVERTED TO COHb	EFFECTS
0,3 – 0,7	PHYSIOLOGICAL LEVEL FOR NONSMOKERS
2,5 – 3	CARDIAC FUNCTION DECREMENTS IN IMPAIRED INDIVIDUALS, BLOOD FLOW ALTERATIONS, CHANGES RED BLOOD CELL CONC.
4 – 6	VISUAL IMPAIRMENTS, VIGILANCE DECREMENTS, REDUCED MAX WORK CAPACITY
3 – 8	ROUTINE VALUES IN SMOKERS
10 – 20	HEADACHE, LASSITUDE, BREATHLESSNESS, DILATATION SKIN BLOOD CELLS, ABNORMAL VISION, POTENTIAL DAMAGE TO FETUS
20 – 30	SEVERE HEADACHE, NAUSEA, ABNORMAL MANUAL DEXTERITY
30 – 40	WEAKNESS, NAUSEA, VOMITING, DIMNESS OF VISION, SEVERE HEADACHE, IRRITABILITY, IMPAIRED JUDGMENT
50 – 60	FAINTING, CONVULSIONS, COMA
60 – 70	COMA, DEPRESSED CARDIAC ACTIVITY AND RESPIRATION, SOMETIMES FATAL
> 70	FATAL

2.9.11 MEAN LIFE IN ATMOSPHERE OF POLLUTANTS AND CONTAMINANTS

- **τ RELATED TO NATURAL REMOVAL MECHANISMS**

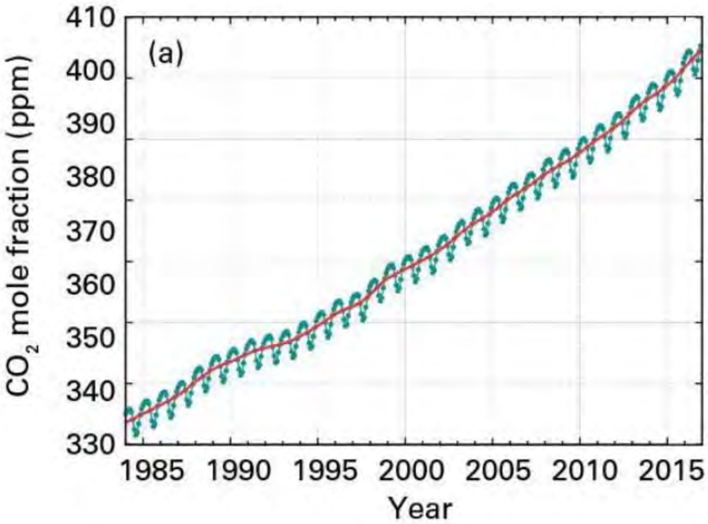
$$d(X - X_{eq}) \propto -(X - X_{eq})\, dt$$

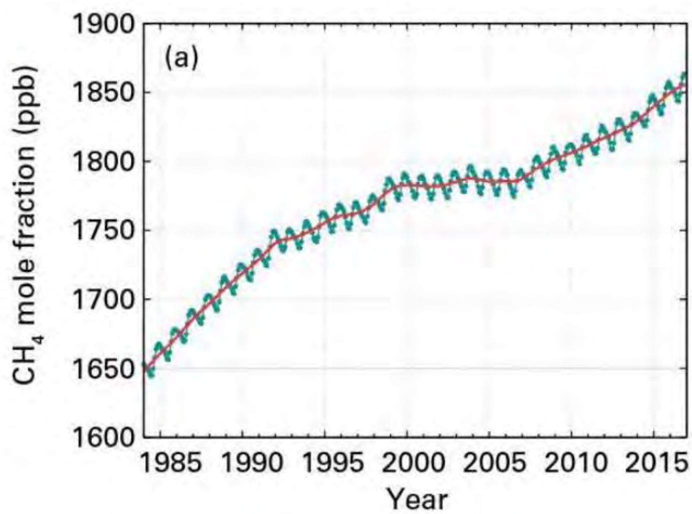
$$= -(X - X_{eq})\, \frac{dt}{\tau}$$

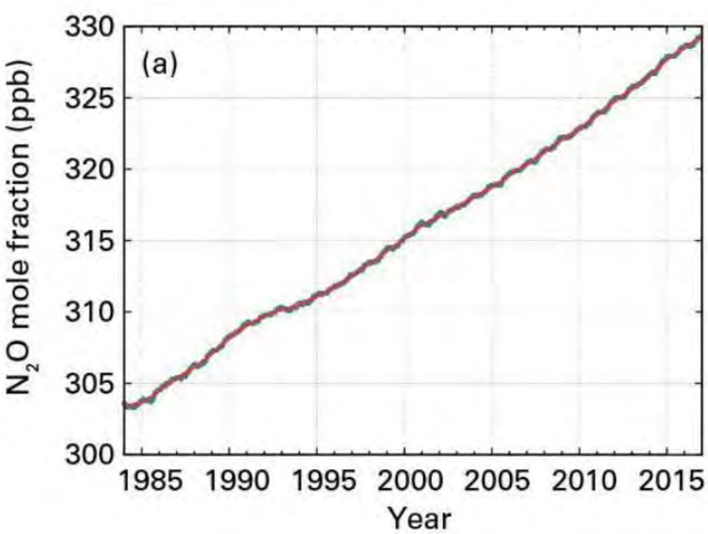
$$X(t) - X_{eq} = (X^* - X_{eq})\, \exp(-t/\tau)$$

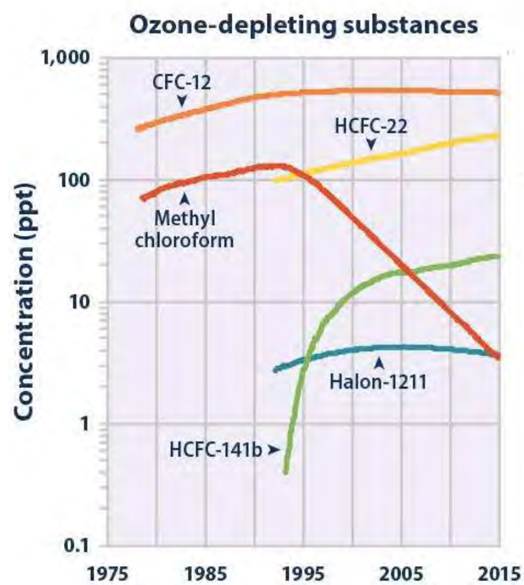
CHEMICAL SPECIES	PRE–INDUSTR CONCENTRN ppb	CURRENT CONCENTRN ppb	MEAN LIFE a	% VARIATN DUE TO COMBUST
CARBON DIOXIDE CO_2	278000	411000	120	> 90
METHANE CH_4	700	1868	14	10
NITROUS OXIDE N_2O	270	330	120	20
CFC–11 $CFCl_3$	0	0,232	50	0
CFC–12 CF_2Cl_2	0	0,516	102	0
CARBON MONOXIDE CO	60	120 (N EMISPH)	0,2	> 90
TROPOSPHERIC NO_x	?	10 − 1000	$< 0{,}03$	> 50
NON–METHANE HCs	?	?	0 − 0,24	...
STRATOSPHERIC WATER H_2O	3500	5500	~ 2	10
TROPOSPHERIC OZONE O_3	25	34	$< 0{,}1$	> 50
STRATOSPHERIC OZONE O_3	4000	3800	~ 2	< 5
SULPHUR DIOXIDE SO_2	?	> ?	...	> 90
SOOT C	?	> ?	$f(D, z)$	> 90

2.10 GROWTH OF ATMOSPHERIC CONTAMINANT CONCENTRATION









2.11 WEATHER CONDITIONS

- **POLLUTANT DISPERSION AFFECTED BY:**
  - **VERTICAL TEMPERATURE GRADIENT**
  - **WIND SPEED AND DIRECTION**
  - **ATMOSPHERIC TURBULENCE**

2.12.1 GLOBAL WARMING (GREENHOUSE EFFECT)

- **CAUSES:**
  - **GREENHOUSE GASES (GHGs)**
  - **AIRCRAFT CONTRAILS (*CONDENSATION TRAILS*)**
  - **CARBON BLACK (SOOT)**

2.12.2 EFFECTS OF GLOBAL WARMING

- **DESTRUCTION OF ECOSYSTEMS (e.g., CORAL REEF), REDUCTION BIODIVERSITY**
- **PROLIFERATION WEEDS AND INSECTS NOXIOUS TO CULTIVATIONS**
- **PROLIFERATION MOSQUITOES → DISEASES**
- **REDUCTION GROWTH PHYTOPLANKTON AND ALGAE**
- **DESERTIFICATION**
- **INCREASED OCCURRENCE OF EXTREME WEATHER CONDITIONS**
- **MELTING POLAR CAPS AND GLACIERS**
- **RELEASE CH_4 DUE TO MELTING TUNDRA**
- **FLOODING COASTAL AREAS (ALSO DUE TO THERMAL DILATATION OF OCEANS)**
- **POSSIBLE EFFECT ON GULF STREAM, EL NIÑO, LA NIÑA**
- **INCREASED AGRICULTURE YIELDS (IF $\Delta T < 2$ K**
- **(OCEAN ACIDIFICATION)**

2.12.3 EFFECT ON FREQUENCY OF EXTREME WEATHER

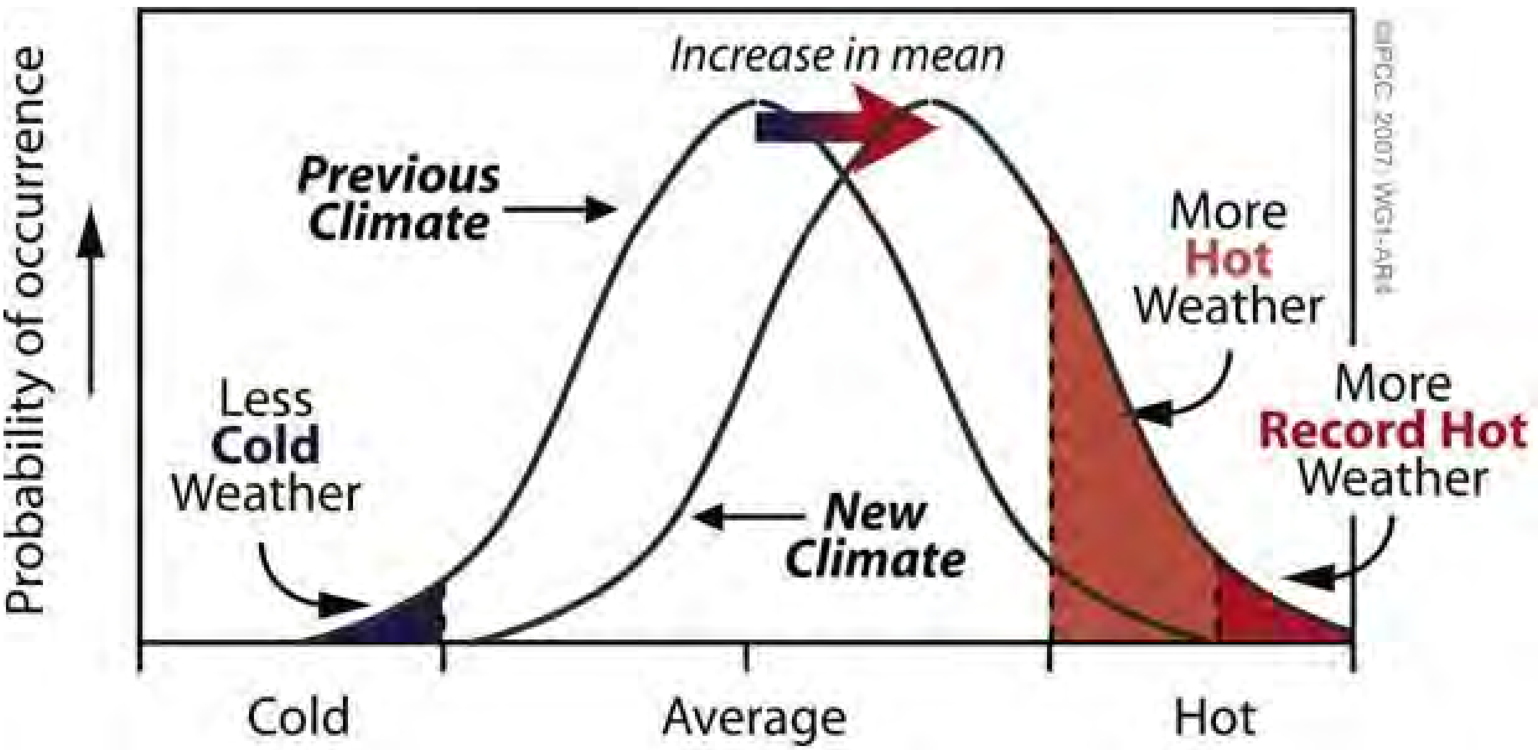


Figure 24: Increased yearly probability of occurrence of very hot days after a small increase of average temperature.

- **ABOUT 60 000 DEATHS/YEAR DUE TO WEATHER–RELATED NATURAL DISASTERS**
- **MORE THAN TRIPLED w.r.t. 1960s**

2.13.1 GREENHOUSE GASES

- **GHGs: CO_2 (∼ 77%), CH_4 (∼ 14%), N_2O (∼ 8%), CFC (∼ 1%), (H_2O)**
- **CAUSE GLOBAL WARMING (0,74 K IN 20th CENT.; 1,1 TO 6,4 K ANTICIPATED IN 21st)**
- **X_{CO_2} = 278 ppm IN PRE–INDUSTRIAL AGE, CURRENTLY ∼ 411 ppm; GROWTH CONTINUES...**

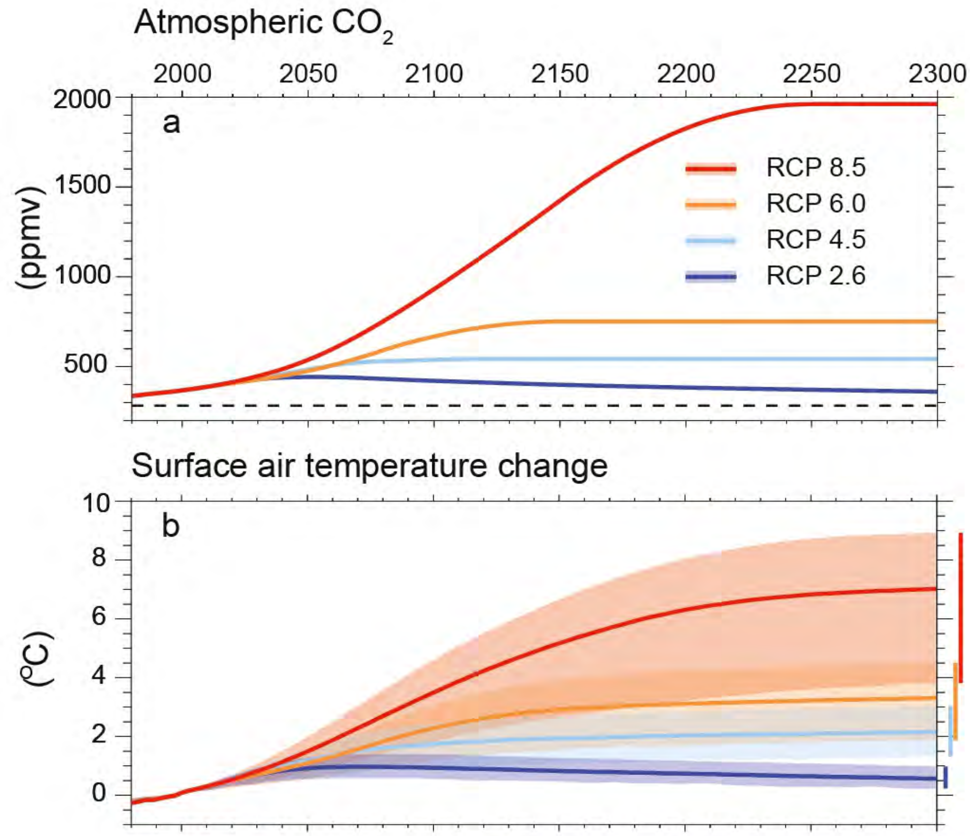


Figure 25: Anticipated CO_2 concentration and temperature rise for different scenarios.

- **LONG CO_2 MEAN LIFE → EVEN HALTING GHGs EMISSIONS NOW, WARMING WOULD LAST FOR CENTURIES (e.g., +0.6 K in 21st CENT.)**

2.13.2 CONTRIBUTION OF DIFFERENT GHGs

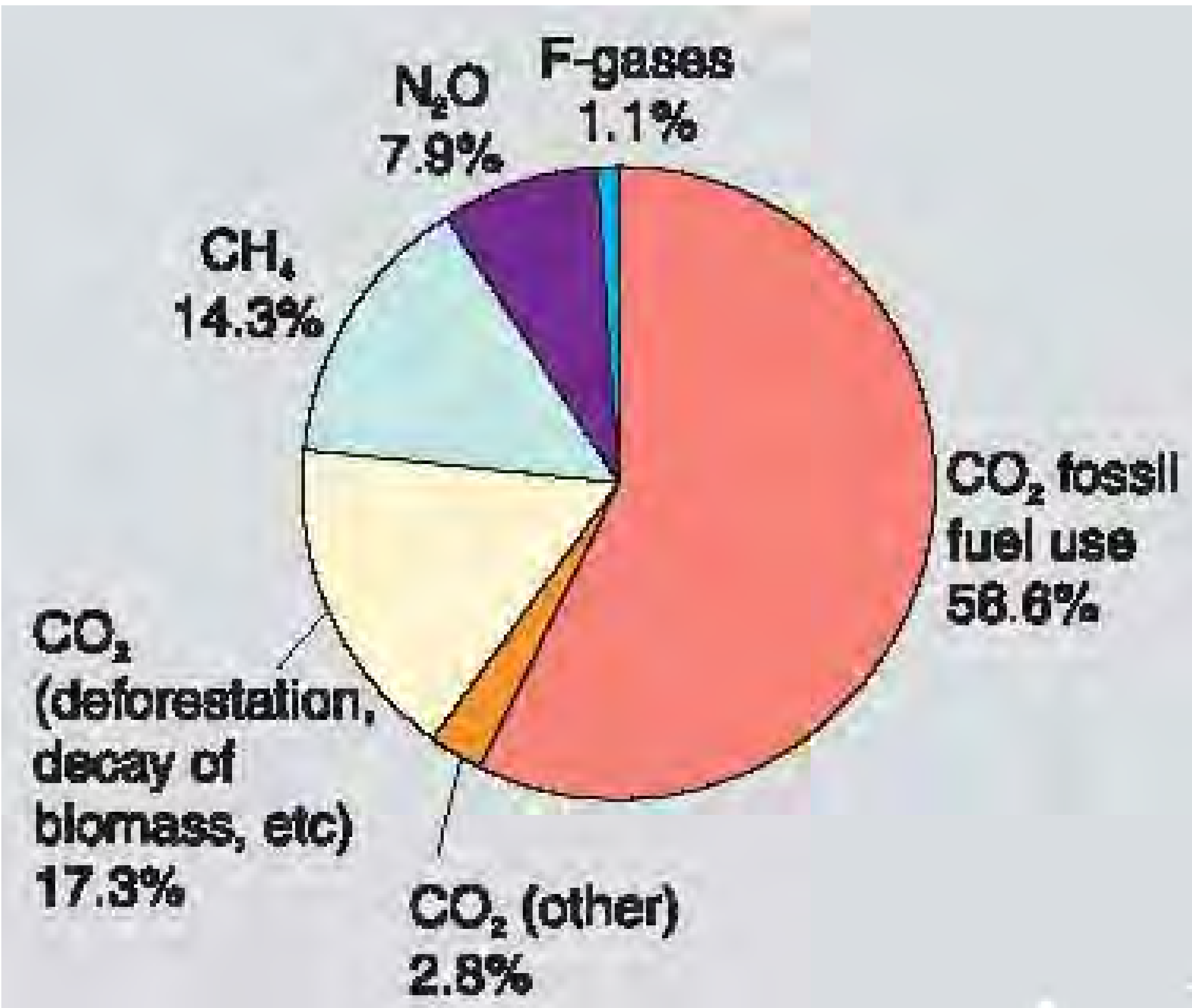
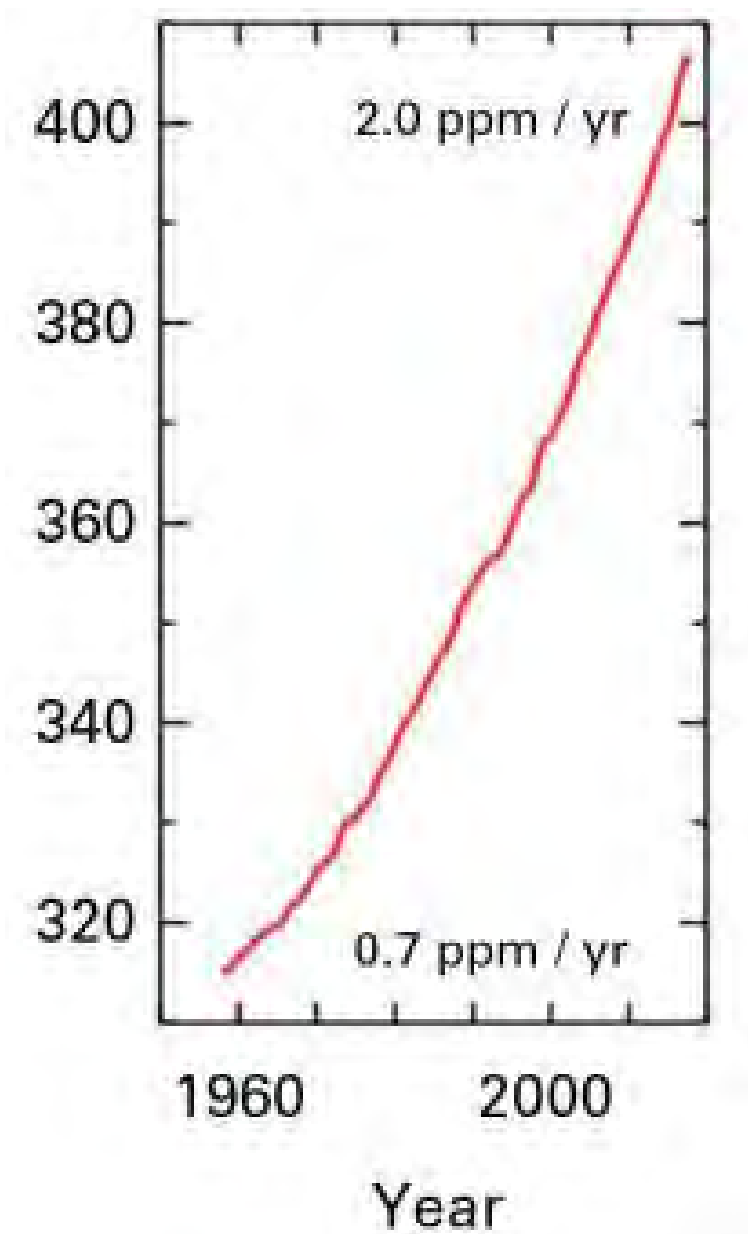
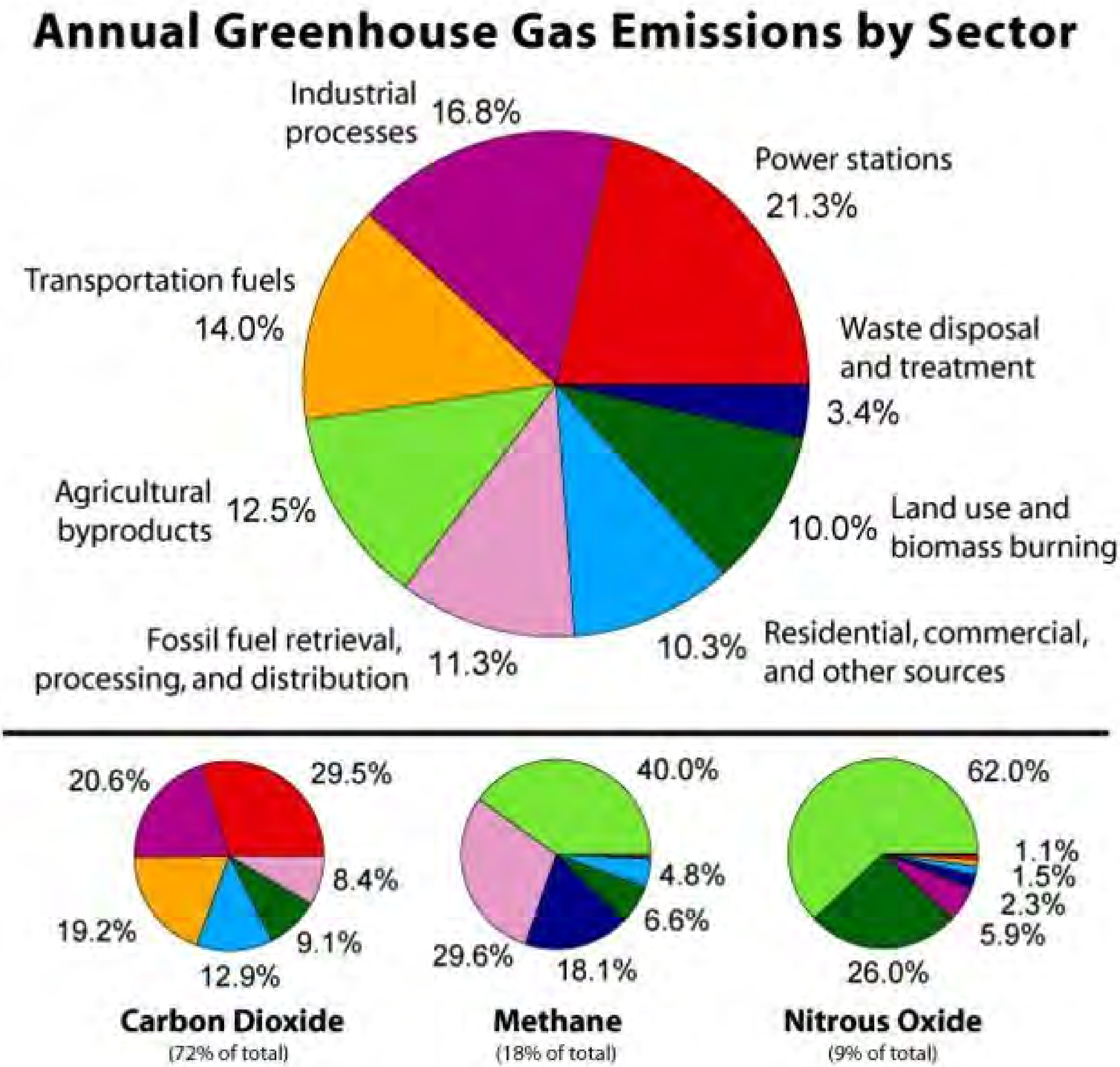


Figure 26: Contribution of the different greenhouses gases to global warming.

2.13.3 CO_2 GROWTH RATE



2.13.4 GHG EMISSION SOURCES



2.13.5 CORRELATION BETWEEN CO_2 CONCENTRATION AND SURFACE TEMPERATURE

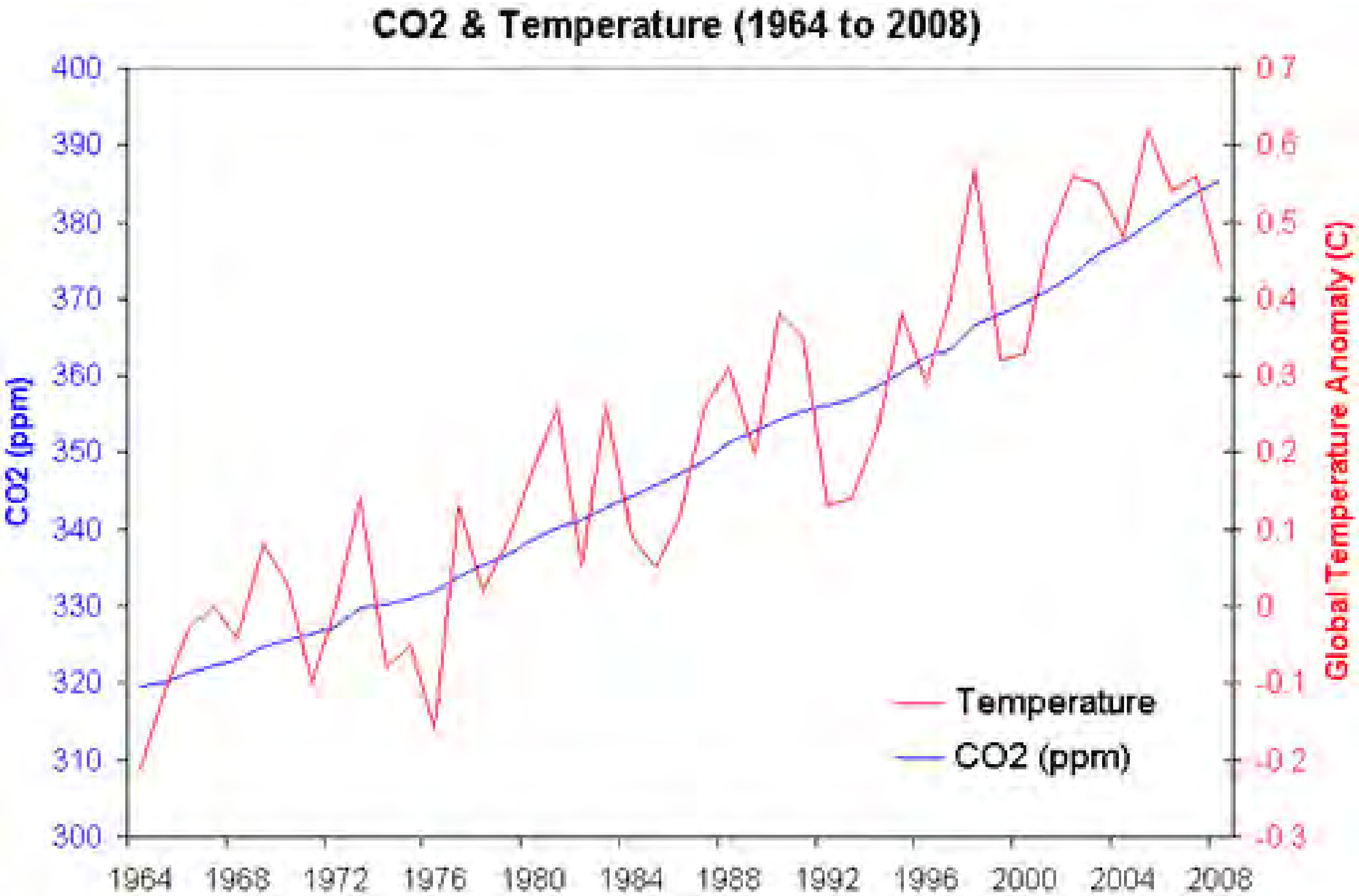


Figure 27: Increase of CO_2 concentration and global mean surface temperature.

2.13.6 YET, ON A DIFFERENT TIME SCALE...

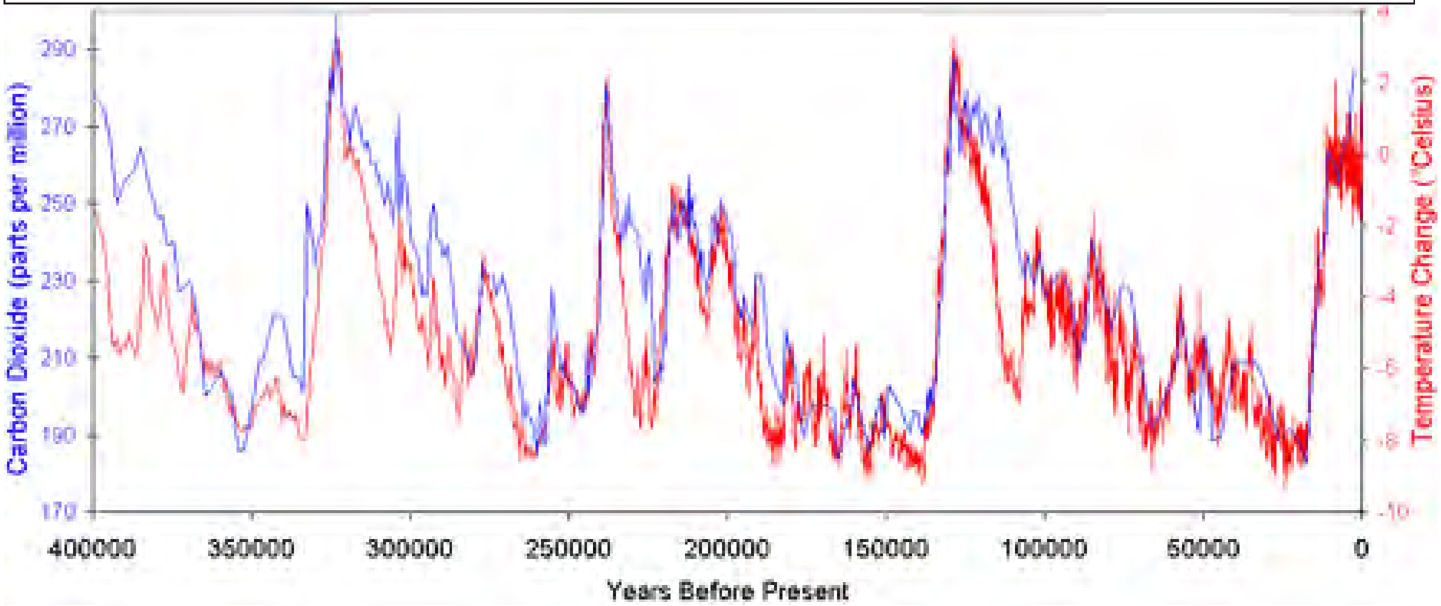


Figure 28: CO_2 concentration and mean temperature in the past 400000 years.

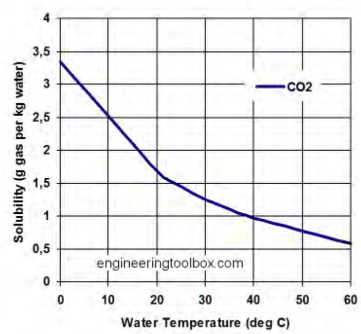


Figure 29: CO_2 solubility in water as a function of temperature.

- **OCEANS HEAT UP/COOL DOWN MUCH MORE SLOWLY THAN ATMOSPHERE OWING TO MUCH LARGER THERMAL INERTIA**
- **SUBSEQUENT CO_2 RELEASE/ABSORPTION**
  - $m_{atm} \simeq$ **5 000 Tt**, $c_p \simeq$ **1 kJ / (kg K)**
  - $m_{oce} \simeq$ **1 400 000 Tt**, $c \simeq$ **4 kJ / (kg K)**

2.13.7 OCEAN ACIDIFICATION

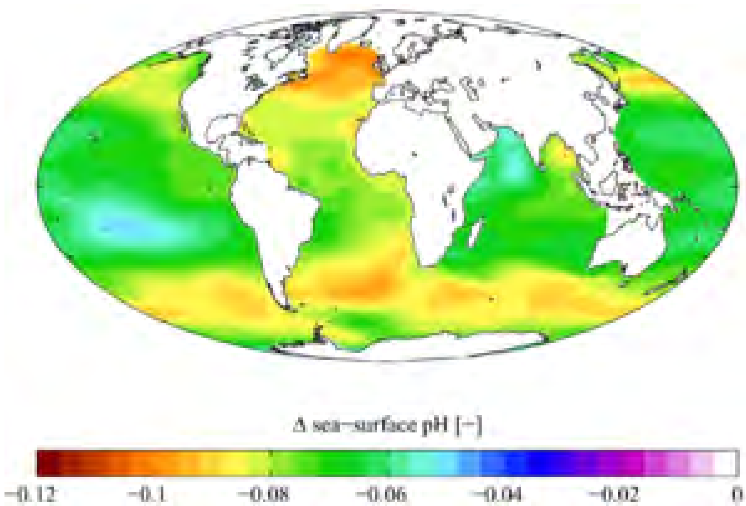


Figure 30: Variation of ocean surface pH from the beginning of the industrial era to the 1990's.

- **pH DECREASED 0,1 SO FAR**
- **PERHAPS 0,3 – 0,5 IN 21st CENTURY**

→ **EFFECT ON CORAL REEF, SHELL CRUSTACEANS AND MOLLUSCS, ...**

2.13.8 EFFECT OF TROPOSPHERIC H_2O

- **GHG, BUT IMPACT OF HUMAN ACTIVITIES GLOBALLY NEGLIGIBLE IN TROPOSPHERE; SHORT MEAN LIFE ($\sim$ 10 d)**

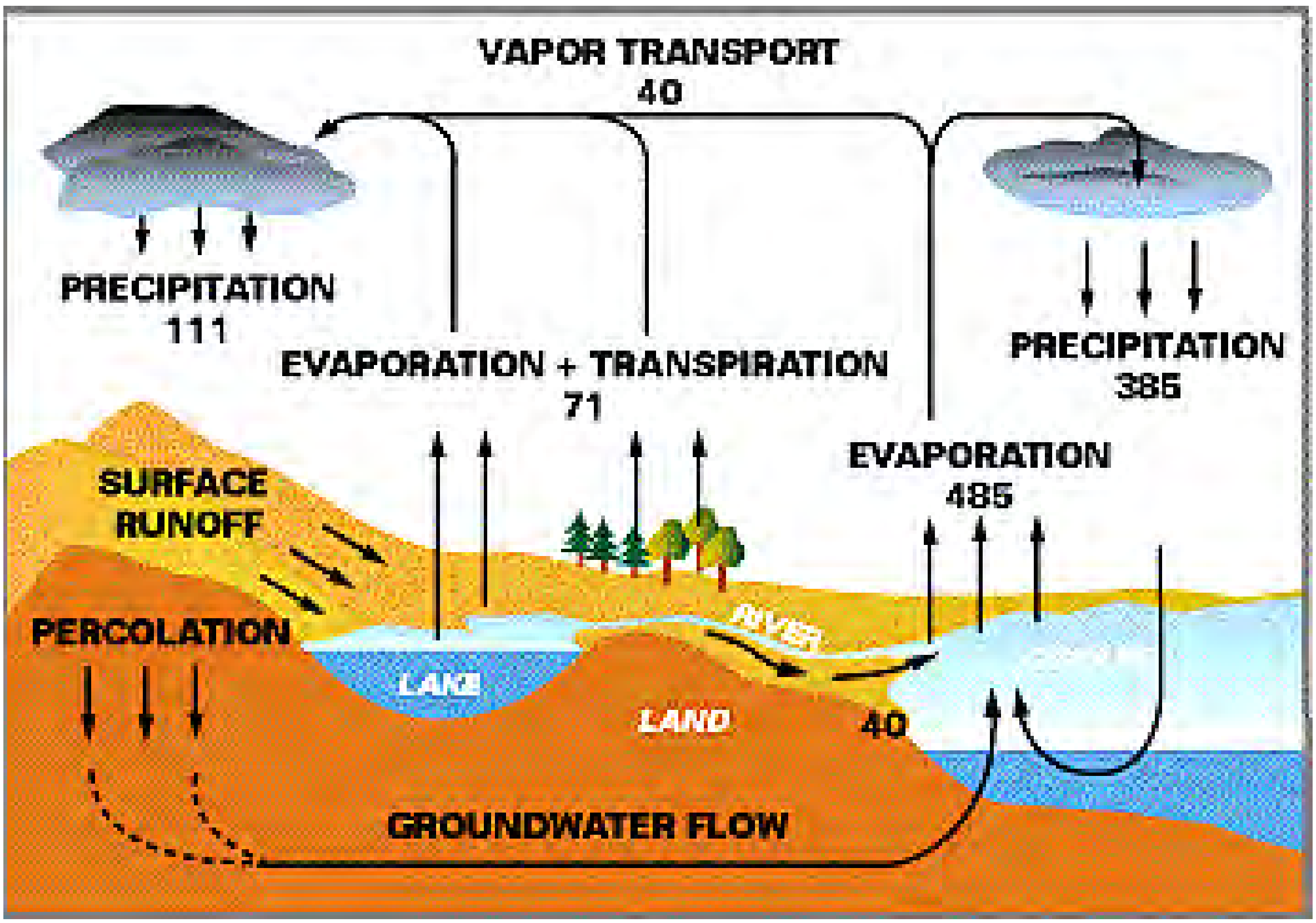


Figure 31: Global water flows (in Tt/a).

2.13.9 GLOBAL WARMING FROM GHGs

- **EARTH RECEIVES ENERGY FROM SUN IN FORM OF RADIATION, DISTRIBUTED OVER A WIDE RANGE OF WAVELENGTHS λ (OR FREQUENCIES ν)**
- $\lambda = c/\nu$, $c \simeq 300\,000$ km/s **LIGHT SPEED**
- **EARTH RADIATES ENERGY TOWARDS SPACE, OVER A WIDE RANGE OF WAVELENGTHS**
- **SUN SURFACE TEMPERATURE $\simeq$ 6000 K**
- **EARTH SURFACE TEMPERATURE $\simeq$ 288 K**
- **WAVELENGTH OF MAX EMISSION (WIEN's LAW)** $\lambda_{max} = 2{,}897 \cdot 10^{-3} \; / \; T$
- **FOR THE SUN** $\lambda_{max} = 0{,}483$ μm **(VISIBLE)**
- **FOR THE EARTH** $\lambda_{max} = 9{,}99$ μm **(INFRARED)**
- **ATMOSPHERIC TRANSPARENCY/OPACITY TO RADIATION OF DIFFERENT λ**

2.13.10 ATMOSPHERIC ABSORPTION AND EMISSION SPECTRA

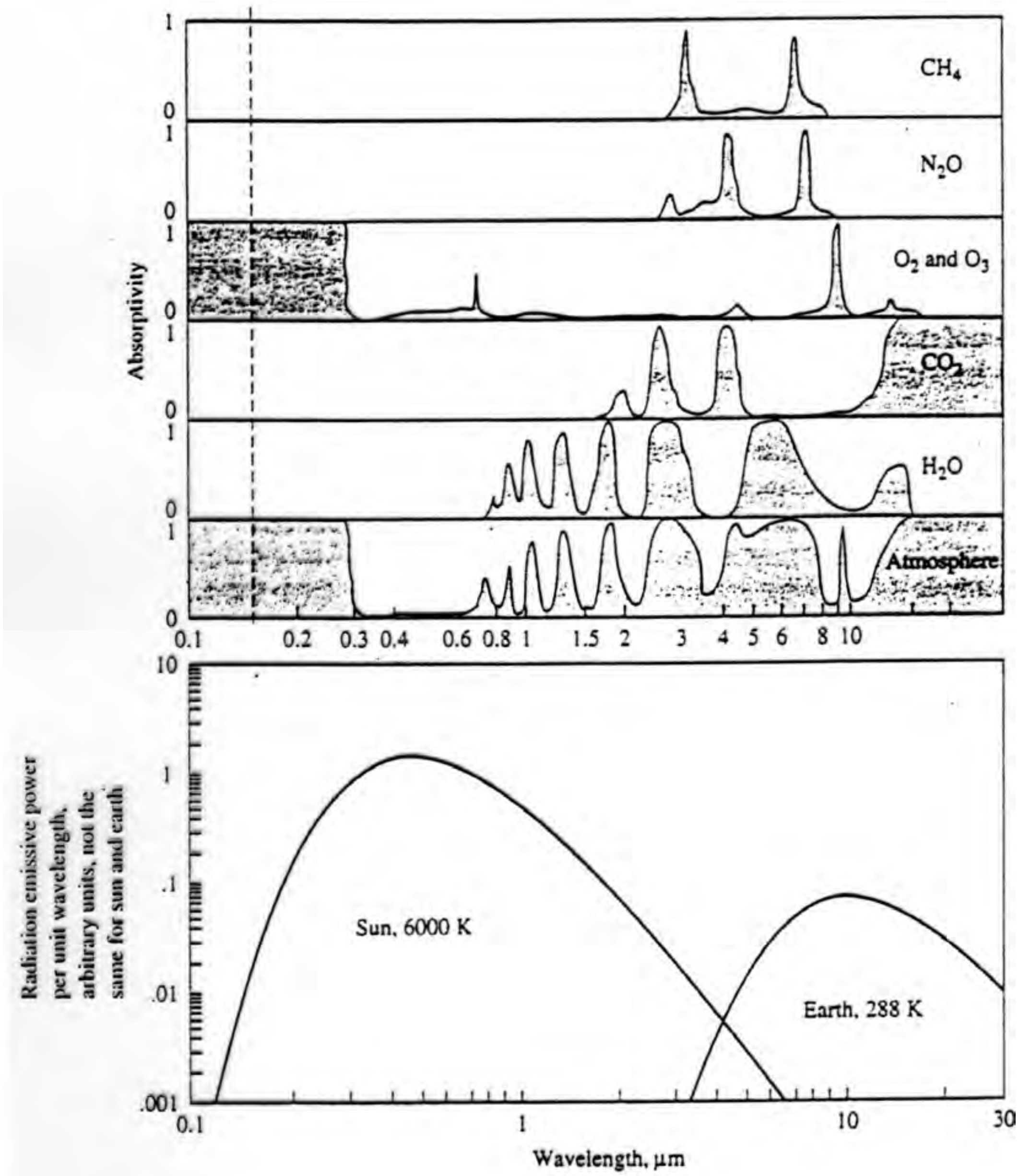


Figure 32: Fraction of radiant energy absorbed by some atmospheric components as a function of wavelength (top), and emission spectra of the Sun and the Earth (bottom, not at scale).

2.13.11 PROCESSES INTERACTING IN GLOBAL WARMING

• PROCESSES NOT YET FULLY UNDERSTOOD

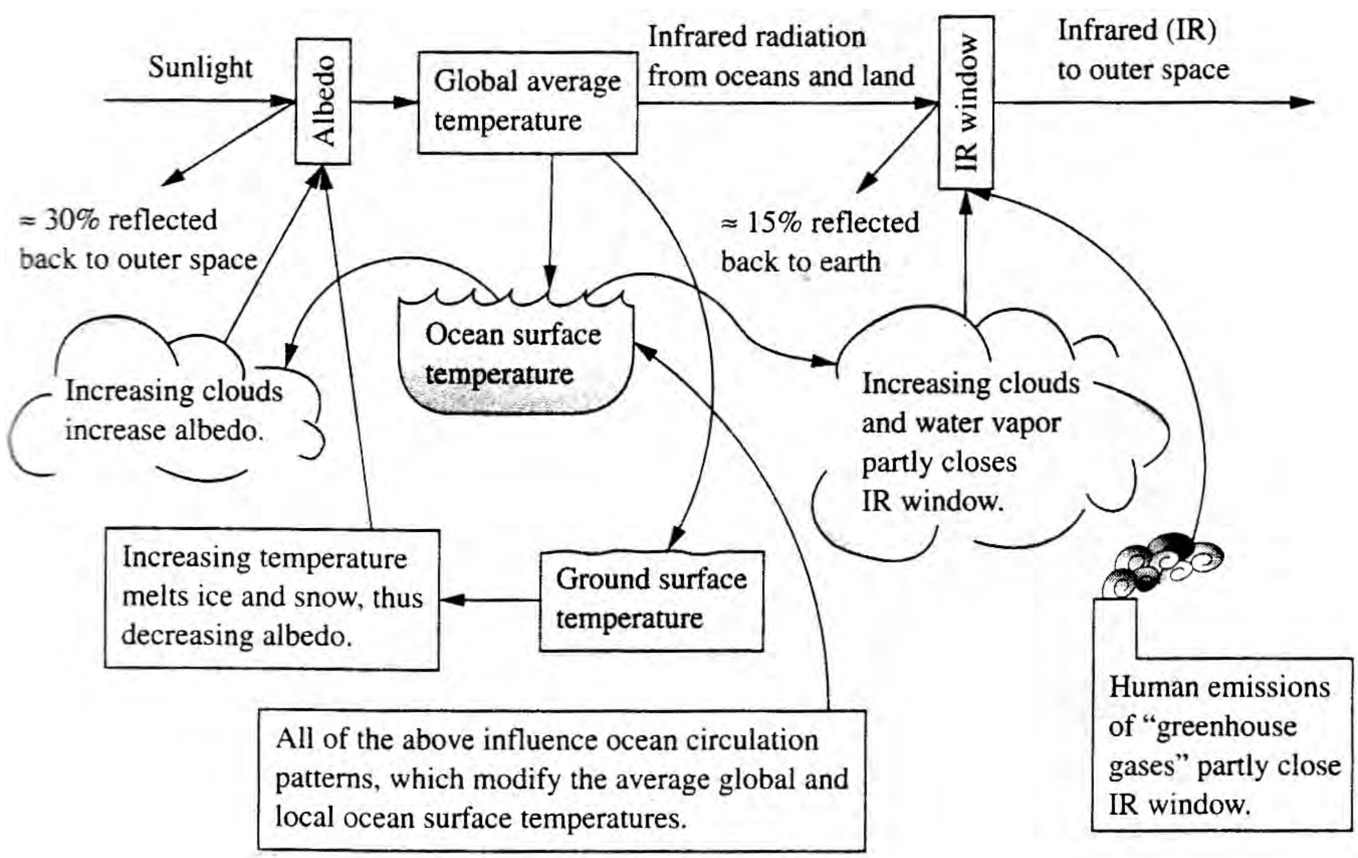


Figure 33: Scheme (simplified) of processes interacting in global warming.

2.13.12 FOSSIL FUELS AND CONTAMINANT EMISSIONS

- **(ELEMENTAL COMPOSITIONS APPROXIMATED <u>QUITE CRUDELY</u>)**

FUEL	YEARLY CONSUMPTN Gt	APPROX COMPOSITN (MASS)	C RELEASED Gt	CO_2 RELEASED Gt	H_2O RELEASED Gt
OIL	4.13	86% C 14% H	3.54	12.98	5.31
NATURAL GAS	2.45	75% C 25% H	1.84	6.75	5.51
COAL	3.73	76% C 3.5 % H	2.80	10.26	1.17
TOTAL	10.3		8.2	30	12

- **MORE ACCURATE BOOKKEEPING GIVES $\sim$ 10.1 Gt CARBON RELEASED $\rightarrow$ 37.1 Gt CO_2 (2018)**

2.13.13 CARBON FLUXES

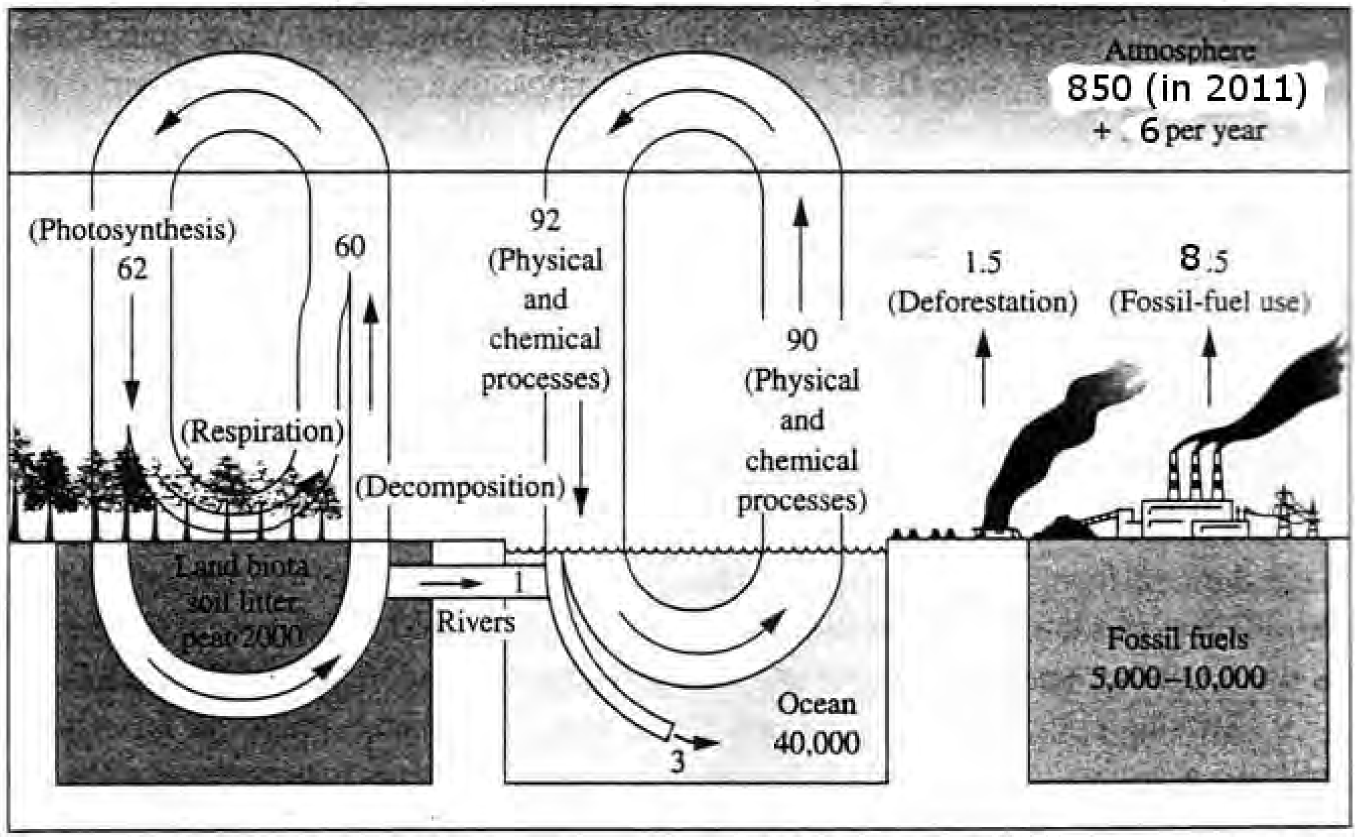


Figure 34: Global fluxes (in Gt/a) and reserves (in Gt) of carbon.

2.13.14 GLOBAL WARMING POTENTIAL (GWP)

- **EFFECT OF 1 kg OF A GIVEN GHG ON GW, RELATIVE TO 1 kg CO_2**
- **DEPENDING ON TIMEFRAME UNDER CONSIDERATION**

GREENHOUSE GAS	20 a	100 a	500 a	YEARLY CONCENTR. RISE
CO_2	1	1	1	0,4%
CH_4	56	21,5	6,5	0,6%
N_2O	280	310	170	0,25 %
CFC–11 CCl_3F		12000		0 %
CFC–12 CCl_3F_2		16000		0 %
HFC–23	9100	11700	9800	
HFC–32	2100	650	200	
SF_6	16300	23900	34900	

2.14.1 EFFECT OF STRATOSPHERIC H_2O

- **VERY LOW CONCENTRATION $\sim$ 5,5 ppm**
- **MEAN LIFE MUCH LONGER IN STRATOSPHERE ($\sim$ 2 a)**
- **STRATOSPHERIC H_2O FROM OXIDATION CH_4 AND EMISSIONS JET ENGINES**
- **H_2O EMITTED FROM JET ENGINES AT ALTITUDE FORMS CRYSTALS AND CLOUDS (*CONTRAILS* – CONDENSATION TRAILS)**

2.14.2 CONTRAILS

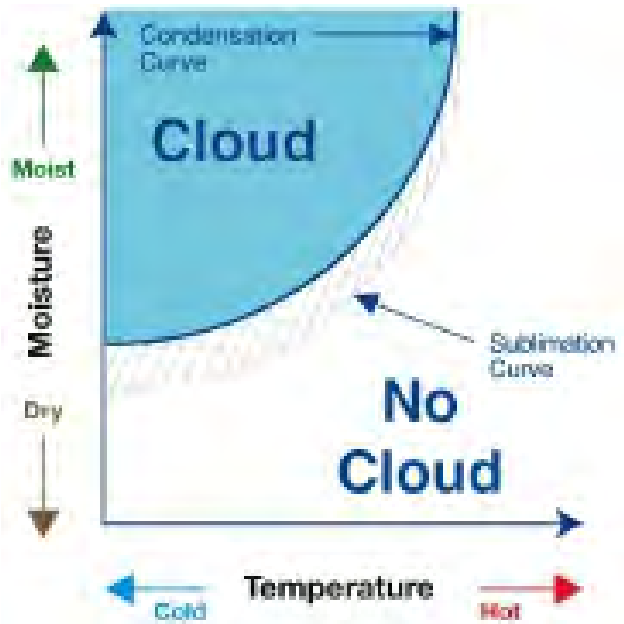
- **H_2O SOLIDIFIES OWING TO LOW T**
- **SOOT ACTS AS SOLIDIFICATION NUCLEUS (FOR STRATOSPHERIC H_2O, TOO)**

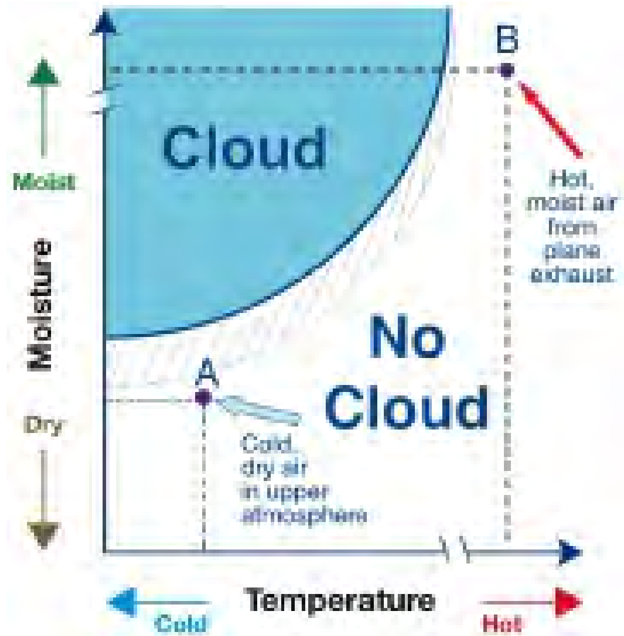
Figure 35: *Contrails* issuing from an aircraft.

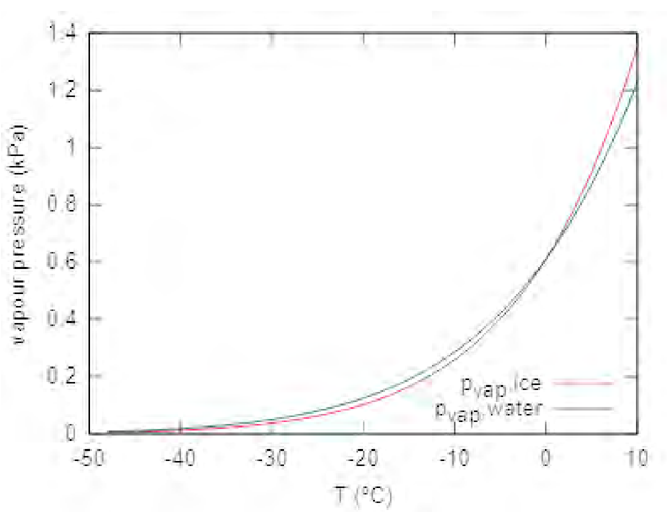
- **AERODYNAMIC CONTRAILS**

2.14.3 CONTRAIL FORMATION TEMPERATURE–HUMIDITY PLANE

- (from NASA LARC)







- (PURE H_2O STAYS LIQUID BELOW 0ºC IN ABSENCE OF CONDENSATION NUCLEI → ***SUBCOOLED*** WATER)

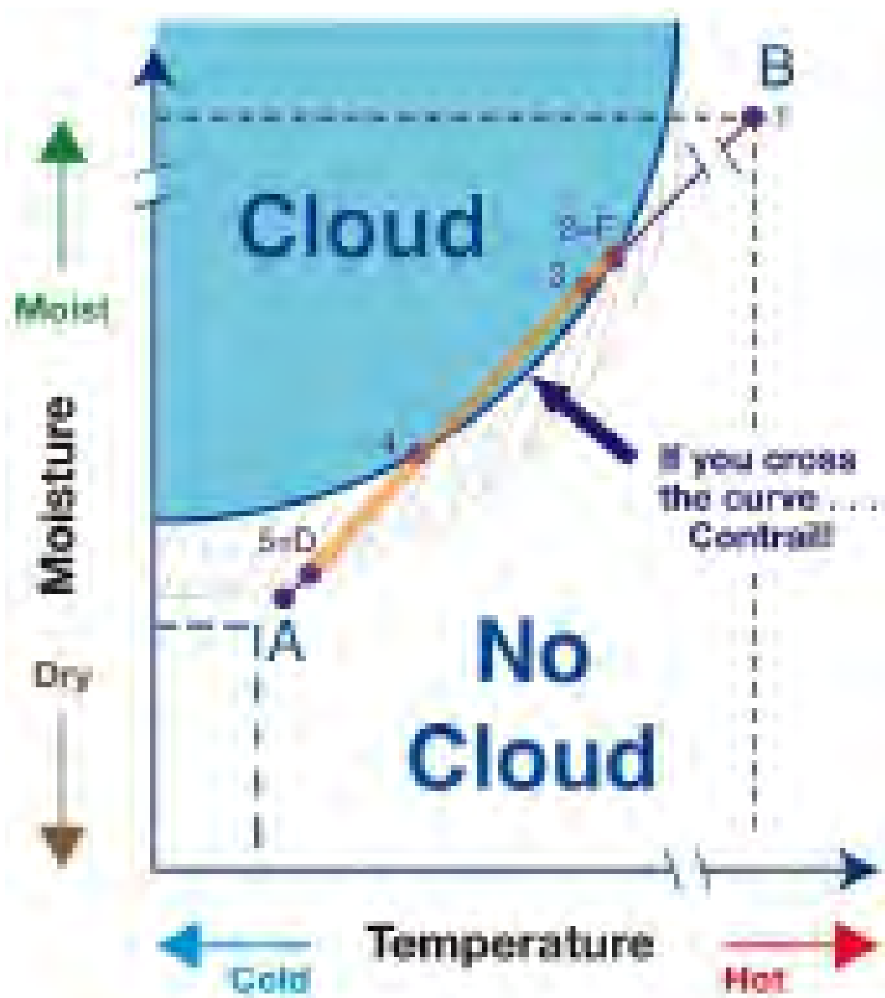
2.14.4 EVOLUTION OF EXHAUST GASES

2. CONTRAIL FORMS

3. DROPLETS FREEZES TO ICE

4. DROPLETS EVAPORATES, ICE PERSISTS

5. CONTRAIL DISAPPEARS



2.14.5 SLOPE OF HUMIDITY–TEMPERATURE LINE

- **1 kg EXHAUST GAS + N kg AIR → (N + 1) kg MIXTURE**
- **N SPANS THE RANGE 0 → ··· (VERY LARGE)**
- $T_{ex} + N\,T_{amb} = (N+1)\,T_{mix}, \qquad (c_p = \text{const})$

$$\rightarrow \Delta T = T_{mix} - T_{amb} = (T_{ex} - T_{amb})/(N+1)$$

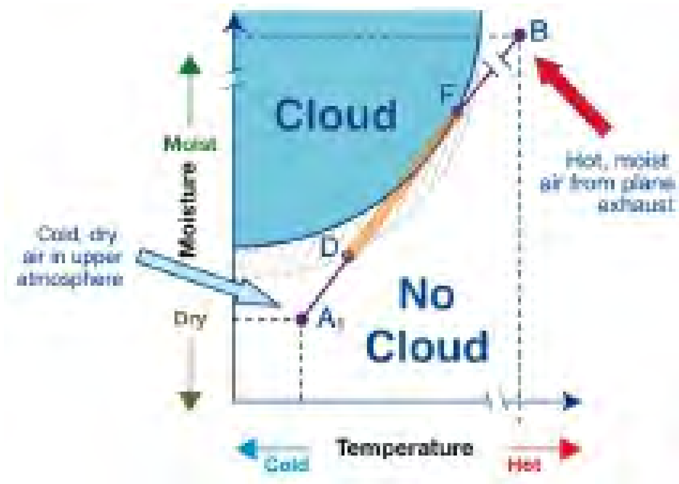
- **SAME FOR HUMIDITY Y_{H_2O}**

$$\rightarrow \Delta Y_{H_2O} = Y_{H_2O,mix} - Y_{H_2O,amb} = \frac{Y_{H_2O,ex} - Y_{H_2O,amb}}{N+1}$$

$$\Longrightarrow \Delta Y_{H_2O}/\Delta T = \frac{Y_{H_2O,ex} - Y_{H_2O,amb}}{T_{ex} - T_{amb}} = \text{const}$$

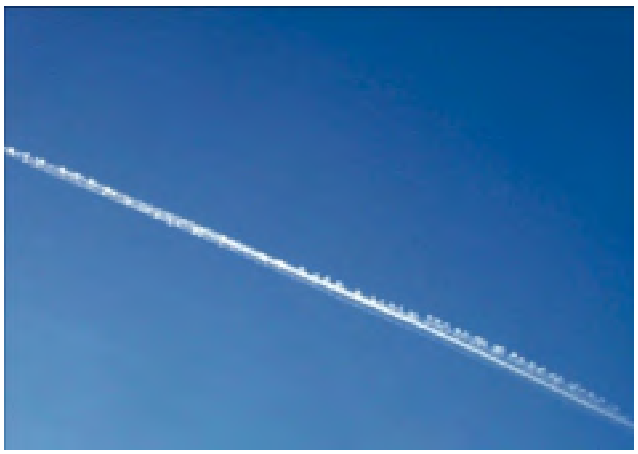
2.14.6 SHORT–LIVED (LINEAR) CONTRAILS

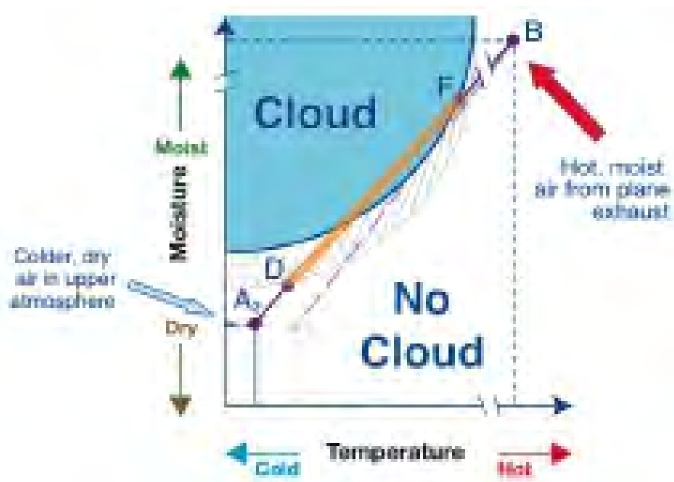
- **DRY, RELATIVELY WARM ATMOSPHERE**



2.14.7 PERSISTENT CONTRAILS

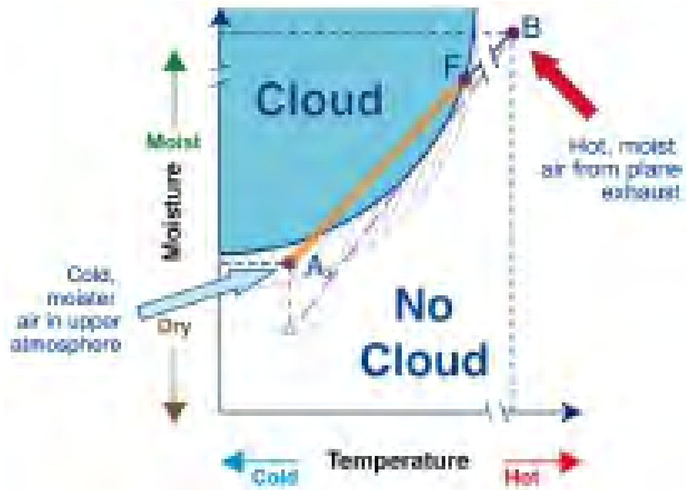
- **COLDER, MORE HUMID ATMOSPHERE**





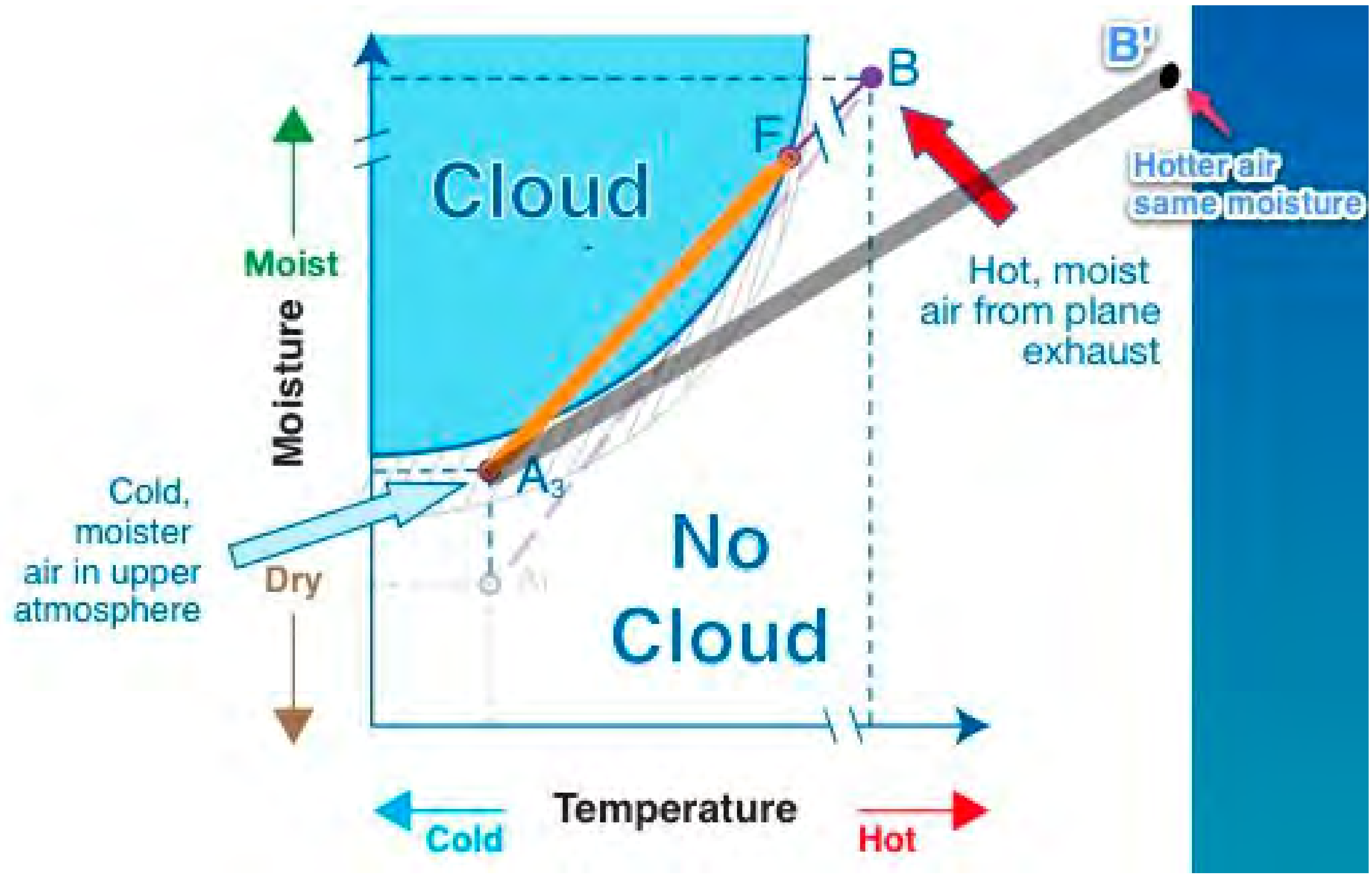
2.14.8 PERSISTENT, SPREADING CONTRAILS

• **EVEN COLDER, MORE HUMID ATMOSPHERE**



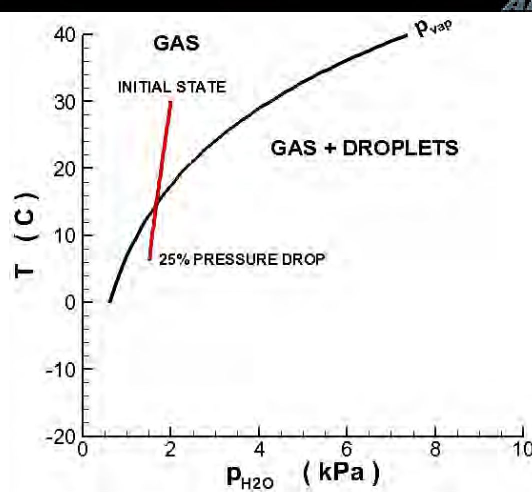
2.14.9 EFFECT OF η_o ON CONTRAILS

- **HIGHER η_o → LOWER EXHAUST T**



2.14.10 AERODYNAMIC CONTRAILS

- **DUE TO PRESSURE DROP AT VORTEX CORE**



2.14.11 EFFECT CONTRAILS ON CLIMATE

1. **SHIELD SUNLIGHT AT DAYTIME**
2. **BLOCK OUTGOING IR RADIATION AT NIGHT**

- **BALANCE: $\boxed{2} > \boxed{1} \Longrightarrow$ CONTRIBUTE TO GW**
- **EFFECT $\sim$ 1.1% OF TOTAL, TO BE ADDED TO 2% FROM CO_2 EMISSIONS FROM A/Cs**

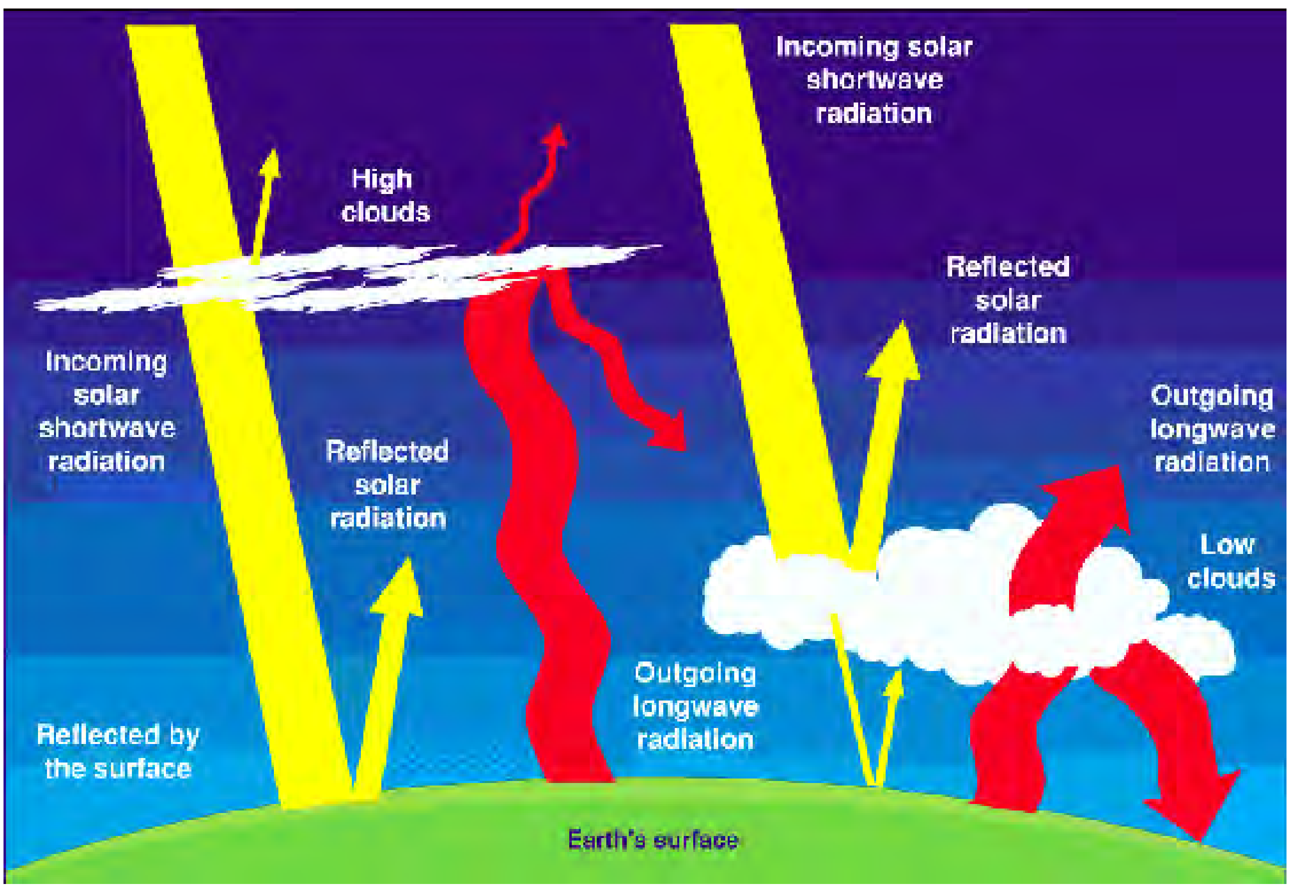


Figure 36: Schematic of the impact of *contrails* on global warmimg.

2.14.12 EFFECT OF CONTRAILS: REDUCED DAILY TEMPERATURE RANGE

- **IN DAYS FOLLOWING 11.09.2001, US AIRSPACE CLOSED**
- **DAILY TEMPER. RANGE ΔT INCREASED 1,1 °C**
- **RADIATION FROM EARTH $\propto \sigma T^4$**
- **$\Delta(\sigma T^4)^+ > \Delta(\sigma T^4)^-$ DUE TO NONLINEARITY**
- **NET FLUX INCREASES WITH ΔT**

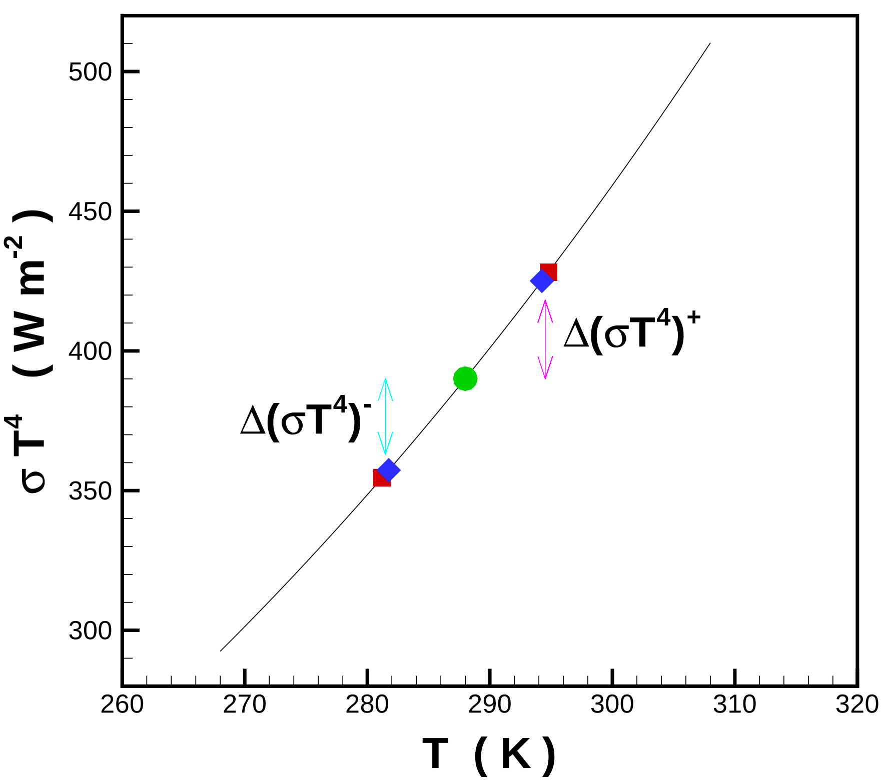


Figure 37: Effect of daily temperature range on radiative flux outgoing from Earth.

2.14.13 DURATION OF CONTRAILS

- **FROM < 1 min UP TO > 1 d**
- **IF SHORT–LIVED (< 30 min), LITTLE HARM**
- **IF PERSISTENT, PROMOTE GW**
- **DURATION DEPENDS ON ATMOSPHERIC HUMIDITY AND TEMPERATURE**

→ **MORE PERSISTENT IN HUMID CLIMATES, AT NIGHT, IN WINTER**

- **(FURTHER, IN WINTER SUN SHIELD EFFECT LESS IMPORTANT)**

2.14.14 PROPOSED COUNTERMEASURES AGAINST CONTRAILS

- **INCREASE FLIGHT LEVEL AT MID–LATITUDES (BUT OZONE...), REDUCE IT AT THE TROPICS (...ATC)**
- **AVOID ZONES FAVOURING PERSISTENCE (FLEXIBLE FLIGHT LEVELS)**
- **REDUCE no. OF NIGHT FLIGHTS, CONCENTRATE AT DAWN/SUNSET**
- **BREAKING ICE CRYSTALS WITH MWs OR ULTRASONIC WAVES**

2.14.15 FLIGHT LEVEL FOR OPTIMAL SAR

- SAR SPECIFIC AIR RANGE
  (DISTANCE TRAVELLED FOR UNIT FUEL MASS)

$$SAR = \frac{V_0}{TSFC \cdot F} = \frac{V_0}{TSFC} \cdot \frac{L}{D} \cdot \frac{1}{W} = \frac{a \cdot M_0}{TSFC} \cdot \frac{L}{D} \cdot \frac{1}{W}$$

- LEVEL FLIGHT: $L = W, \quad F = D$
- COMPONENTS OF DRAG D: VISCOUS, INDUCED (WING TIPS), WAVE (TRANSONIC)
- GIVEN $W \rightarrow SAR = SAR(V_0, z) = SAR(M_0, z)$

2.14.16 AERODYNAMIC EFFICIENCY *vs.* $\rho(z)$

- C_D = FRICTION + INDUCED + WAVE =

$$C_{D0} + \frac{C_L^2}{\pi\, AR\, e} + 20\,(M_0 - M_c)^4\, H(M_0 - M_c)$$

- AR ASPECT RATIO, e OSWALD EFFICIENCY, M_c CRITICAL MACH NUMBER

- LET $K = \dfrac{1}{\pi\, AR\, e}$; $L = W = C_L \dfrac{\rho V_0^2}{2} \cdot S_{wing}$

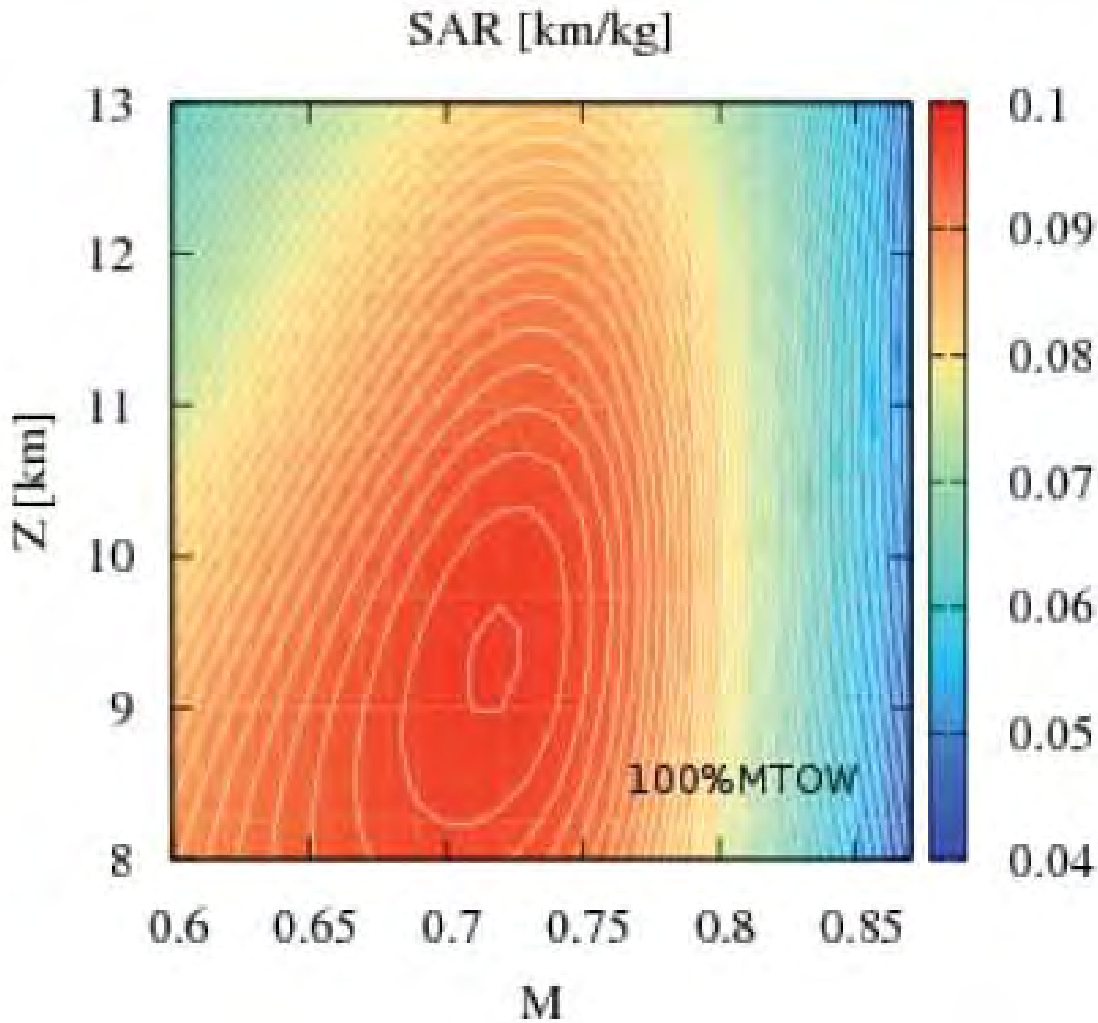
$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{1}{\dfrac{C_{D0}}{C_L} + K C_L + \dfrac{20\,(M_0 - M_c)^4}{C_L}} =$$

$$= \frac{1}{\dfrac{C_{D0} + 20\,(V_0/a_0 - M_c)^4}{W} \dfrac{\rho V_0^2}{2} \cdot S_{wing} + \dfrac{2\,K\,W}{\rho V_0^2\, S_{wing}}}$$

- 1st TERM DENOM. DECR. WITH z, 2nd INCR. $\longrightarrow \exists\, z_{opt}$

- $TSFC$ TOO DEPENDS ON $(z,\, M_0)$ $\longrightarrow$ $SAR = SAR(z,\, M_0)$

2.14.17 OPTIMAL (z, M_0)



- **AIRLINES TEND TO FLY AT SOMEWHAT HIGHER M_0 TO INCREASE PRODUCTIVITY**
- **(HIGHER z ALSO IMPLY A HEAVIER A/C, OWING TO LARGER WINGS, TAILPLANE, ENGINES, Δp CABIN/AMBIENT)**
- **JET STREAM**

2.14.18 JET STREAM AND ROUTES

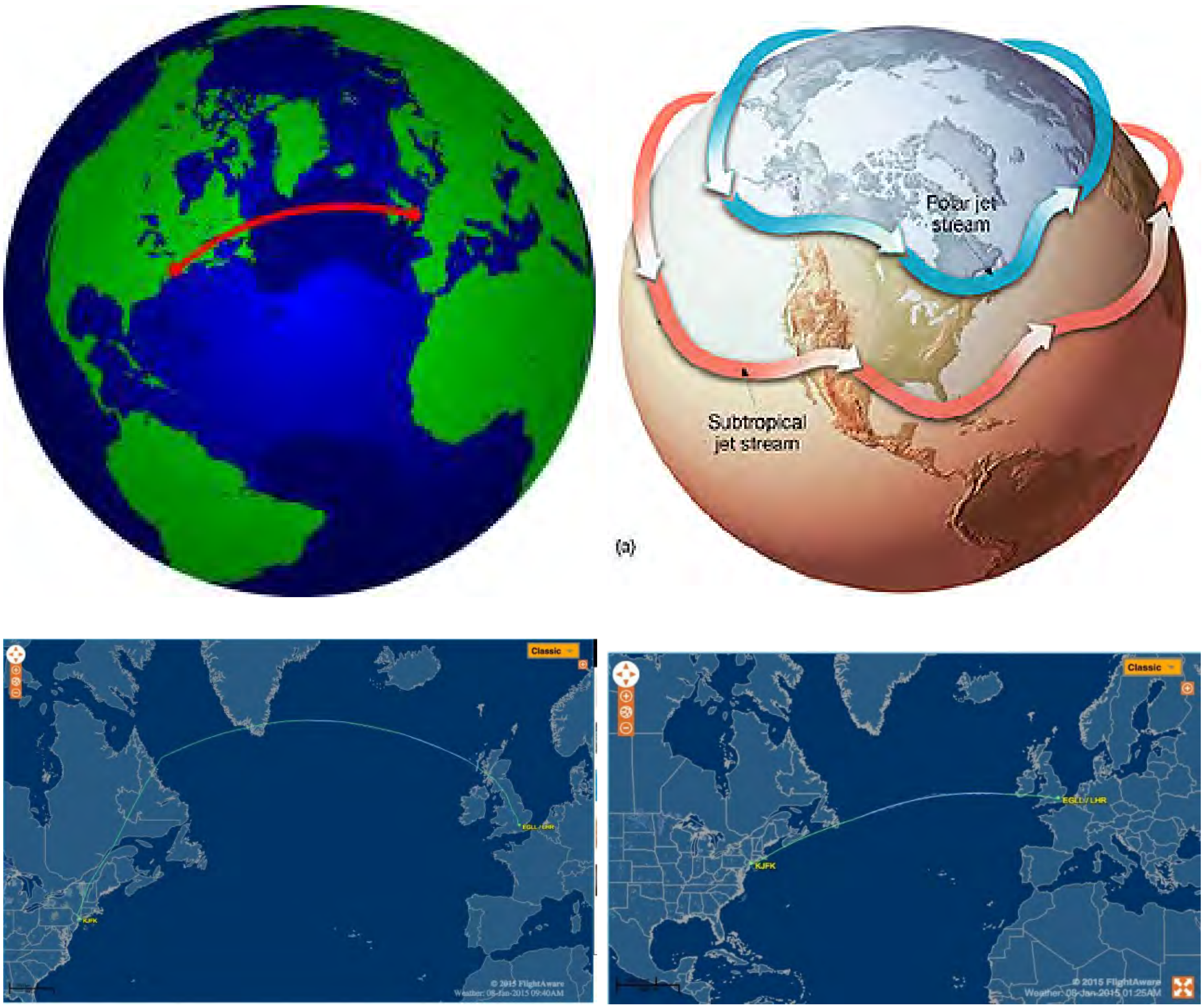


Figure 38: Westward (left) and eastward (right) London – New York routes.

- **POLAR JET STREAM 7000 – 12000 m**
- **SUBTROPICAL JET STREAM 10000 – 16000 m**

2.15 EFFECT OF BLACK CARBON

- **MAYBE 2nd LEADING CAUSE GW AFTER CO_2**
  - **WARMS THE ATMOSPHERE DIRECTLY**
  - **REDUCES ALBEDO OF ICE CAPS, SNOW**
- **ENSUING EFFECT ON RIVERS**
- **MEAN LIFE DAYS OR WEEKS**
- **ACTIONS: PARTICULATE FILTERS FOR DIESEL ENGINES, REGULATE BURNING OF AGRICULTURAL RESIDUES AND COOKING STOVES**

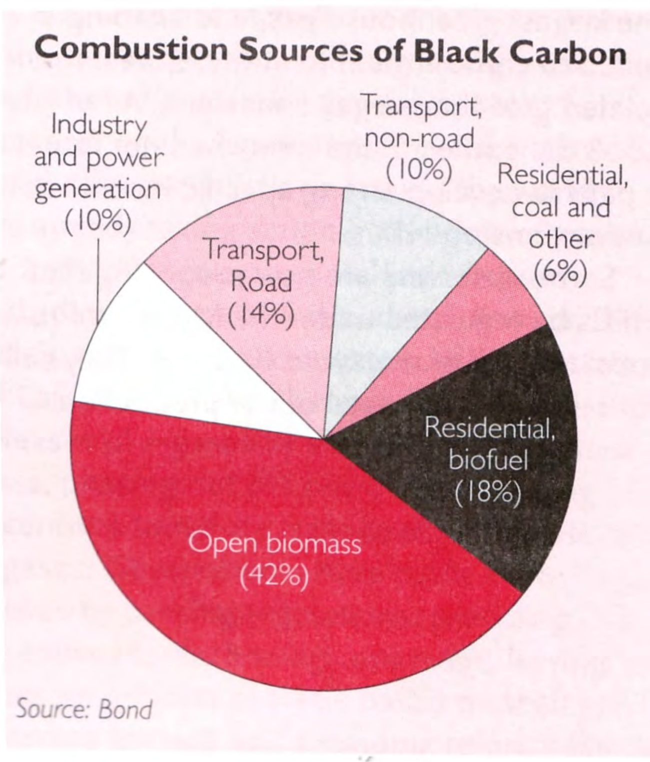


Figure 39: Combustion sources of black carbon.

2.16 PROPOSED COUNTERMEASURES AGAINST GLOBAL WARMING

- **REDUCE FOSSIL FUEL USAGE**
- **BIOFUELS (1% GLOBAL FUEL CONSUMPTION, BUT USING 1% ARABLE LAND – 2006; AGRICULT. RESIDUES, ALGAE)**
- ***CARBON CAPTURE AND STORAGE*** **(FOR GROUND PLANTS)**
- **(CONTAIN POPULATION GROWTH)**
- ***GEOENGINEERING*****:**
  - **SULPHATE AEROSOLS IN STRATOSPHERE (BY A/Cs, PROJECTILES, BALLOONS)**
  - **SEAWATER SPRAYS**
  - **OCEAN FERTILIZATION WITH IRON**
  - **BIOCHAR**
  - **REFLECTING ROOFS**
  - **SPACE SHIELDS**
  - *** COSTS AND RISKS**
  - *** DO NOT COUNTER OCEAN ACIDIFICATION**

2.17 GEOENGINEERING

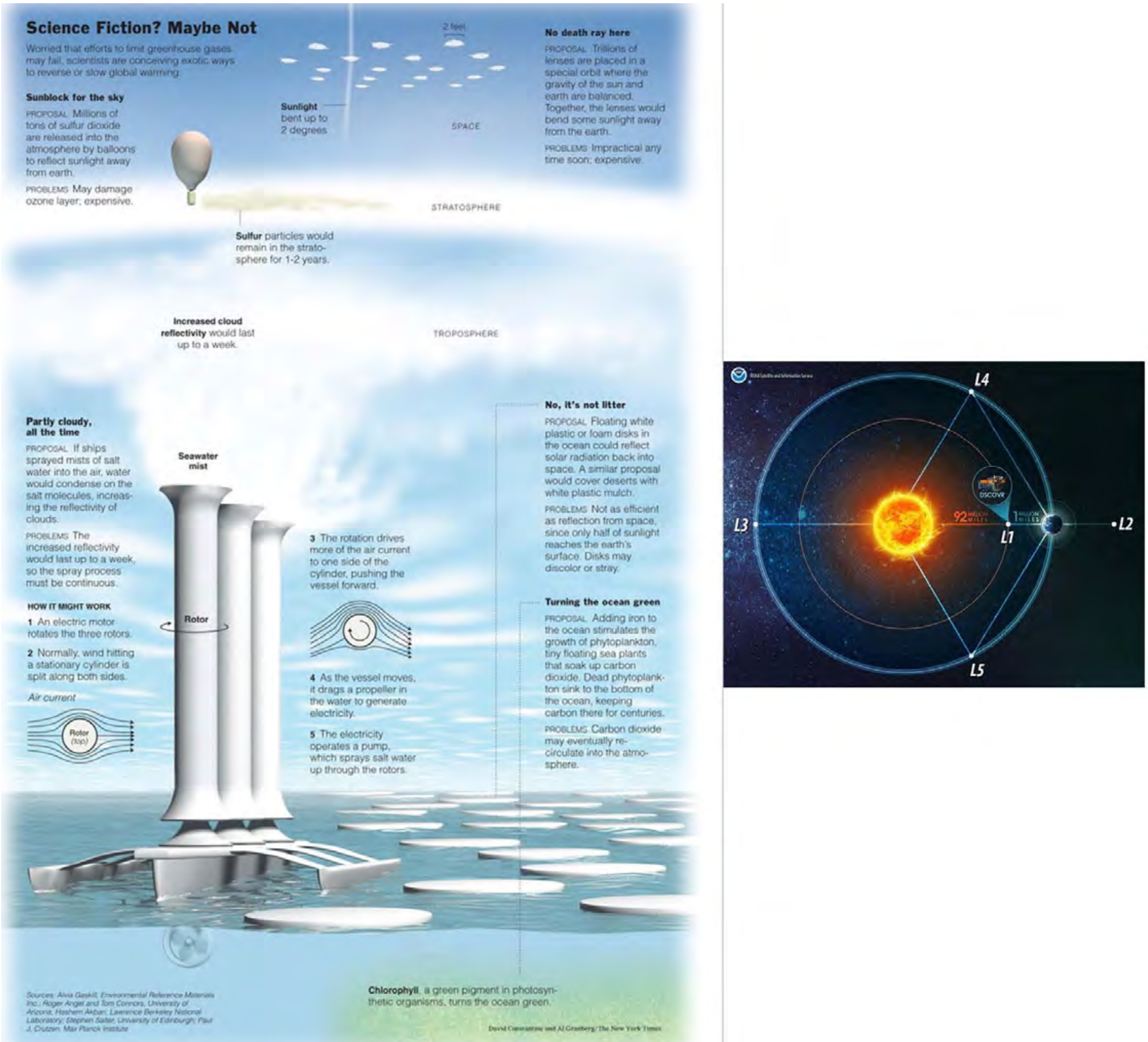
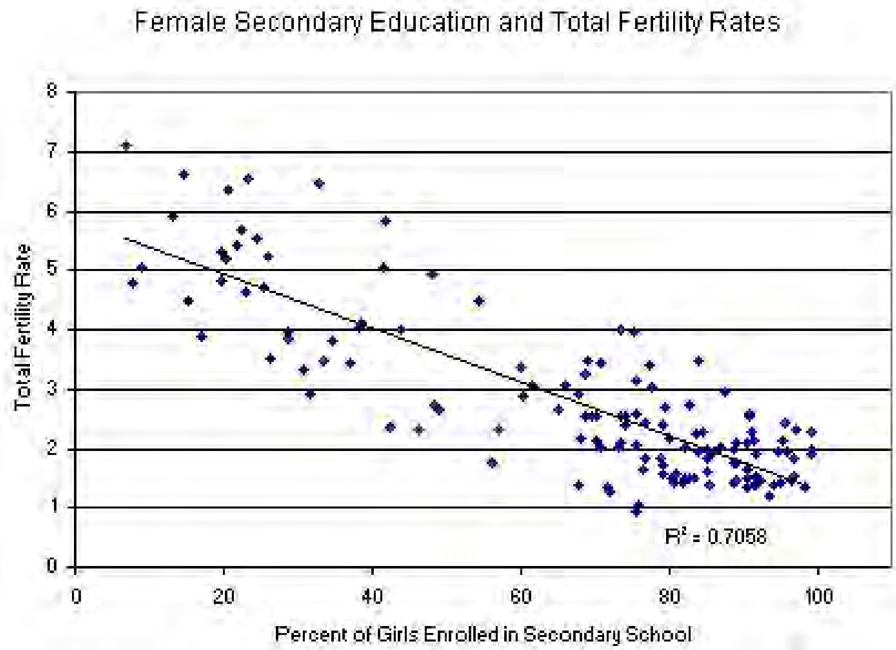


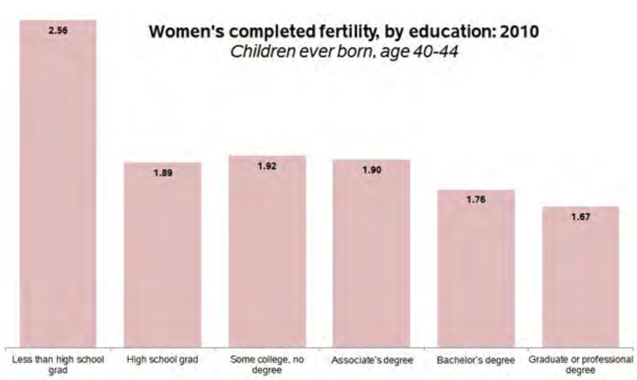
Figure 40: (left) Geoengineering options, (right) location of Lagrange points.

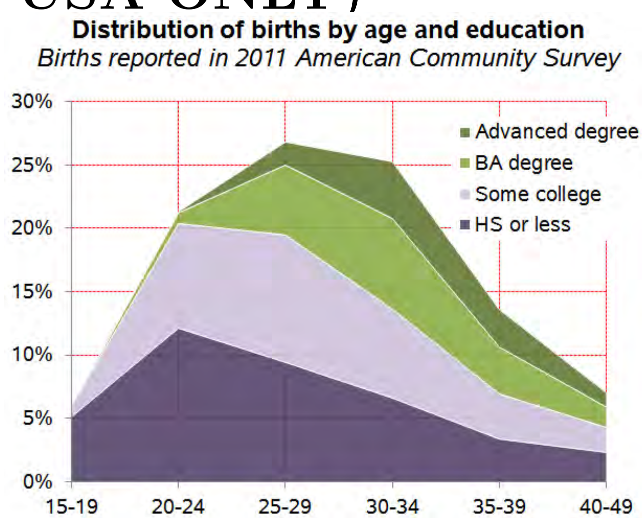
2.17.19 STRICTLY RELATED ISSUES 1. POPULATION GROWTH

- **RATE POPULATION GROWTH: $r = \log R_0 / T$**
  - **R_0 AVERAGE no. DAUGHTERS PER WOMAN (NET OF MORTALITY)**
  - **T INTERVAL BETWEEN GENERATIONS**



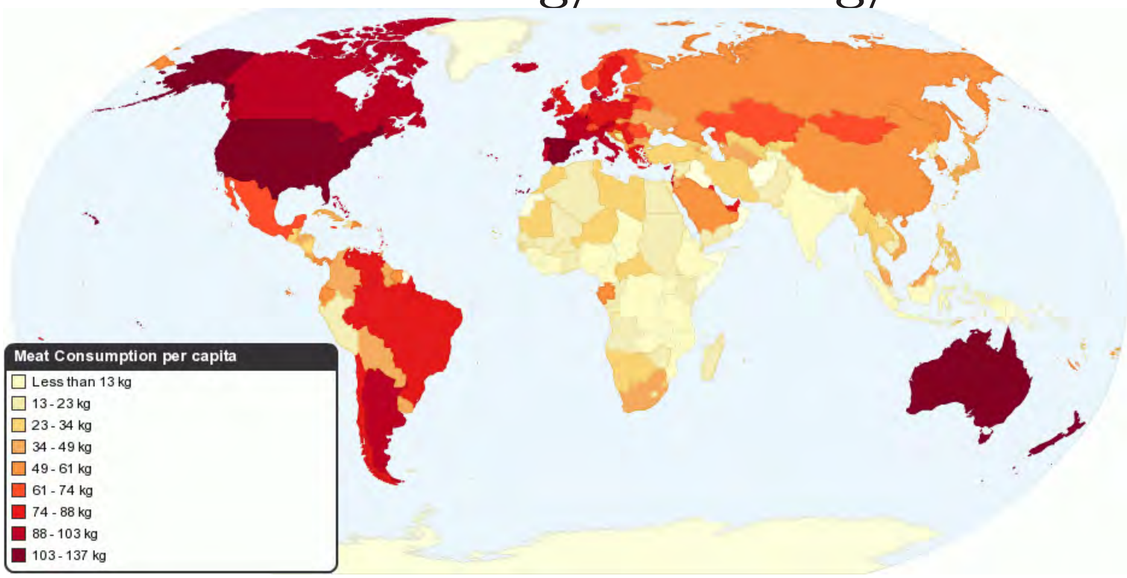
- **(DATA BELOW FOR USA ONLY)**



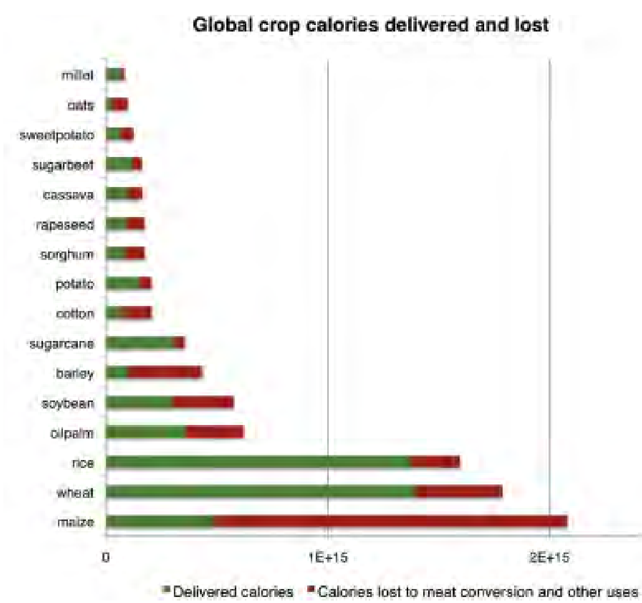


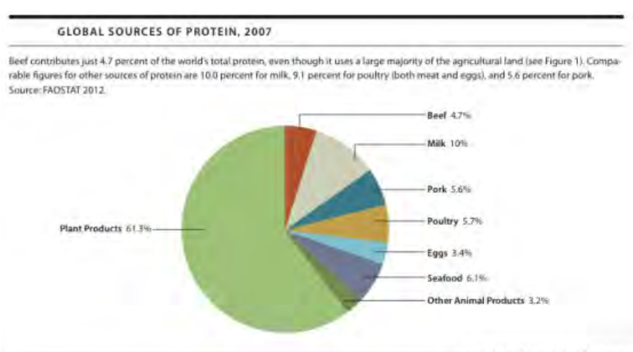
2.17.20 STRICTLY RELATED ISSUES 2. LAND USE

- **MEAT: RECOMMENDED MAX DAILY ALLOWANCE ∼ 70 g/d ∼ 25 kg/a**



- **MORE THAN 2/3 LAND → ANIMAL FEED**
- **RESPONSIBLE 18% GHGs EMISSIONS**





2.17.21 STRICTLY RELATED ISSUES 3. FRESH WATER RESOURCES

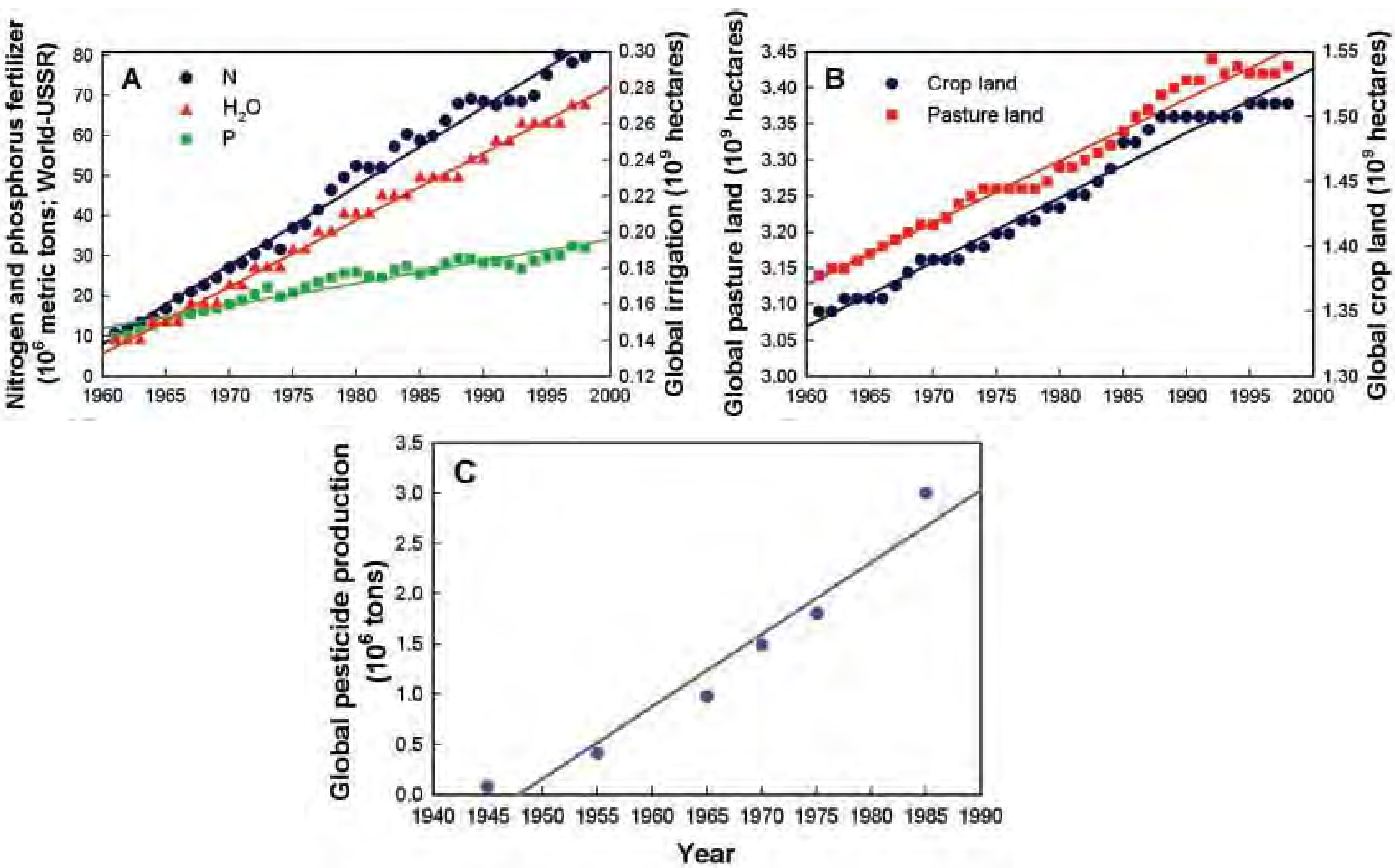
- **FRESH WATER RESOURCES ARE LIMITED**
- **DRIP IRRIGATION**

Water Consumed to Supply Protein and Calories, Selected Foods[1]

Food	Water Consumed to Supply 10 Grams of Protein	Water Consumed to Supply 500 Calories
	(liters)	
Potatoes	67	89
Groundnut	90	210
Onions	118	221
Maize (corn)	130	130
Pulses (beans)	132	421
Wheat	135	219
Rice	204	251
Eggs	244	963
Milk	250	758
Poultry	303	1,515
Pork	476	1,225
Beef	1,000	4,902

2.17.22 STRICTLY RELATED ISSUES 4. AGRICULTURAL EXPANSION

- **HUMANS ADD AS MUCH N AND P TO ECOSYSTEMS AS ALL NATURAL SOURCES**
- **EUTROPHICATION OF SURFACE WATERS**
- **PESTICIDES (200 000 DEATHS PER YEAR)**
- **INCREASED IRRIGATION LEADS TO SALINIZATION OF SOILS**



2.18.1 DEPLETION OF THE STRATOSPHERIC OZONE LAYER

- **GROUND–LEVEL OZONE O_3 POWERFUL RESPIRATORY/EYE IRRITANT; GHG**
- **OZONE CONCENTRATION PEAKS IN BETWEEN 10 AND 30 km ALTITUDE**
- **ONLY GAS SHIELDING UV RADIATION $\lambda < 0{,}28\ \mu m$**
- **ODG (OZONE DEPLETING GASES): CFC (Freon), NO_x, N_2O (INDIRECTLY)**

2.18.2 OZONE CONCENTRATION vs. ALTITUDE

- **TROPOSPHERE $\sim$ 50 ppb**
- **STRATOSPHERE $\sim$ 3,8 ppm = 3800 ppb**
- **O_3 FORMED BY UV RADIATION WITH $0{,}18 < \lambda < 0{,}23$ μm**
- **O_3 ABSORBS UV RADIATION $0{,}22 < \lambda < 0{,}32$ μm**

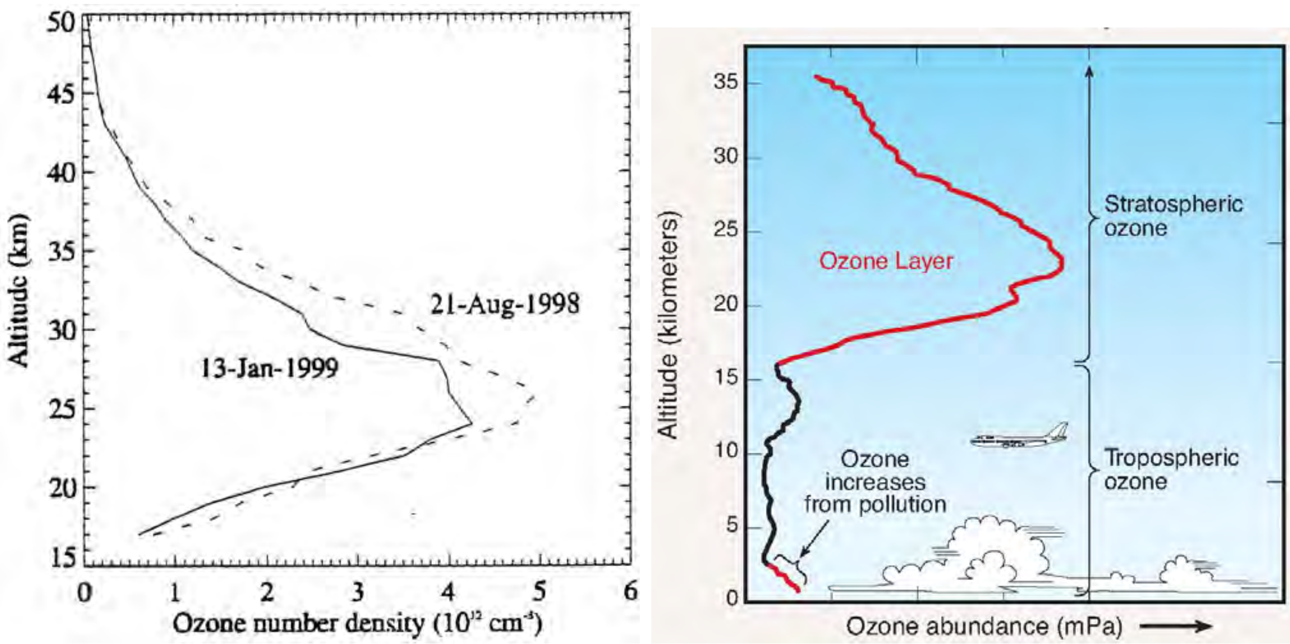


Figure 41: Typical winter/summer ozone concentrations as a function of altitude (mean latitude, left); ozone concentration vs altitude, and typical A/C flight altitude (right).

2.18.3 STRATOSPHERIC ODGs

1. **LONG–LIVED CHEMICAL SPECIES (∼INERT), DIFFUSING FROM TROPOSPHERE:**
   - **CHLOROFLUOROCARBONS CFC (Freon) (MEAN LIFE CFC–11 50 a, CFC–12 102 a)**
   - **NITROUS OXIDE N_2O (MEAN LIFE 120 a)**
2. **JET ENGINE EMISSIONS:**
   - **NITRIC OXIDE NO**
   - **NITROUS OXIDE N_2O**

2.18.4 OZONE DEPLETION BY CFCs

- **UV RADIATION SPLITS CFCs, LIBERATING ATOMIC Cl**
- **OZONE DESTRUCTION *VIA* MECHANISM:**

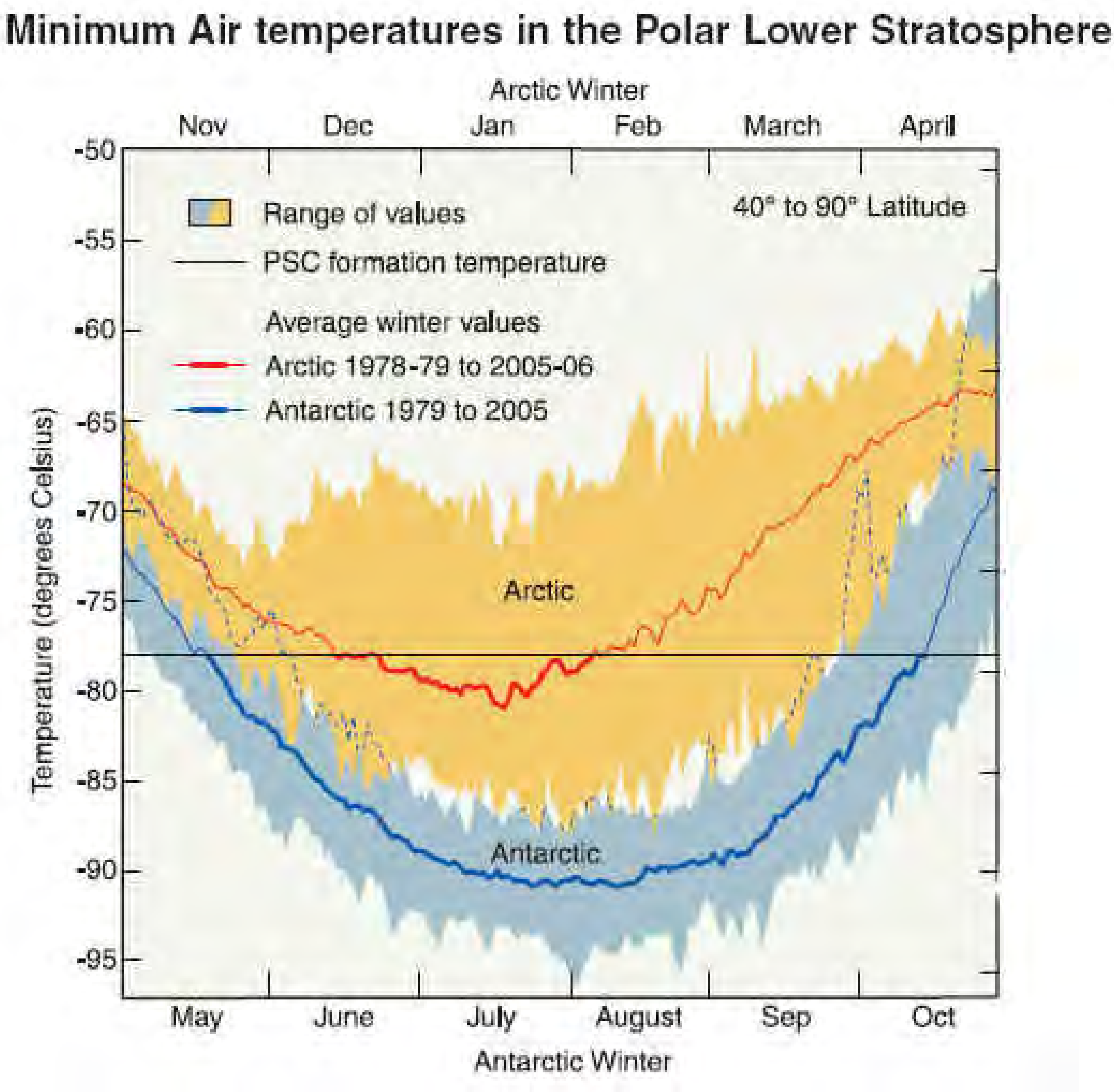
1. $Cl + O_3 \rightarrow ClO + O_2$
2. $ClO + O_3 \rightarrow Cl + 2\ O_2$

- **WITHOUT NET Cl CONSUMPTION**

→ **A SINGLE Cl ATOM CAN DESTROY FROM 10 000 UP TO 1 000 000 O_3 MOLECULES!**

- **Br–CONTAINING CFCs (HALON) 8 – 50 TIMES MORE NOXIOUS**
- **ANTARCTIC OZONE HOLE**
- **CFCs BANNED, REPLACED BY:**
  - **HCFC, HYDROCHLOROFLUOROCARBONS (SHORTER MEAN LIFE, WEAK ODGs, YET GHGs**
  - **HFC (GHGs)**
  - **PENTANE (VOC)**
  - **POSSIBLY CO_2 OR NH_3**

2.18.5 POLAR TEMPERATURES AND PSC (POLAR STRATOSPHERIC CLOUDS)



2.18.6 OZONE DEPLETION POTENTIAL AND GWP

- **ODP REFERRED TO CFC–11 (CCl_3F)**
- **GWP REFERRED TO CO_2**

Gas	Atmospheric Lifetime (years)	Global Emissions in 2008 (Kt/yr) [a]	Ozone Depletion Potential (ODP) [c]	Global Warming Potential (GWP) [c]
Halogen source gases				
Chlorine gases				
CFC-11	45	52–91	1	4750
CFC-12	100	41–99	0.82	10900
CFC-113	85	3–8	0.85	6130
Carbon tetrachloride (CCl_4)	26	40–80	0.82	1400
HCFCs	1–17	385–481	0.01–0.12	77–2220
Methyl chloroform (CH_3CCl_3)	5	Less than 10	0.16	146
Methyl chloride (CH_3Cl)	1	3600–4600	0.02	13
Bromine gases				
Halon-1301	65	1–3	15.9	7140
Halon-1211	16	4–7	7.9	1890
Methyl bromide (CH_3Br)	0.8	110–150	0.66	5
Very short-lived gases (e.g., $CHBr_3$)	Less than 0.5	[b]	[b] very low	[b] very low
Hydrofluorocarbons (HFCs)				
HFC-134a	13.4	149 ± 27	0	1370
HFC-23	222	12	0	14200
HFC-143a	47.1	17	0	4180
HFC-125	28.2	22	0	3420
HFC-152a	1.5	50	0	133
HFC-32	5.2	8.9	0	716

2.18.7 OZONE DEPLETION BY NO

- **OZONE DEPLETION *VIA* MECHANISM:**

  $NO + O_3 \rightarrow NO_2 + O_2$

- **REACTION VIRTUALLY IRREVERSIBLE**

→ **MOLECULE OF NO IS CONSUMED**

- **STRATOSPHERIC NO FROM:**

1. **N_2O DIFFUSING FROM THE GROUND, *VIA* REACTION**

$$N_2O + O^* \rightarrow 2\,NO$$

   (PLUS OTHERS);
   $O^* \equiv O(1D)$ EXCITED STATE OF ATOMIC O BY

$$O_3 + h\,\nu \rightarrow O^* + O_2$$

   $ODP_{N2O} = 0{,}017$

2. **<u>JET ENGINE EMISSIONS</u>**

2.18.8 PROJECTED OZONE CONCENTRATION

- **HAD THE MONTREAL PROTOCOL NOT BEEN ENFORCED...**

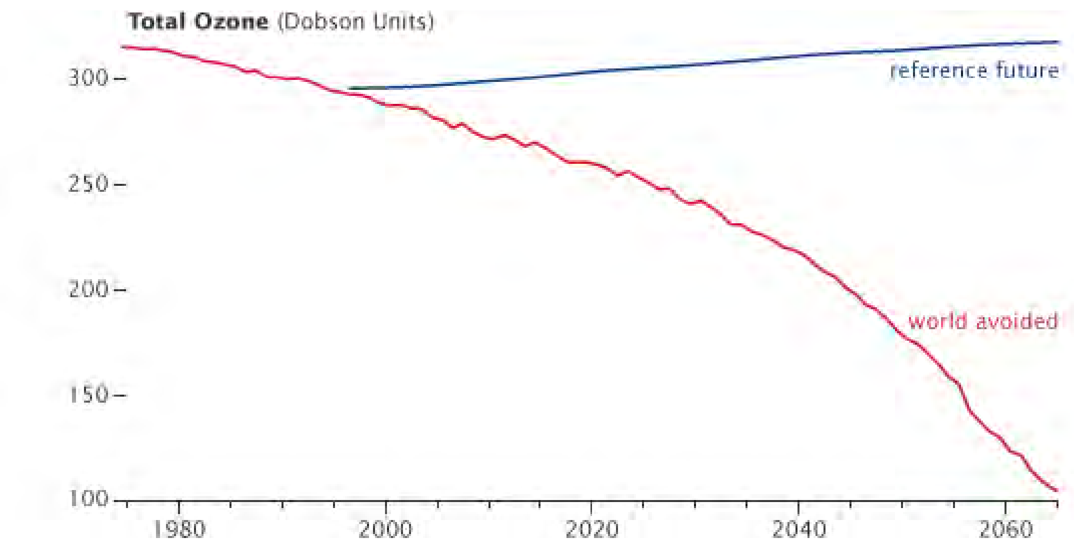


Figure 42: Projected ozone concentrations under current regulations (blue) and without (red).

- **DOBSON UNIT = 0,01 mm O_3 AT STANDARD T, p**
- **A 1% REDUCTION OF THE OZONE COLUMN HEIGHT h_{O_3} RESULTS IN A 2% INCREASE OF GROUND UV RADIATION INTENSITY I**

$$\frac{dI}{I} = -\,\kappa\, dh_{O_3} \quad \rightarrow \quad I = I_0 \exp\left(-\,\kappa\, h_{O_3}\right)$$

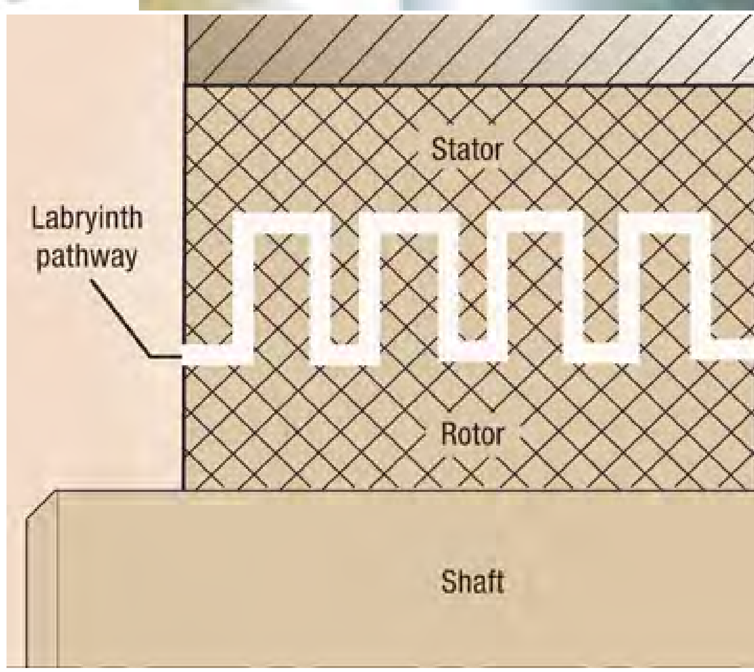
κ OZONE ABSORPTION COEFFICIENT

3.1.1 COMBUSTION CHAMBER: FUNDAMENTAL ASPECTS

- **CONSTRAINTS:**
  - **CROSS SECTION (LIMITED TO CONTAIN DRAG, SIZE, WEIGHT)**
  - **LENGTH (LIMITED TO CONTAIN DRAG, SIZE, WEIGHT, STRESS ON TURBOMACHINERY AXIS) (EACH EXTRA kg $\rightarrow \simeq 3$ kg EXTRA AT TAKE–OFF)**
  - **SMALL PRESSURE DROP ($\epsilon_b = p_4/p_3 \rightarrow$ LOW M)**
- **DESIDERATA:**
  - **LOW POLLUTANT EMISSIONS**
  - **STABLE COMBUSTION ON WIDE RANGE $\dot{m}_f$, f, V_0, p_a**
  - **η_b CLOSE TO 100%**
  - ***PATTERN FACTOR* $(T_{4,max} - T_{4,min})/(\overline{T_4} - T_3)$ LOW (OR APPROPRIATE ANYWAY)**
  - **LONG DURATION (COOLING AND MATERIALS)**
  - **RELIABLE IGNITION, ALTITUDE RELIGHT**
  - **LIMITED MANUFACTURING AND MAINTENANCE COSTS**
- **TREND TO RISE $\beta_o = \beta_d \beta_f \beta_c$ AND $\tau = T_4/T_a$ (FOR $TSFC$ AND $I_a \rightarrow F/W$) MAKES ACHIEVING SUCH GOALS MORE DIFFICULT (EXCEPT RELIGHT)**

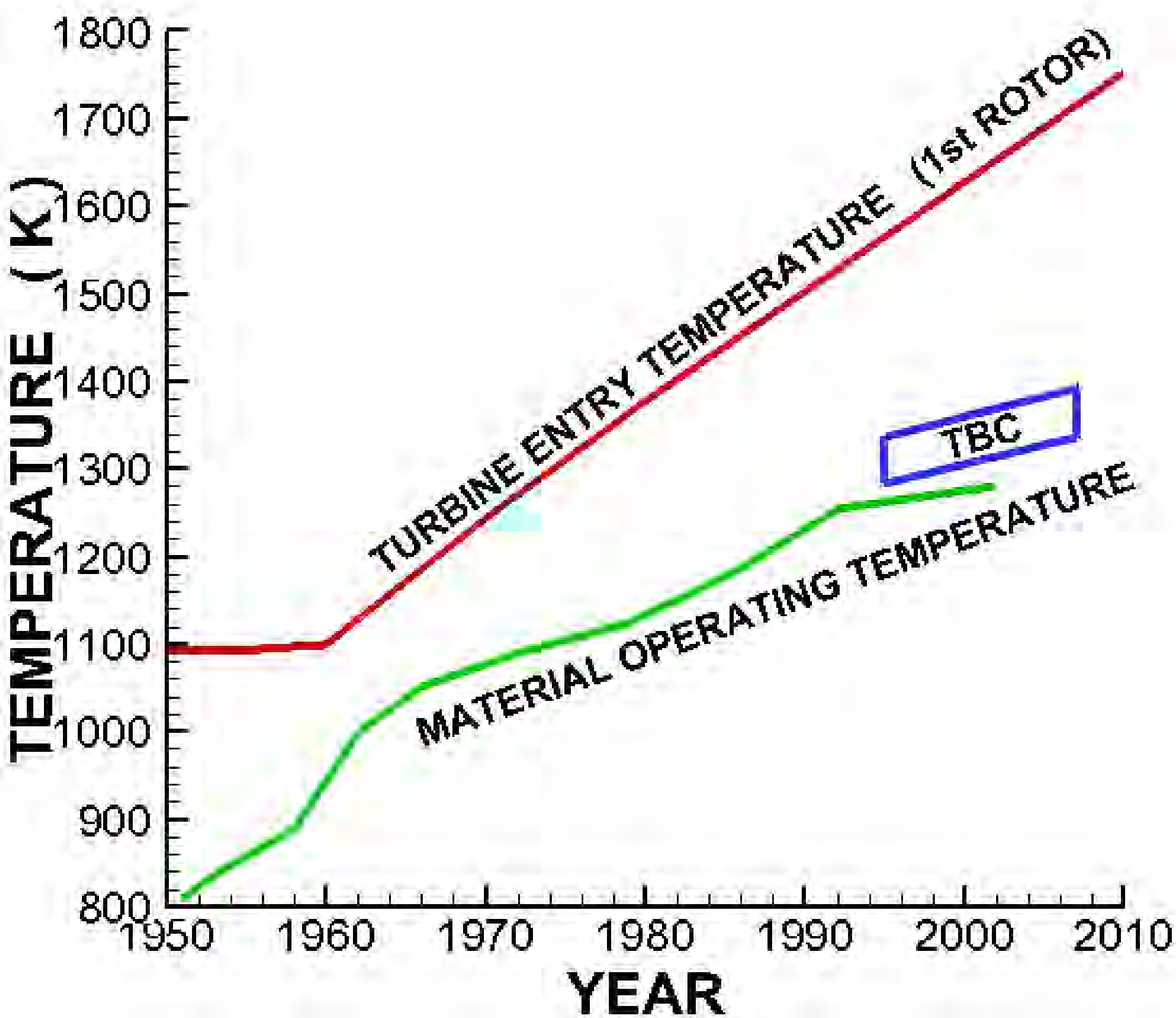
3.1.2 LABIRYNTH SEALS

• **TO REDUCE TIP LEAKAGE**



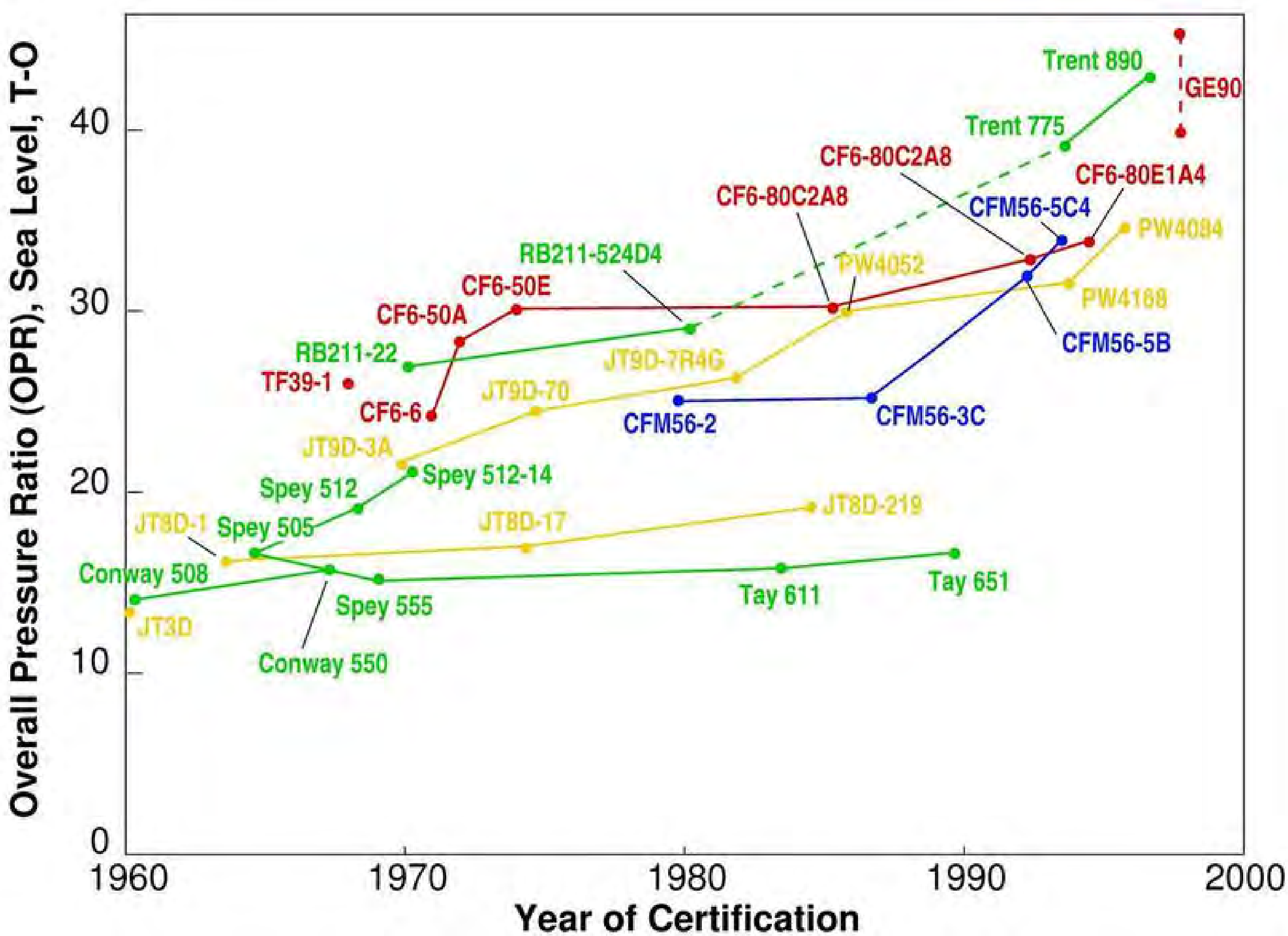
3.1.3 TREND IN TURBINE ENTRY TEMPERATURE

- **INCREASES $I_a \rightarrow$ REDUCED ENGINE SIZE/WEIGHT $\rightarrow$ INCREASED PAYLOAD MASS**
- **PRICE: COSTLIER MATERIALS, HIGHER NEED BLADE COOLING**
- **TBC: THERMAL BARRIER COATING**



3.1.4 TREND IN OVERALL PRESSURE RATIO

- **REDUCING *TSFC*:**
  - **DECREASES DOCs**
  - **INCREASES PAYLOAD MASS**
  - **PRICE: HEAVIER, COSTLIER TURBOMACHINER**



3.1.5 CHAMBER CONFIGURATION

- **CONSTRAINTS: LOW Δp, SUFFICIENT t_s, $f \simeq 0.02$**

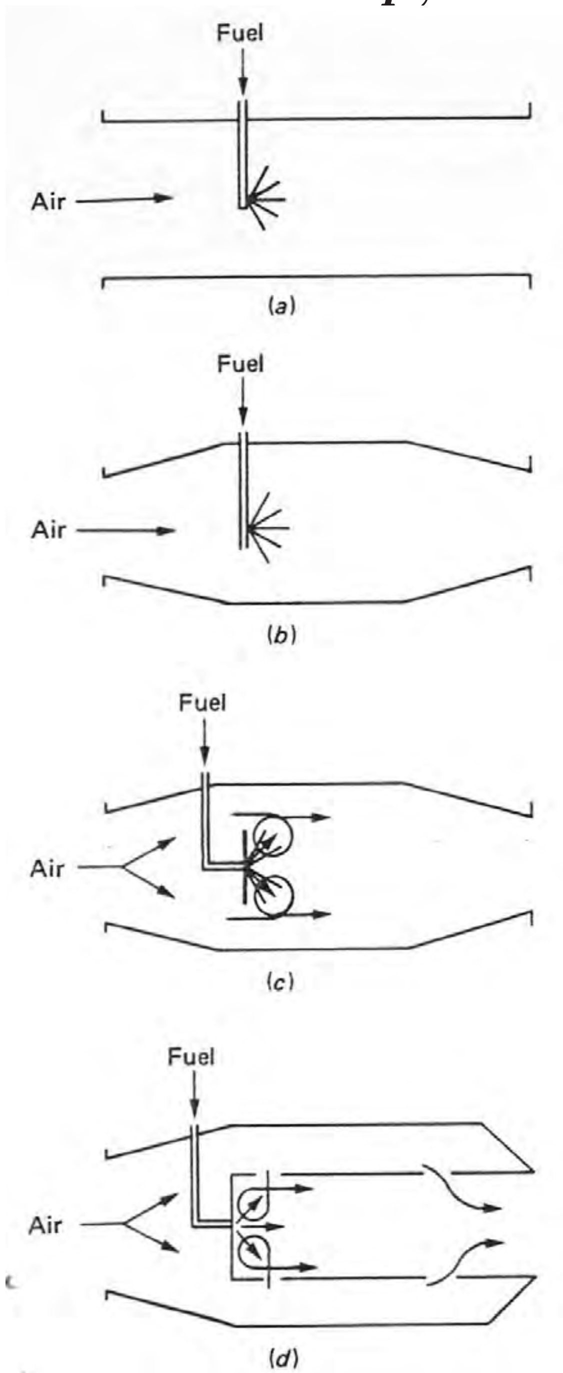


Figure 43: Effect of constraints on chamber design.

3.1.6 IMPACT OF A *TOO* LONG CHAMBER

- **INCREASED WEIGHT COMBUSTION CHAMBER**
- **INCREASED WEIGHT PRIMARY FLOW CASE**
- **INCREASED WEIGHT SECONDARY FLOW CASE**
- **INCREASED WEIGHT TURBOMACHIN. AXES**
- **INCREASED WEIGHT NACELLE**
- **MULTIPLY** $\times \sim$ **3**

- **FURTHER, INCREASED EXTERNAL DRAG**

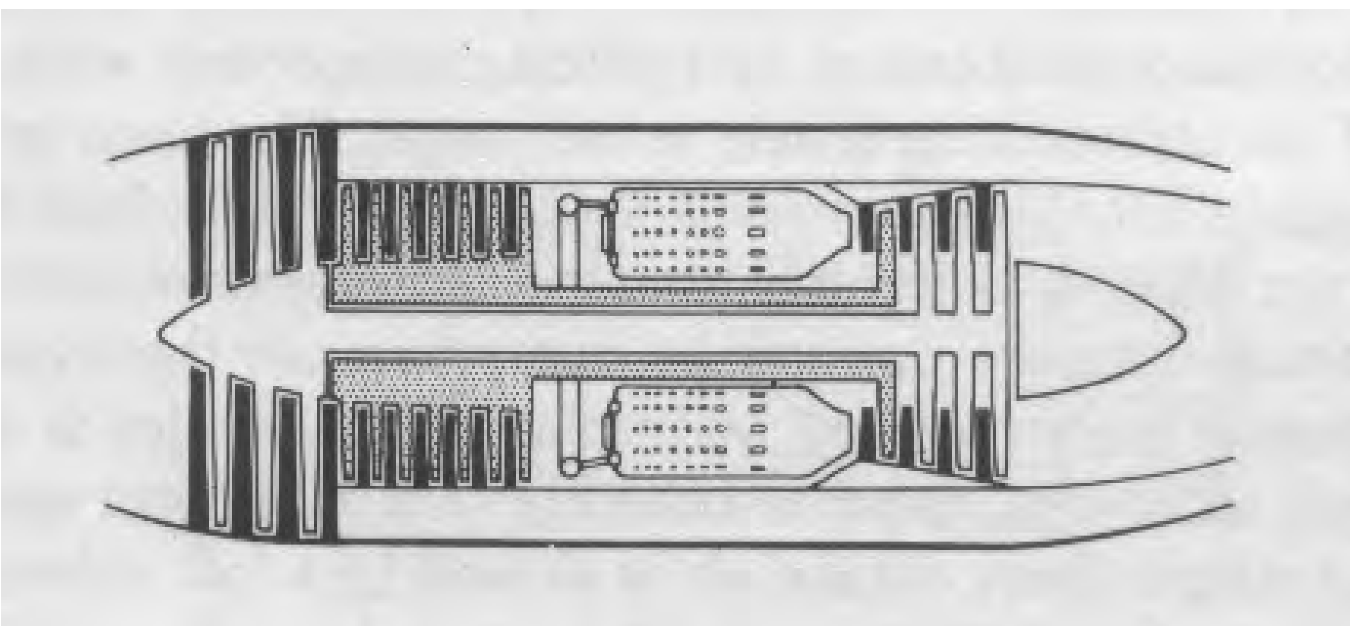
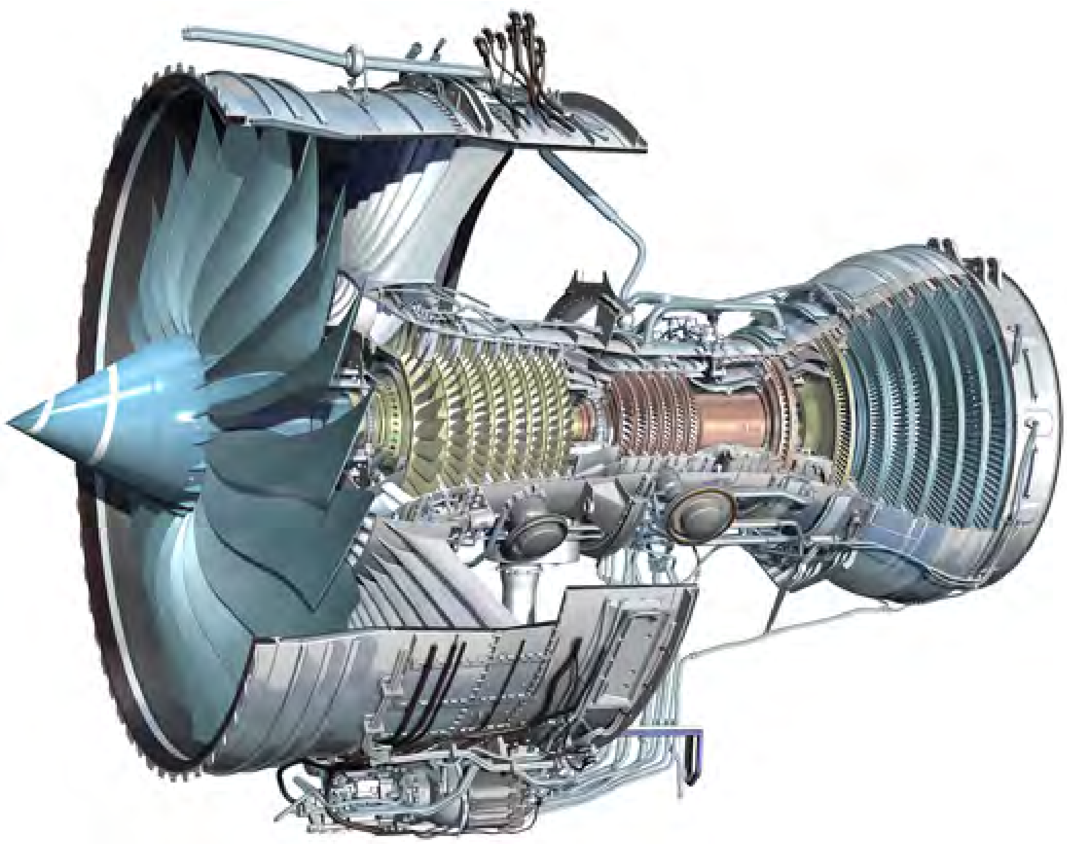


Figure 44: Cross–section of a turbofan.

3.1.7 TURBOFAN MASS BREAKDOWN

	Proportion of total
Fan rotor & casing	18%
IP Comp.	5%
Structures	15%
Shafts	3%
LP Turb.	16%
Nacelle	22%
Core & externals	21%
	100%

Figure 45: Mass breakdown of a high by–pass ratio three–spool turbofan.



3.1.8 COMBUSTOR TYPES (1)

- **TUBULAR (CAN): HEAVY, LONG; EASY TESTING AND MAINTENANCE. ABANDONED (EXCEPT SMALL F)**
- **ANNULAR: LOW Δp, <u>LOW EMISSIONS</u>; DIFFICULT TESTING, MAINTENANCE AND MANUFACTURING, SENSITIVE TO INLET PROFILE DEFORMATION (MOST POPULAR FOR HIGH F)**
- **TUBO–ANNULAR: EASY TESTING**

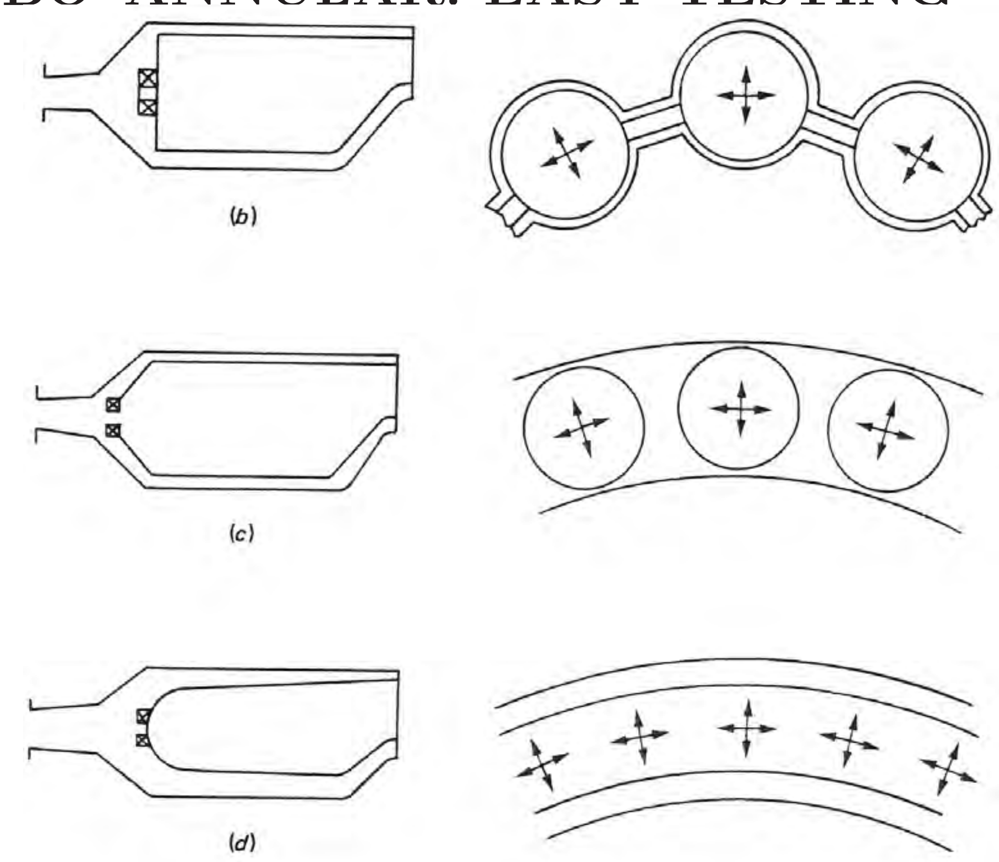


Figure 46: Tubular, tubo–annular, annular chambers (top to bottom). Side view (left), cross–section (right).

3.1.9 COMBUSTOR TYPES (2)

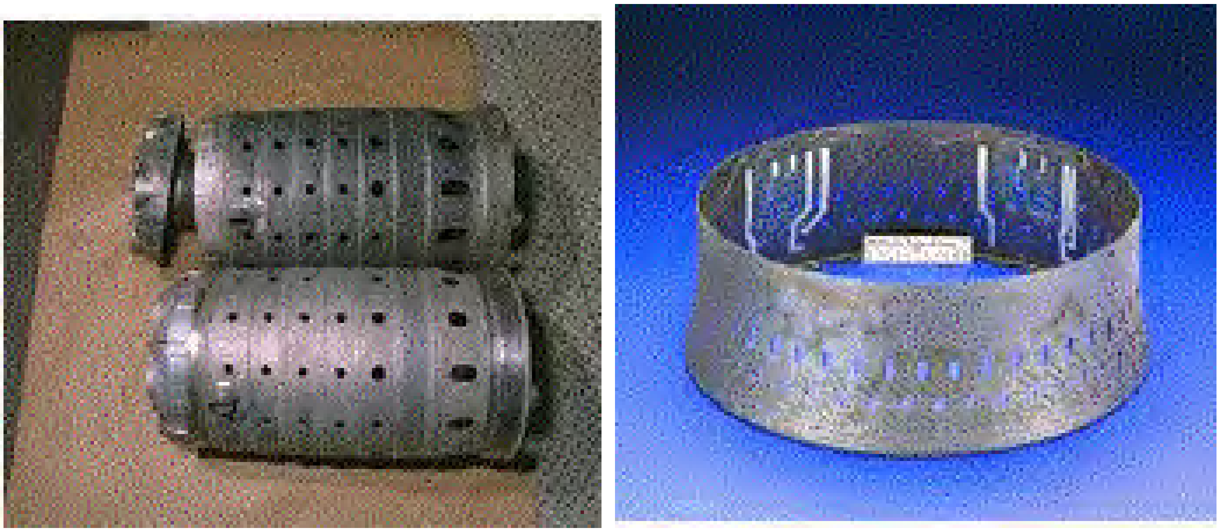


Figure 47: *Liners* of tubular (left) and annular (right) combustion chambers.

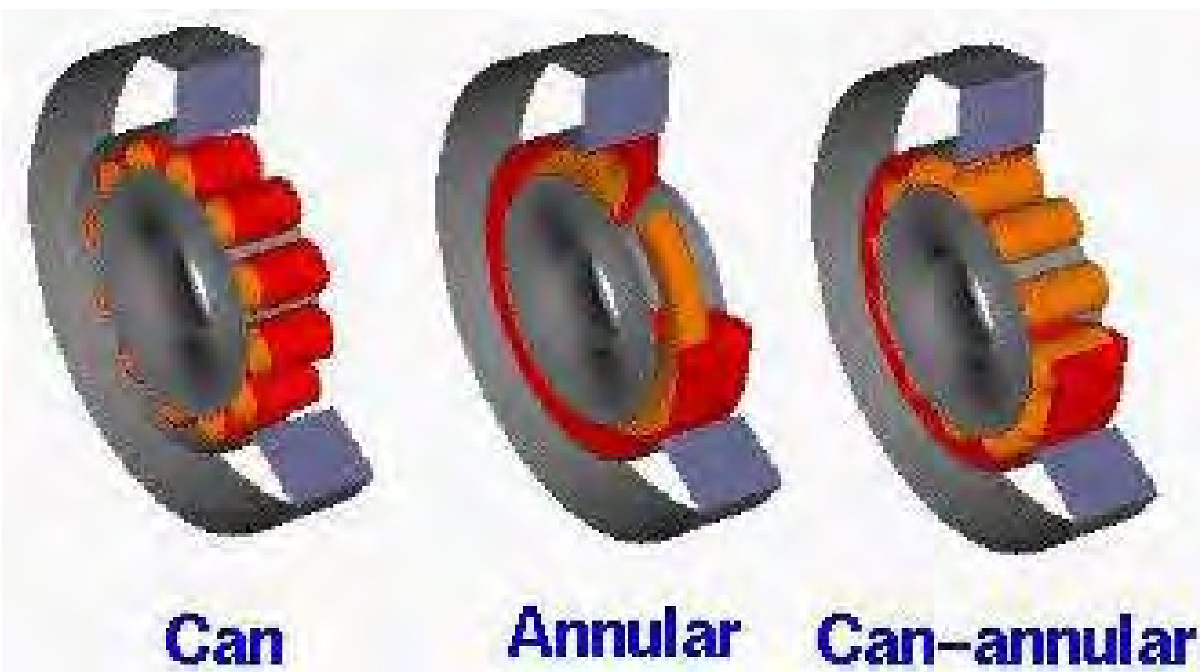


Figure 48: Arrangement of tubular, annular, tubo–annular chambers (left to right).

3.1.10 COMBUSTION CHAMBER COMPONENTS

- **DIFFUSER**
- **LINER**
- **PRIMARY ZONE**
- **INTERMEDIATE ZONE**
- **DILUTION ZONE**
- **INJECTORS**
- **COOLING SYSTEM**

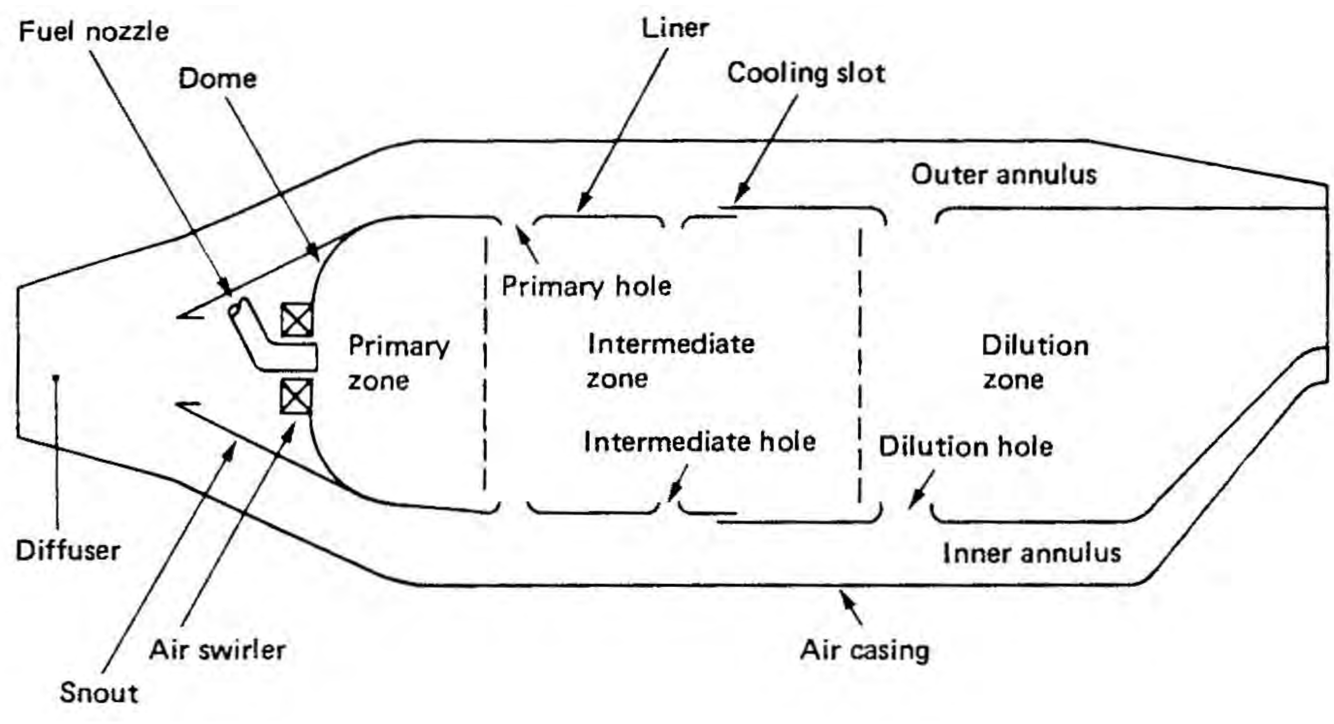


Figure 49: Main combustion chamber components.

3.1.11 PRESSURE DROPS

- $\Delta p = \Delta p_{cold} + \Delta p_{hot}$ $\quad \left(\frac{dp}{p} = -f' \frac{\gamma M^2}{2} \frac{dx}{D} - \gamma M^2 \frac{dQ}{c_p T} \right)$
- Δp_{cold} **IN DIFFUSER AND PERFORATED LINER** $\simeq 2 - 6\ \%\ p_c$
- Δp_{cold}, Δp_{hot} **PROPORTIONAL TO** M^2
- Δp_{hot} **IN COMBUSTOR RISES WITH** T_4

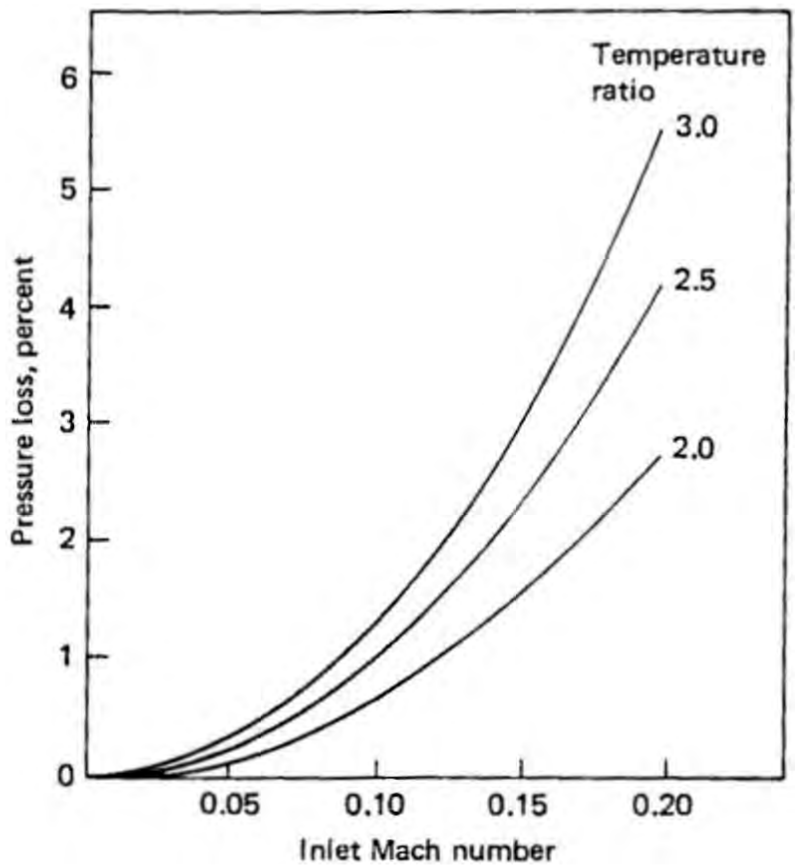


Figure 50: Pressure drop in combustion chamber due to heat release.

3.1.12 DIFFUSER TYPES

- **DIFFUSERS:**
  - **CONICAL (SMALL HALF–ANGLE → LONG)**
  - ***DUMP*** **(HIGHER Δp, SHORT)**

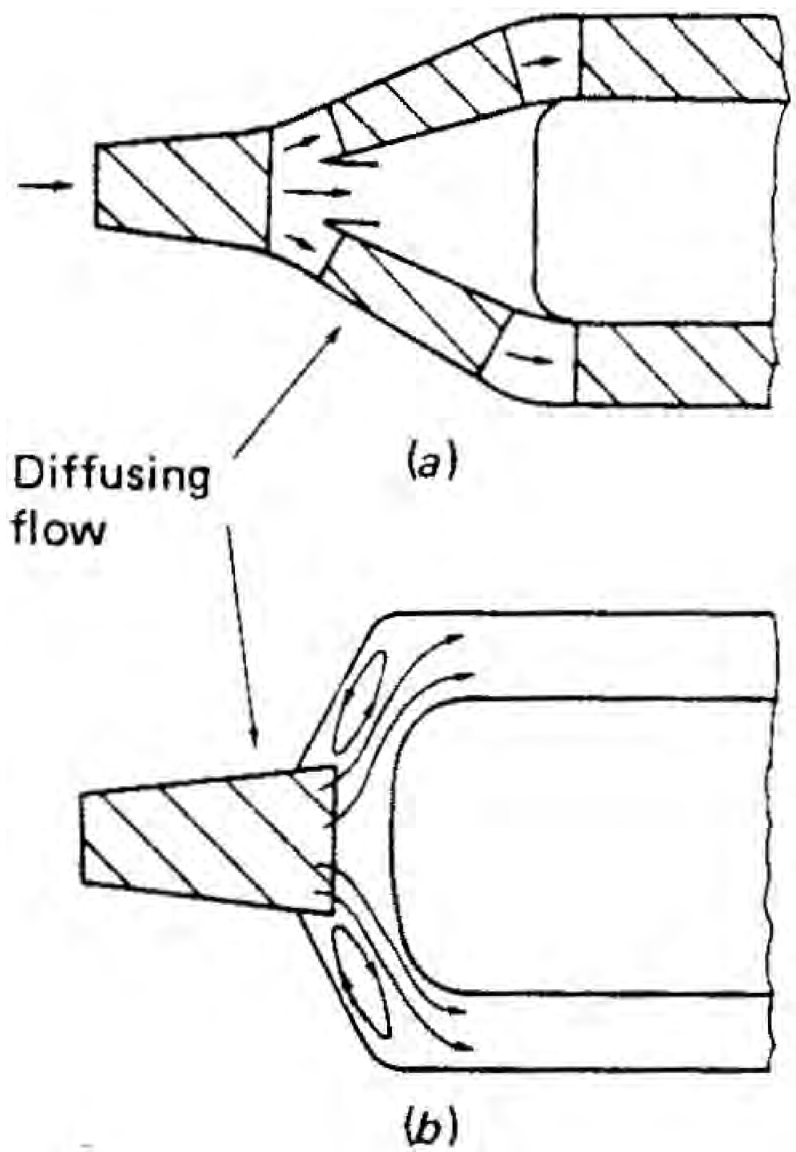


Figure 51: Conical (top) and dump (bottom) diffusers.

3.1.13 PRIMARY ZONE

- $\simeq$ **SEMICIRCULAR SHAPE**
- **PRIMARY AIR $\simeq$ 40% OF $\dot{m}_a$, INJECTED BY *SWIRLERS* AND JETS**
- **RECIRCULATION BY EITHER:**
  - **FEW LARGE DIAMETER JETS $\rightarrow$ MORE STABLE**
  - **MANY SMALL DIAMETER JETS $\rightarrow$ LOWER EMISSIONS, HIGHER HEAT RELEASED PER UNIT VOLUME**
- **COMBUSTION CLOSE TO STOICHIOMETRIC $\rightarrow$ $T \sim$ 2500 K**
- **PRESENCE OF DISSOCIATION PRODUCTS (CO, OH, H, O, ...) AND UHC (*Unburned HydroCarbons*)**

3.1.14 INTERMEDIATE ZONE

- **INTERMEDIATE $\simeq$ 20% OF $\dot{m}_a$, INJECTED THROUGH HOLES AND SLOTS**
- **RECOMBINATION OF CO, OH, H, O, ... AT INTERMEDIATE T**
- **AT HIGH ALTITUDE, LOW p:**
  $\rightarrow$ REACTION RATE $w \propto p^n$ LOW
  $\rightarrow$ INTERMEDIATE ZONE SERVES AS EXTENSION TO PRIMARY
- **$L_{intermediate\ zone} = 0.5 - 0.7\ D_{liner}$, UP TO 1 FOR ENGINES OF LONG–RANGE A/Cs (HIGHER WEIGHT $TSFC$)**

3.1.15 DILUTION

- **DILUTION AIR $\simeq$ 40% OF $\dot{m}_a$, INJECTED THROUGH HOLES AND SLOTS**
- ***PATTERN FACTOR*** **IMPROVES WITH INCREASING $L_{dilution\ zone}$, ASYMPTOTIC TREND**
- $L_{dilution\ zone} = 1.5 - 1.8\ D_{liner}$
- ***PATTERN FACTOR*** **IMPORTANT FOR DURATION AND T_4**
- **IDEAL OUTLET T DISTRIBUTION NOT FLAT: T LOWER AT TURBINE BLADE ROOT (HIGHLY STRESSED) AND TIP (DUE TO SEALS)**

3.1.16 INJECTORS

- **SMALLER DROPLETS → FASTER EVAPORATION**
- **AFFECT STABILITY, η_b, EMISSIONS UHC, CO, SOOT**
- **MUST ENSURE GOOD PERFORMANCE OVER WIDE RANGE OF $\dot{m}_f$ AND f (OR EQUIVALENTLY $A/F = 1/f$)**
- **MAIN TYPES:**
  - ***PRESSURE–SWIRL***
  - ***AIRBLAST***
  - ***VAPORIZER***
  - ***PREMIX–VAPORIZER***

3.1.17 *PRESSURE–SWIRL* INJECTORS

- **SPRAY CONE ANGLE MUST BE CLOSE TO 90^{o} TO MINIMIZE LENGTH**
- **$\Delta p_{injector} \propto \dot{m}_f^2$, BUT $\dot{m}_f$ CAN VARY AS 1:50**
- **DUPLEX: TWO COALESCING JETS**
- **DISADVANTAGES: POSSIBLE BLOCKAGE OF SMALL PASSAGES, TENDENCY TO FORM SOOT AT HIGH p, *COKING***

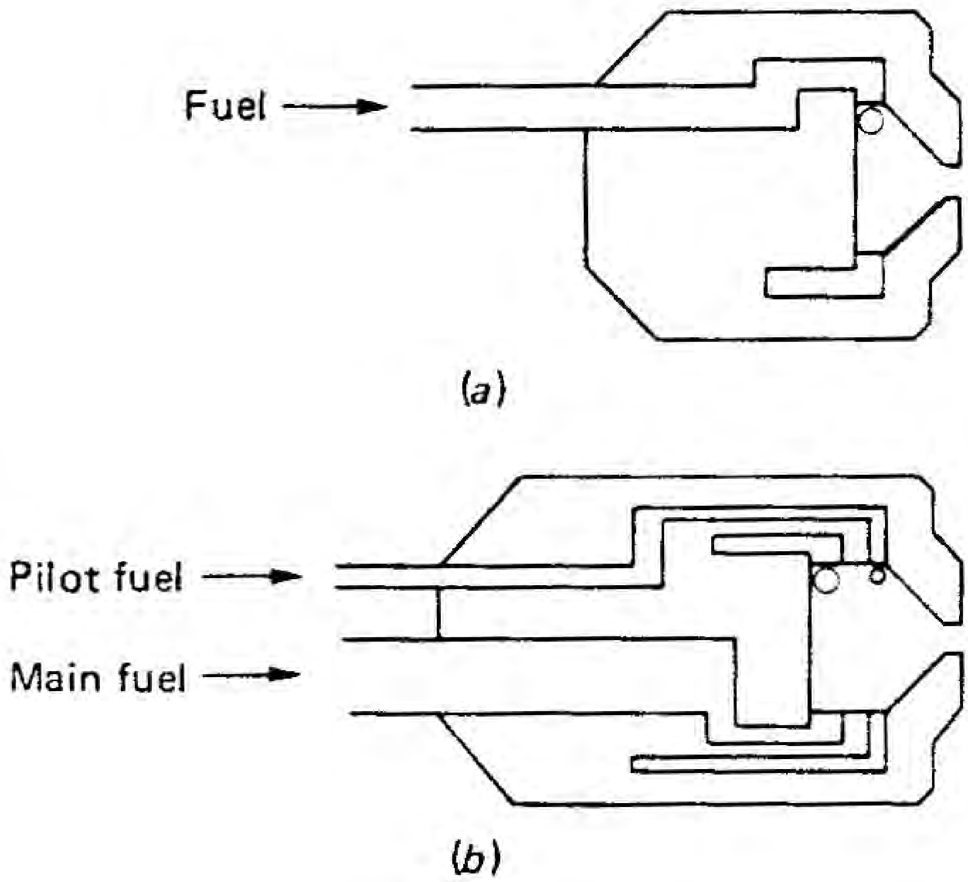


Figure 52: Conical simplex (top) and duplex (bottom) injectors.

3.1.18 EFFECT OF SWIRL

- **SWIRL NUMBER (*R* DUCT RADIUS):**

$$S = \frac{\text{axial flux angular momentum}}{\text{axial flux linear momentum}} = \frac{1}{R} \frac{\int_0^R \rho\, r^2\, u\, w\, dr}{\int_0^R \rho\, r\, u^2\, dr}$$

1. **FLUID PUSHED OUTWARD → DEPRESSION AT CENTRE → (TOROIDAL) RECIRCULATION FOR $S > 0{,}6$**
2. **WHEN MIXING FLUID OF DIFFERENT ρ, DENSER ONE MUST BE INJECTED FROM *INNER* DUCT**

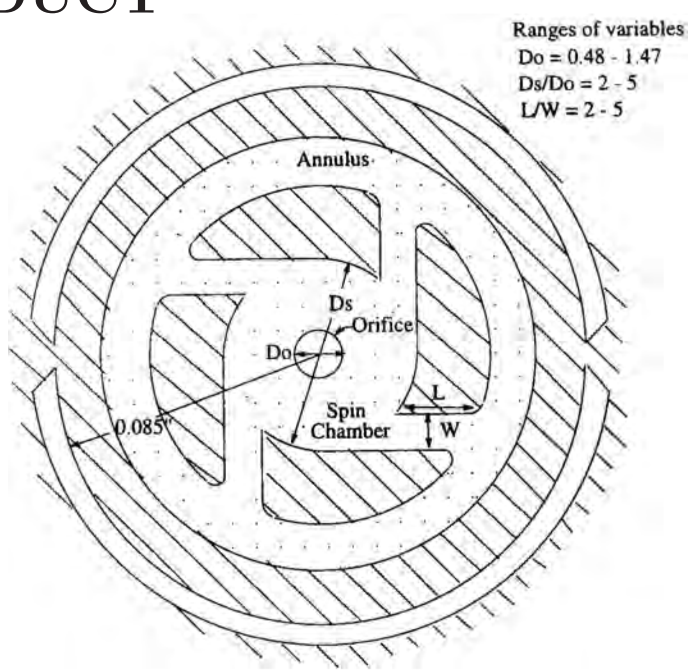


Figure 53: Cross-section of a *pressure–swirl* atomizer (simplex).

3.1.19 *AIRBLAST* INJECTORS

- **FUEL FILM STRAINED ON BOTH SIDES**
- **FORM LITTLE SOOT → LOW RADIATION AND COKING → T_{liner} LOW**
- **DISADVANTAGES: NARROW STABILITY RANGE, ATOMIZATION INADEQUATE AT START–UP**
- **SOLUTION: PILOT**

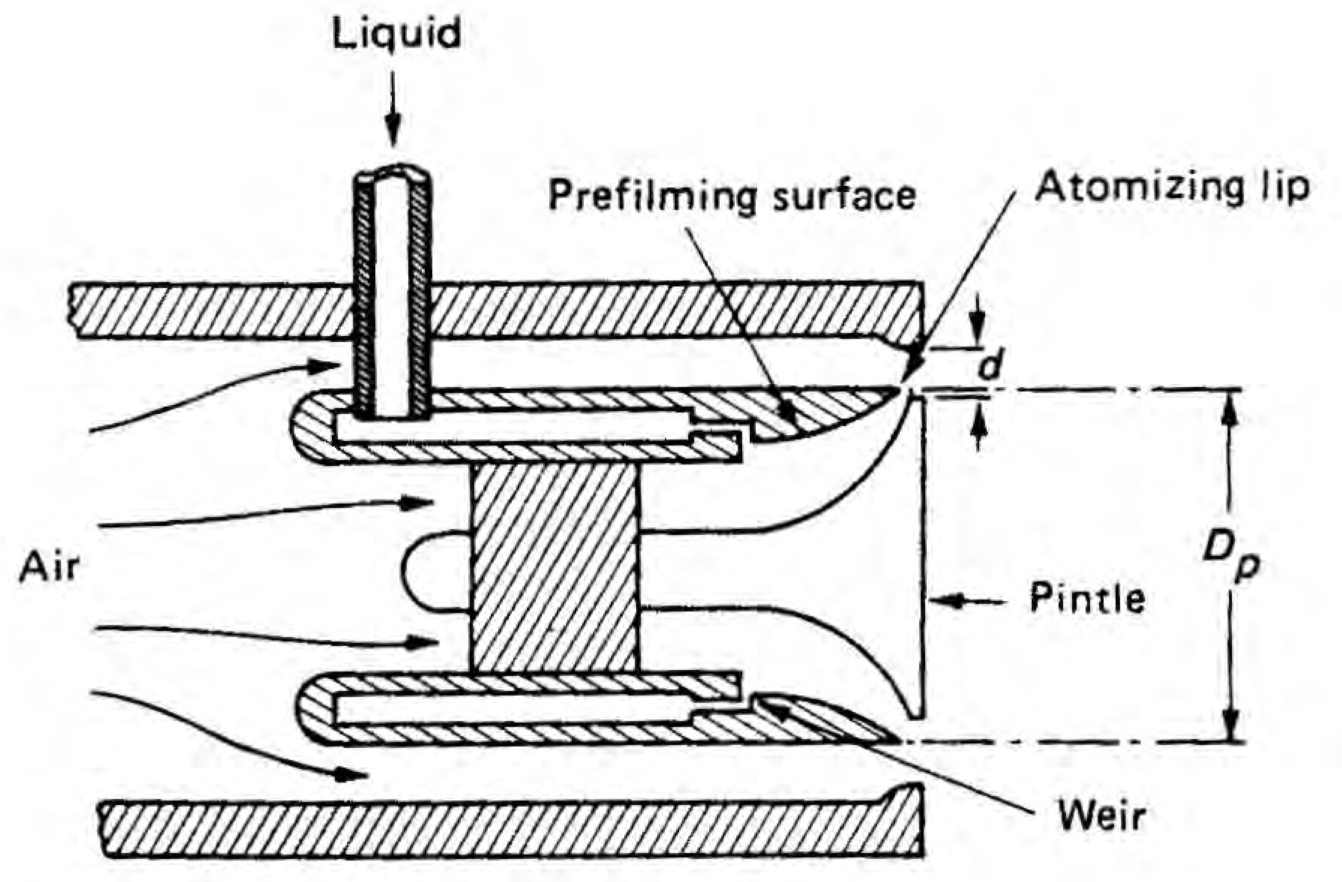


Figure 54: *Airblast* injector.

3.1.20 *VAPORIZER* INJECTORS

- **FUEL 'VAPORIZED' BY HOT AIR FROM COMPRESSOR AND HEAT FROM CHAMBER**
- **VAPORIZATION ACTUALLY INCOMPLETE**

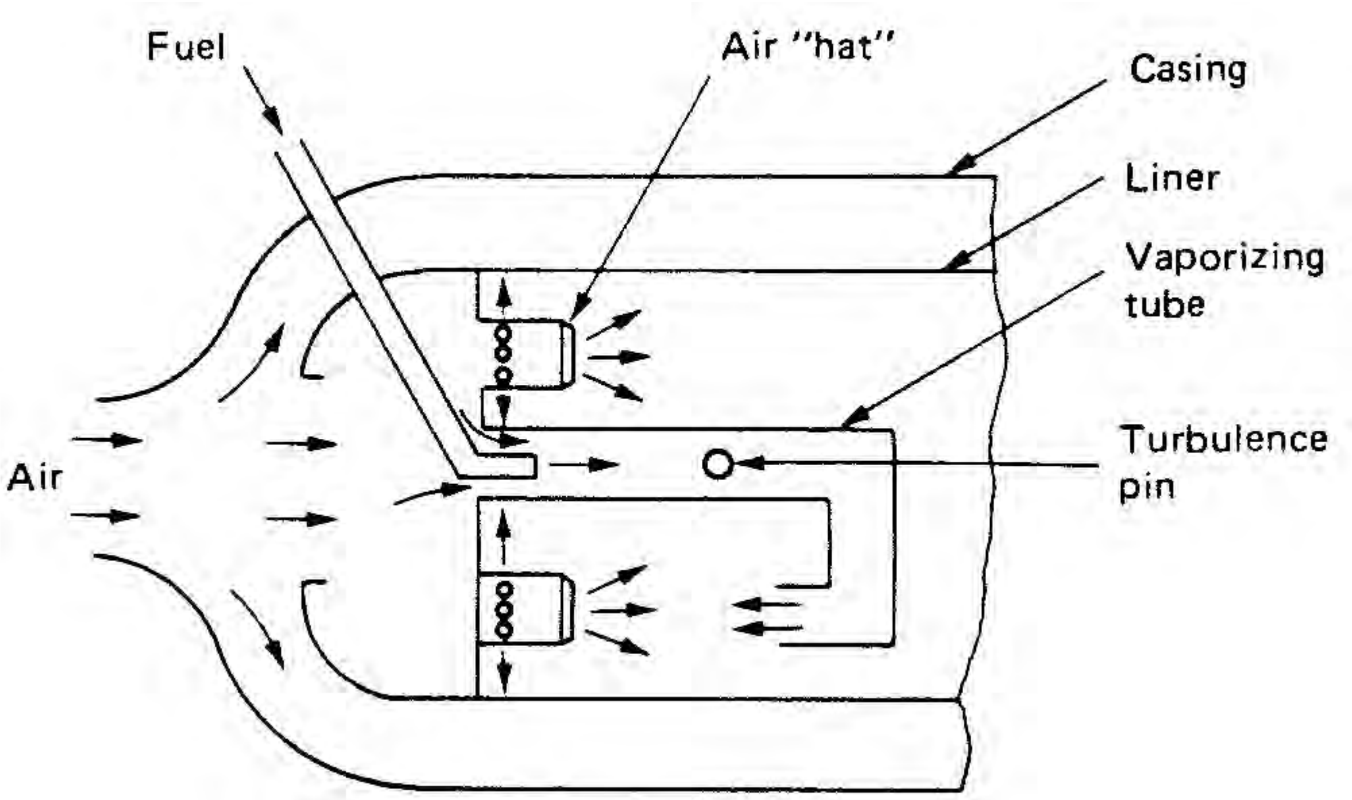


Figure 55: *Vaporizer* injector.

3.1.21 *PREMIX–VAPORIZER* INJECTORS

- **FINELY ATOMIZED FUEL INJECTED IN AIR AT HIGH–SPEED → VAPORIZATION AND MIXING COMPLETE BEFORE IGNITION**
- ***T* MORE UNIFORM → LOWER EMISSIONS**
- **DISADVANTAGES: *FLASHBACK*, START–UP → PILOT**

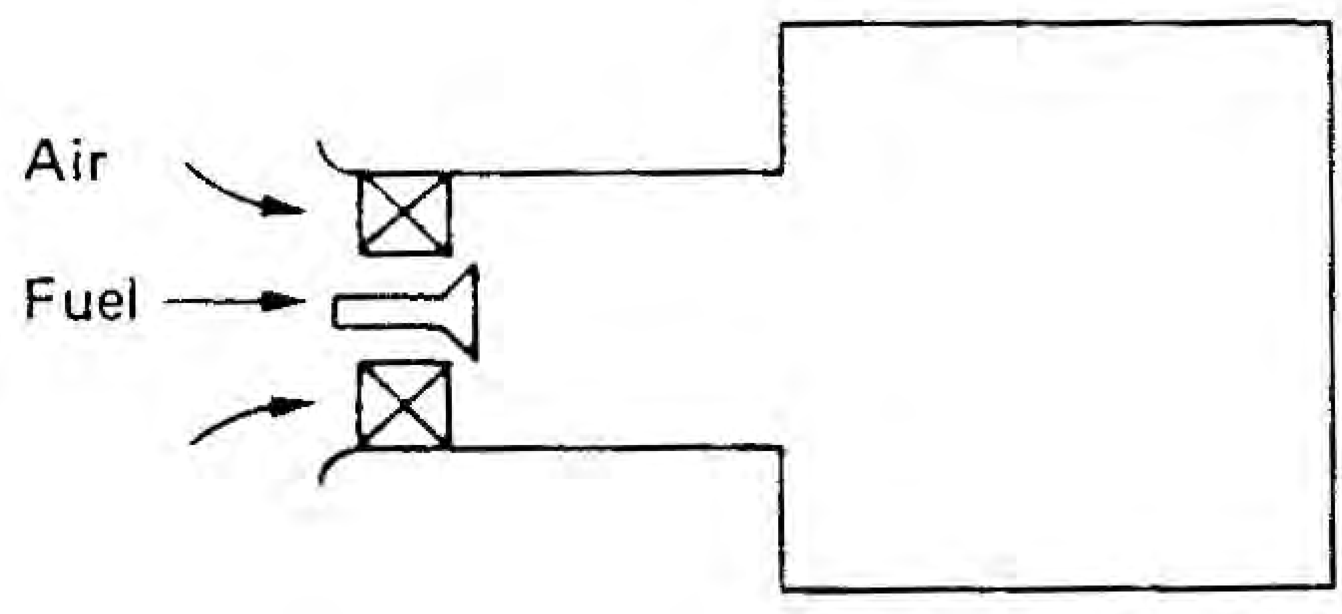


Figure 56: *Premix–vaporizer* injectors.

3.1.22 COOLING (1)

- ***LINER***: **CONTAINS COMBUSTION, DISTRIBUTES AIR**
- **MUST WITHSTAND MECHANICAL AND THERMAL STRESSES, THERMAL FATIGUE**
- **MATERIALS FOR HIGH T; COOLING AIR (UP TO 50% $\dot{m}_a$)**
- **T_{liner} FROM BALANCE q IN AND OUT (DUE TO RADIATION AND CONVECTION)**
- **AS β_o INCREASES, HIGHER $T_3 \rightarrow$ COOLING MORE AND MORE CRITICAL**
- ***FILM–COOLING***, ***CONVECTION–COOLING*** **(ROUGHENED WALLS)**, ***IMPINGEMENT–COOLING***, ***TRANSPIRATION–COOLING***

3.1.23 COOLING (2)

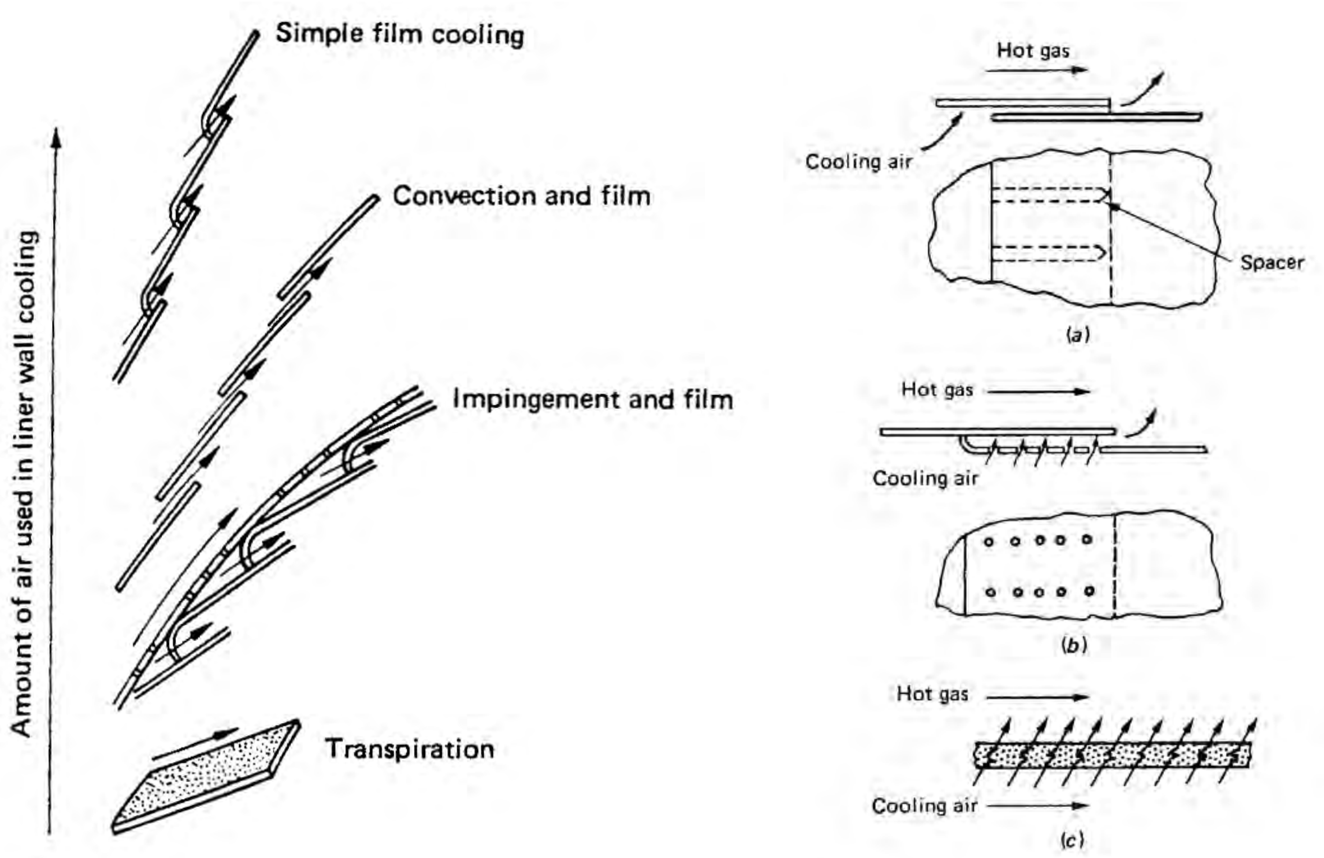


Figure 57: Wall cooling techniques.

3.1.24 COOLING (3)

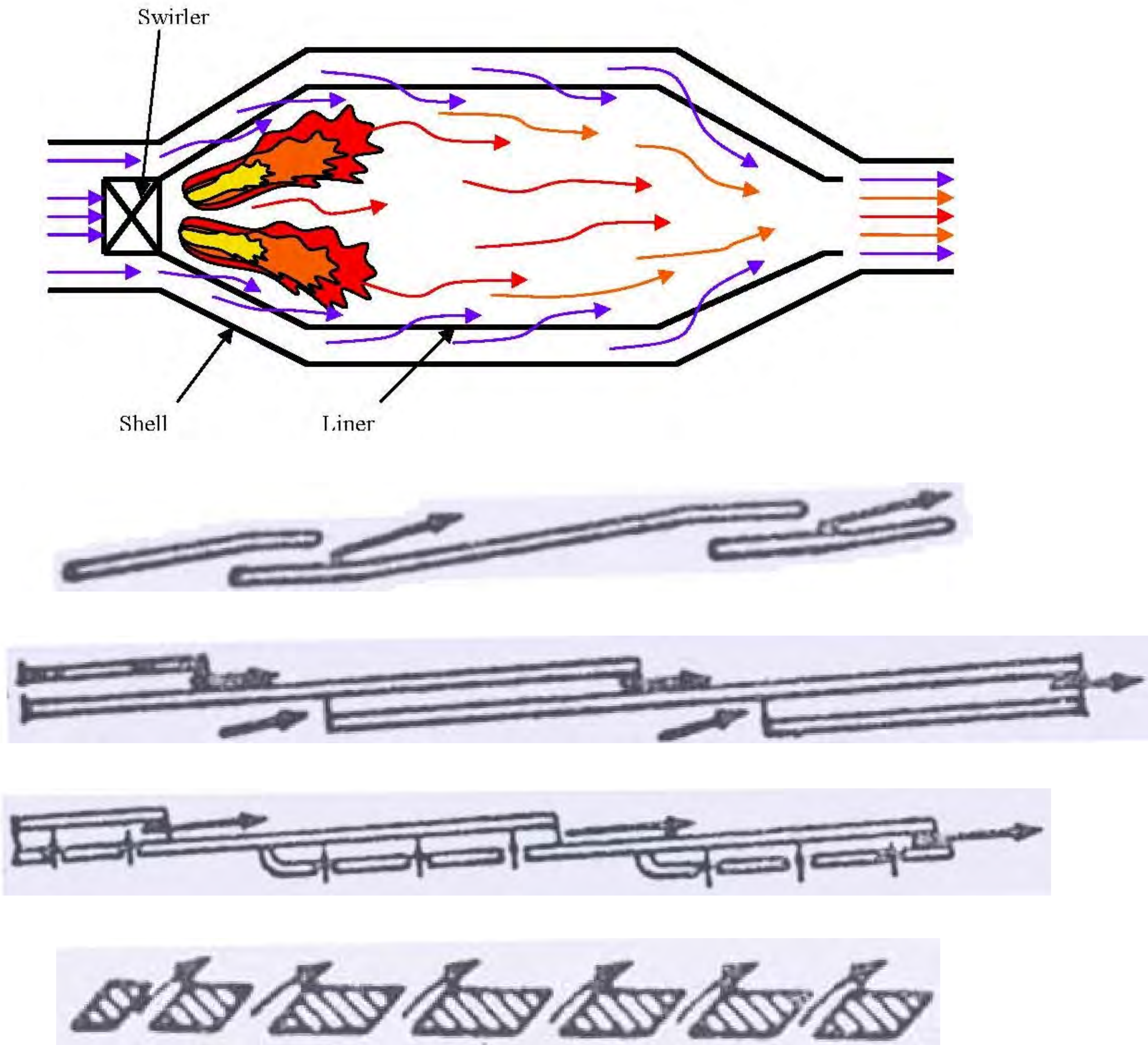
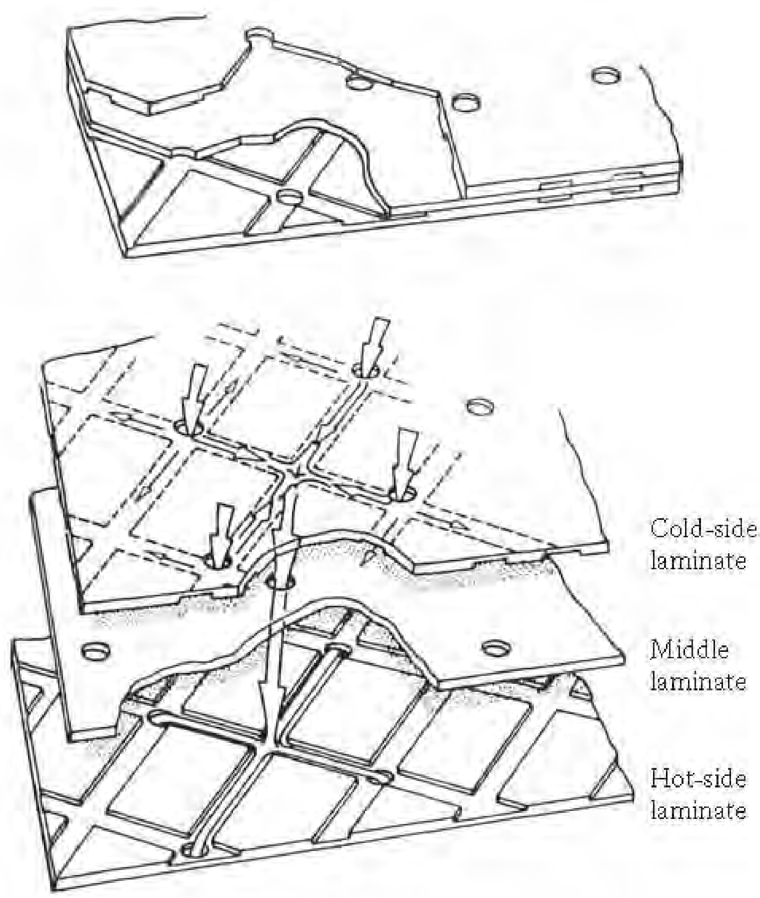


Figure 58: Wall cooling techniques.

3.1.25 COOLING (4)

- **TRANSPIRATING MATERIAL SHOULD FEATURE VERY SMALL, CLOSELY–SPACED HOLES → CLOGGING DUE TO PARTICULATE (SOOT)**
- **"QUASI–TRANSPIRATING" MATERIALS (TRANSPLY, LAMILLOY)**



3.1.26 CONFIGURATION EXAMPLES: GE CF–6 50

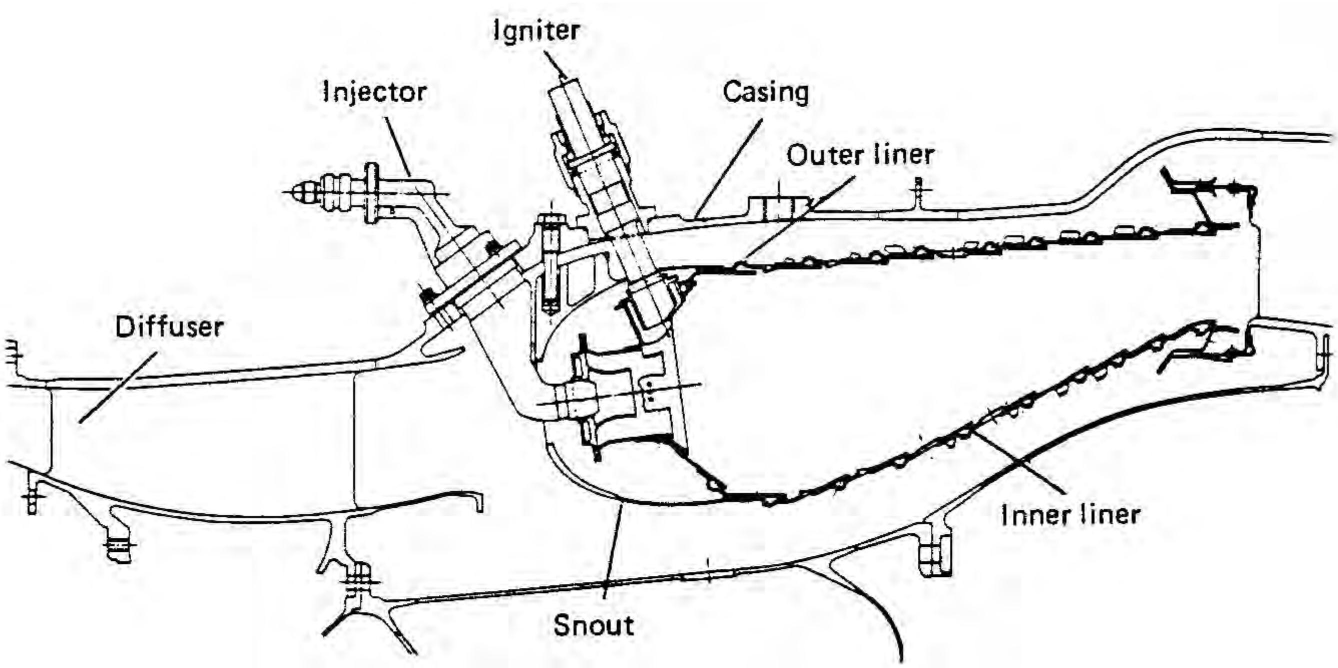


Figure 59: Annular combustor of GE CF6–50 engine.

3.1.27 CONFIGURATION EXAMPLES: GE F–101

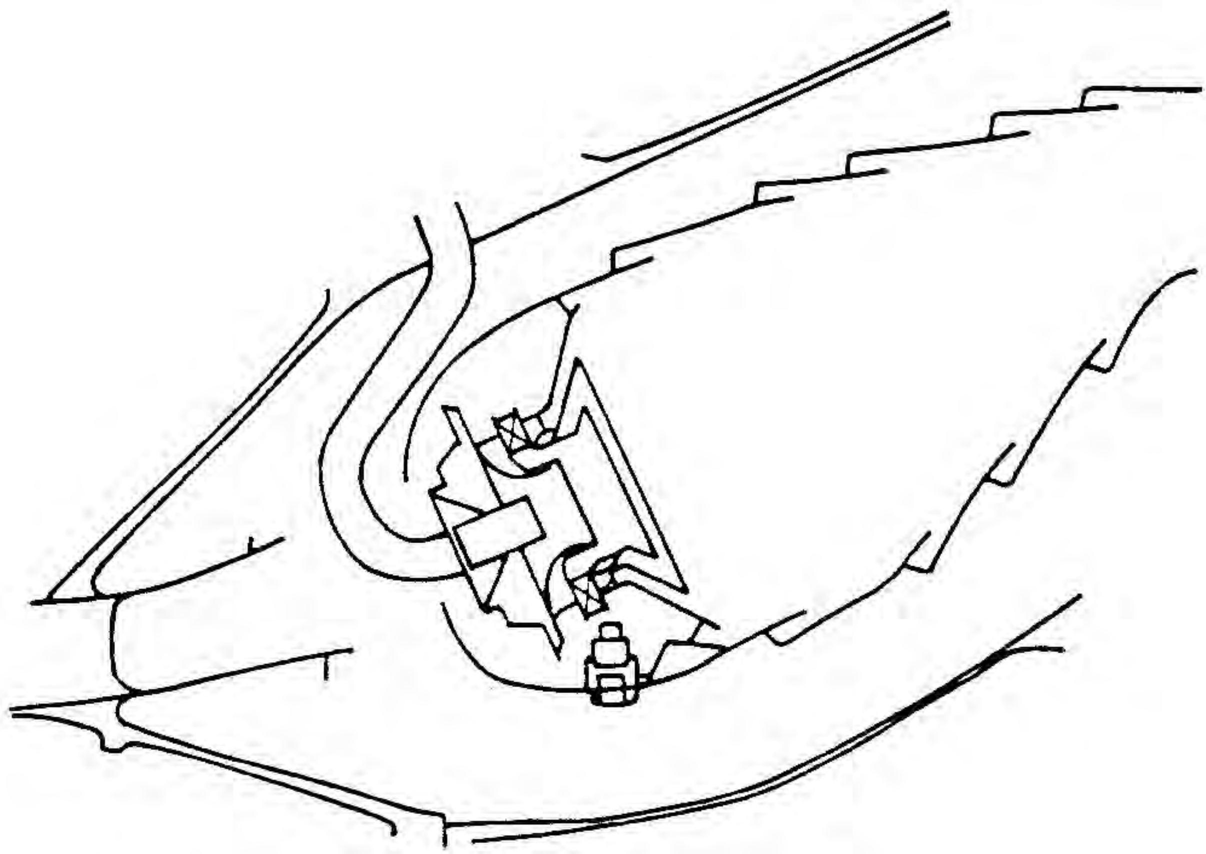


Figure 60: Annular combustor of GE F101 engine.

3.1.28 CONFIGURATION EXAMPLES: RR RB–211

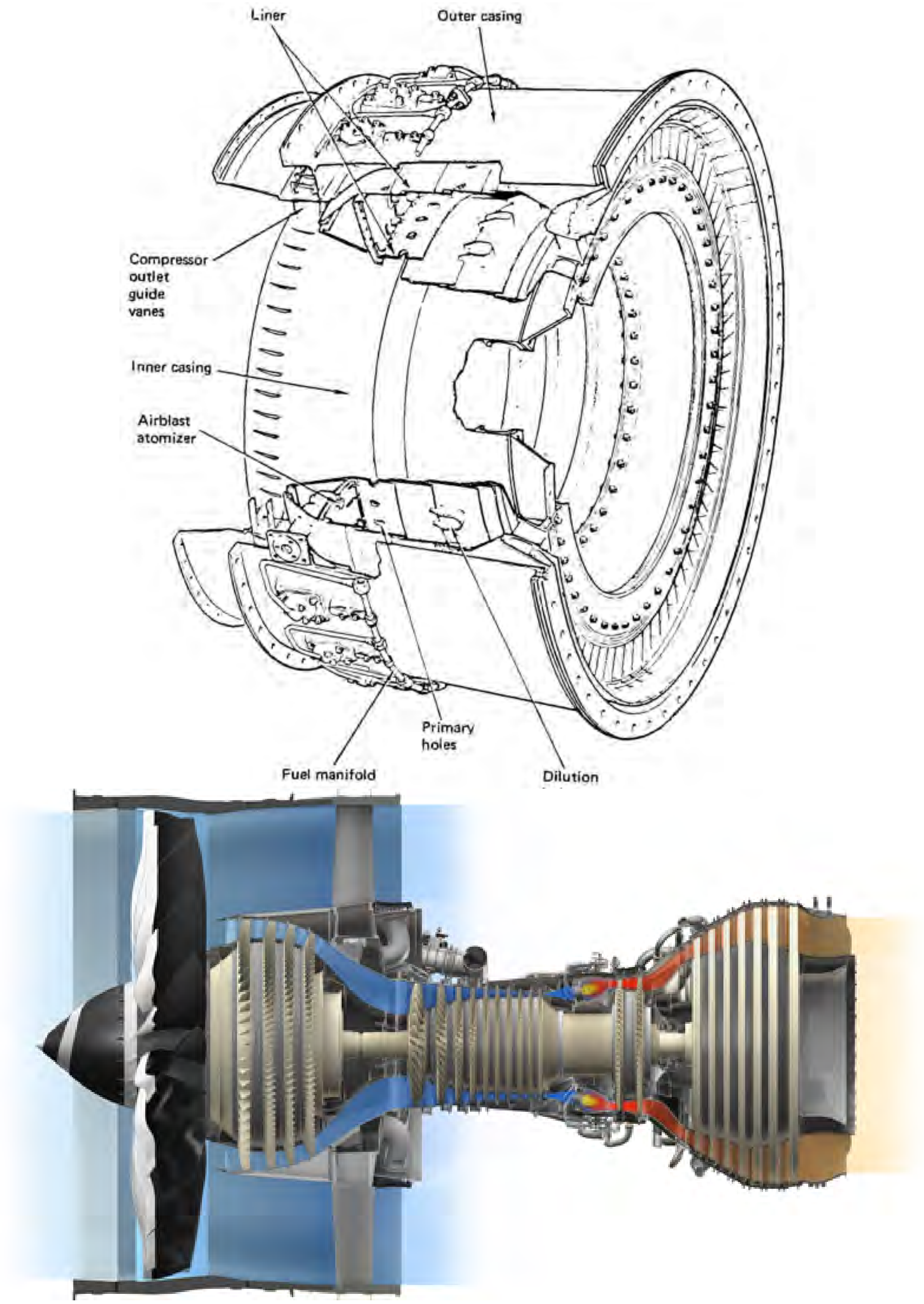


Figure 61: (Top) Annular combustor of RB211 engine, (bottom) cutaway of Rolls–Royce Trent 1000.

3.1.29 CONFIGURATION EXAMPLES: STEALTH AIRCRAFTS

Figure 62: Stealth bomber Northrop Grumman B–2 Spirit..

3.1.30 'STAGED' COMBUSTORS

- **TO OPERATE OVER A WIDE RANGE OF CONDITIONS**

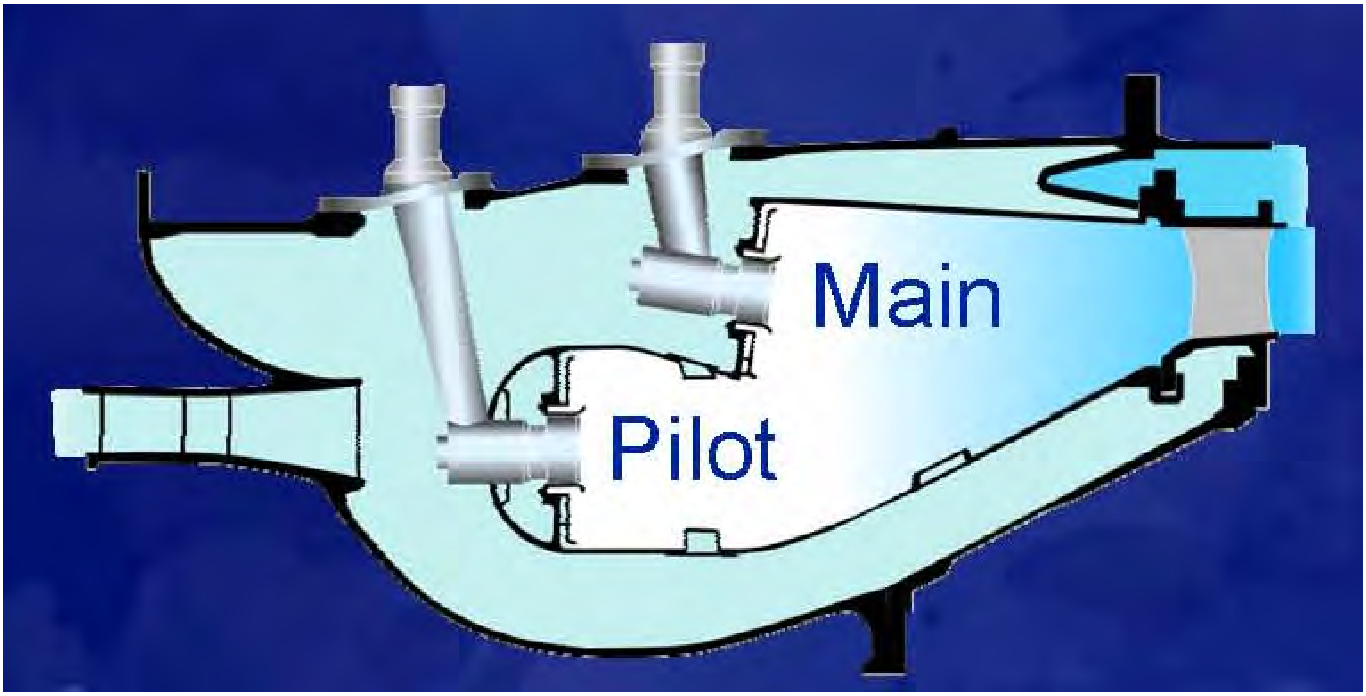


Figure 63: Two–stage combustor.

- **OR (IN THEORY) CATALYTIC COMBUSTION**

3.2.1 COMBUSTION CHAMBERS: COMBUSTION FUNDAMENTALS

- **EXOTHERMIC REACTION BETWEEN FUEL AND OXIDIZER**
- **FLAMES:**
  - **NONPREMIXED (OR DIFFUSION)**
  - **PREMIXED**
  - **PARTIALLY PREMIXED**
- **REGIMES:**
  - **LAMINAR**
  - **TURBULENT** $\leftarrow Re \simeq 10^5$

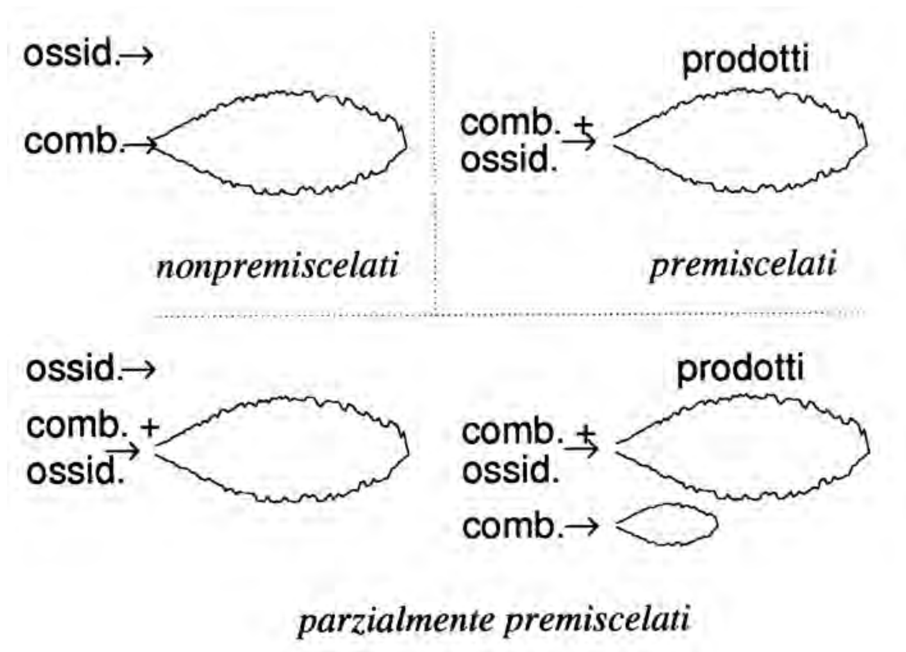


Figure 64: Flames with nonpremixed, premixed, partially premixed reactants.

3.2.2 CONTROLLING FACTORS

- **CHEMICAL:**
  - **REACTION RATES**
- **PHYSICAL:**
  - **DROPLET EVAPORATION**
  - **MIXING (TURBULENT)**
  - **DIFFUSION FUEL AND AIR (FOR NONPREMIXED FLAMES)**
  - **HEAT TRANSFER (CONVECTIVE/RADIATIVE)**

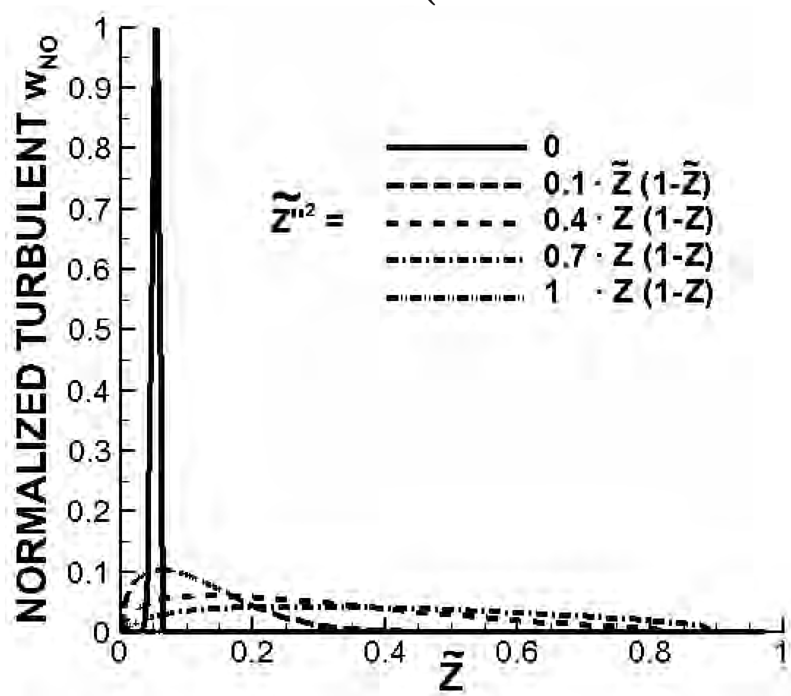


Figure 65: Effect of turbulent fluctuations on *mean* species source term rate (for a particular case, nitric oxide formation from HC combustion); $\varphi = \dfrac{Z/(1-Z)}{(F/O)_{st}}$.

3.2.3 STOICHIOMETRIC COMBUSTION

- **EXAMPLE: n–DECANE $C_{10}H_{22}$ AND AIR**
- $\mathcal{M}_{C_{10}H_{22}} = 142{,}287$ **kg/kmol**
- **AIR COMPOSITION (IN MOLAR FRACTIONS X_i):**
  - N_2 **78,08 %** ($\mathcal{M}_{N_2} = 28{,}0134$)
  - O_2 **20,95 %** ($\mathcal{M}_{O_2} = 31{,}9988$)
  - **Ar 0,934 %** ($\mathcal{M}_{Ar} = 39{,}948$)
  - CO_2 **0,0411%** ($\mathcal{M}_{CO_2} = 44{,}00995$)
  - $\simeq$ **21%** O_2, **79%** N_2 $\rightarrow$ **3,76 MOLECULES OF** N_2 **FOR EACH MOLECULE OF** O_2

$\rightarrow \mathcal{M}_{\text{aria}} = \sum_i X_i \mathcal{M}_i = 28{,}9645 \simeq 29$ **kg/kmol**

- **STOICHIOMETRIC COMBUSTION:**

$$C_{10}H_{22} + 15,5\ (O_2 + 3,76\,N_2) \longrightarrow$$

$$\longrightarrow 10CO_2 + 11\,H_2O + 58,28\,N_2$$

- $X_{C_{10}H_{22},\text{st}} = 1\ /\ (1 + 15{,}5 + 58{,}28) = 0{,}0134$
- $Y_{C_{10}H_{22},\text{st}} = 142{,}287\ /\ (142{,}287 + 496 + 1632{,}6)$ $= 0{,}0625$

3.2.4 FLAMMABILITY LIMITS

- **FOR A MIXTURE OF n–DECANE/AIR AT p=1 atm, COMBUSTION CAN TAKE PLACE ONLY IF $0,75 < \varphi < 6$**
- **IN NONPREMIXED COMBUSTION, SUCH A CONDITION IS CERTAINLY SATISFIED IN SOME ZONES**
- **IN PREMIXED COMBUSTION, CAN OR CANNOT BE SATISFIED, DEPENDING ON MIXTURE COMPOSITION (LESS STABLE)**

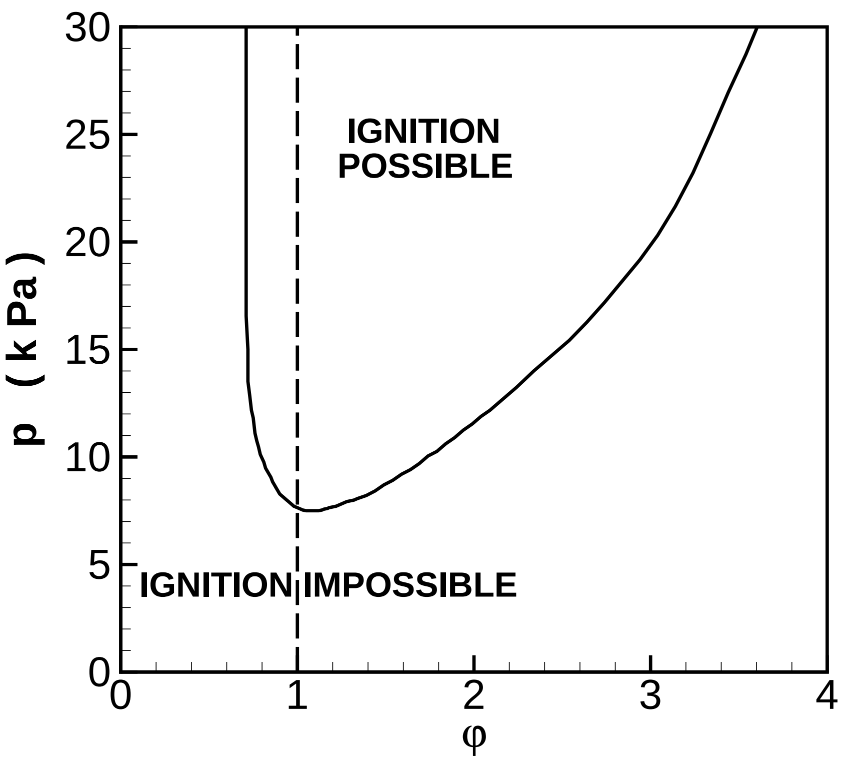


Figure 66: Flammability limits of a fuel/air mixture.

3.2.5 IGNITION LIMITS OF Jet–A AT DIFFERENT MIXTURE T

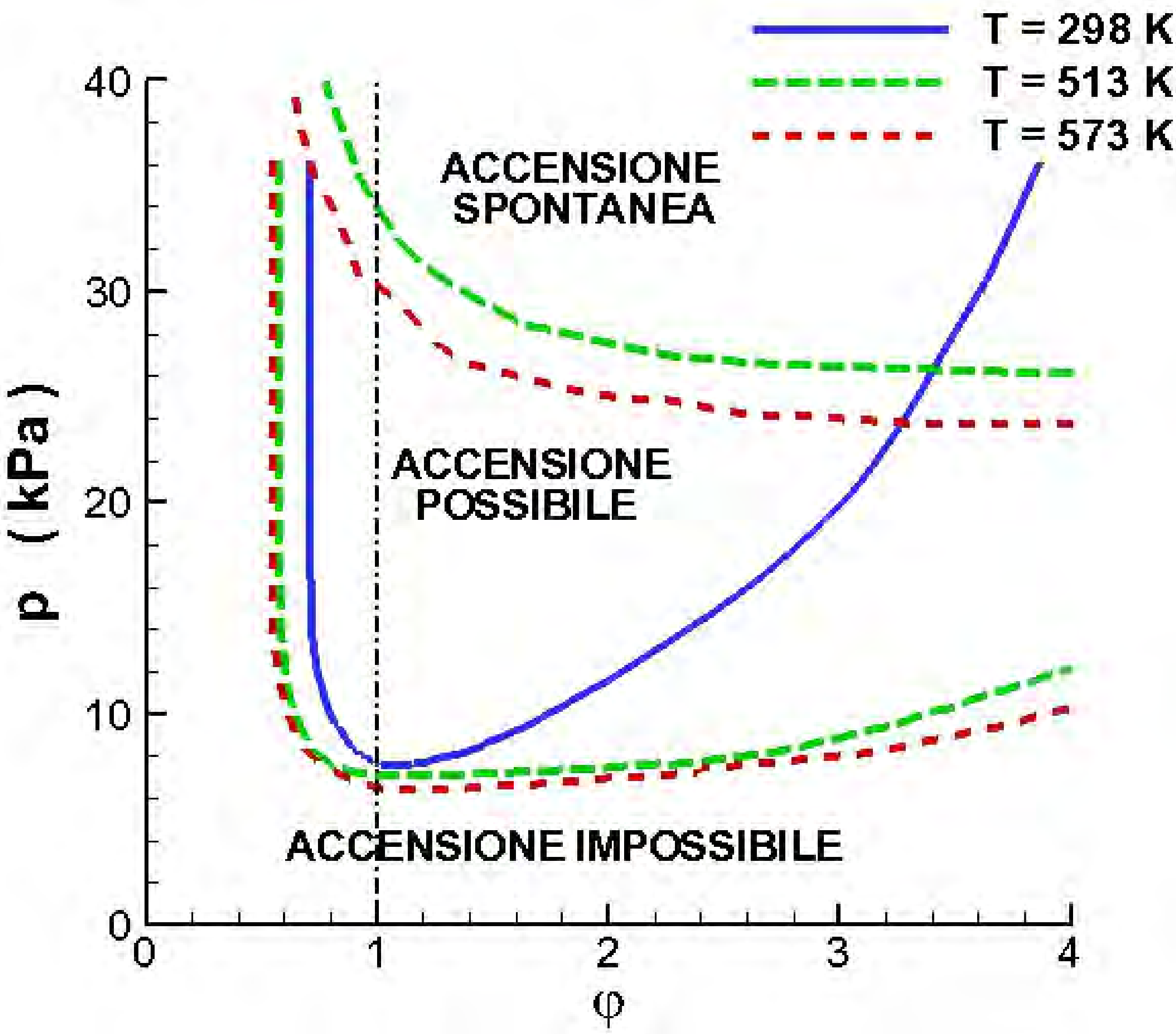


Figure 67: Ignition limits of Jet–A fuel, with the temperature of the fuel/air mixture as a parameter.

3.2.6 FLASH POINT

- **p_{vap} INCREASING WITH T**
- ***FLASH POINT*: T AT WHICH CONCENTRATION FUEL VAPOURS IN AIR = LOWER FLAMMABILITY LIMIT (FOR p=1 atm)**
- **FLAMMABILITY RANGE NARROWER WHEN ADDING AN INERT (N_2, CO_2 → TANK)**

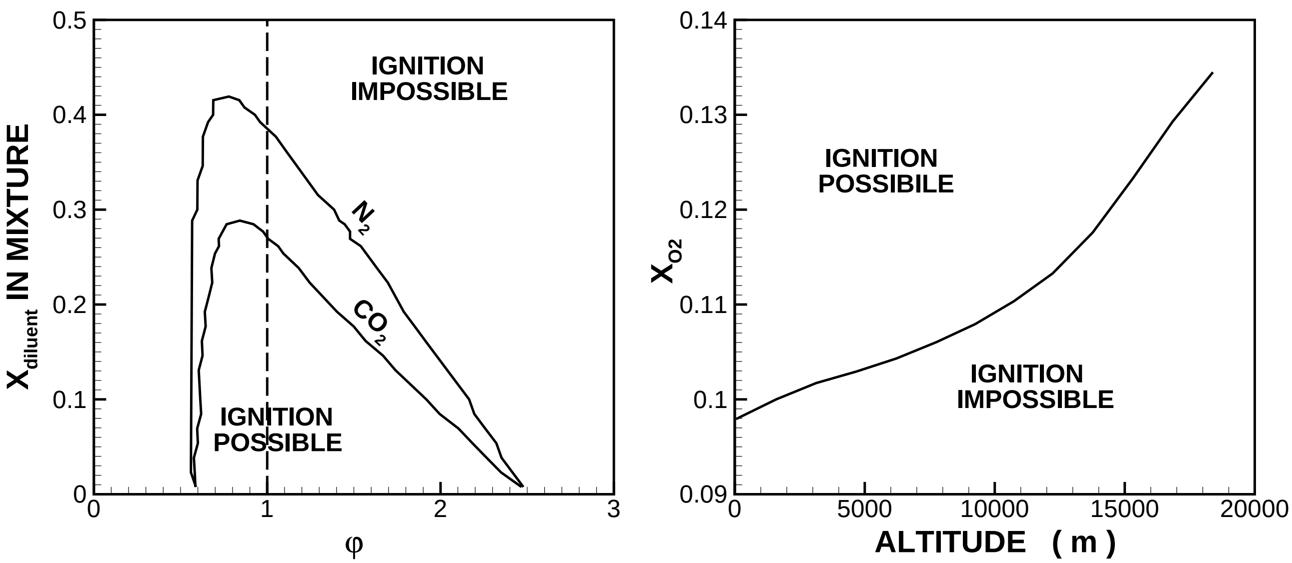


Figure 68: (left) Flammability limits of a propane/air mixture diluted with CO_2 or N_2, for $p = 1$ atm, $T = 298{,}15$ K; (right) concentration of O_2 below which ignition of a mixture containing JP–4 vapours is impossible (diluent N_2).

- **IF IN AIR/VAPOURS (OF JP–4) MIXTURE IT IS $X_{O_2} < 9\%$ → IGNITION IMPOSSIBLE AT ANY p (NOW REVISED < 12%)**

3.2.7 IN–FLIGHT FUEL TEMPERATURE AND Jet–A FLAMMABILITY

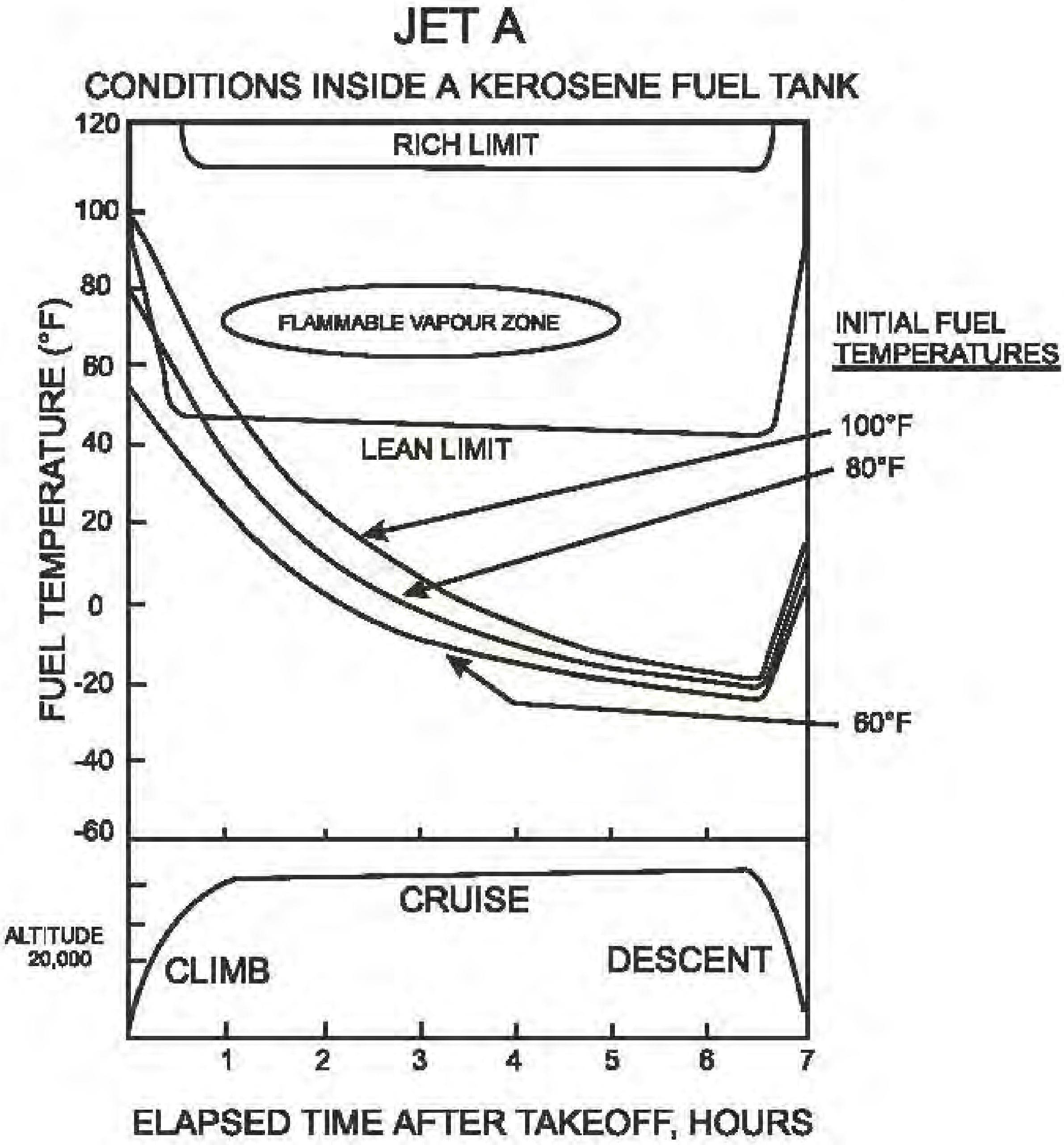


Figure 69: Typical time evolution of fuel temperature in flight, and ensuing risk situations for Jet–A.

3.2.8 IN–FLIGHT FUEL TEMPERATURE AND Jet–B FLAMMABILITY

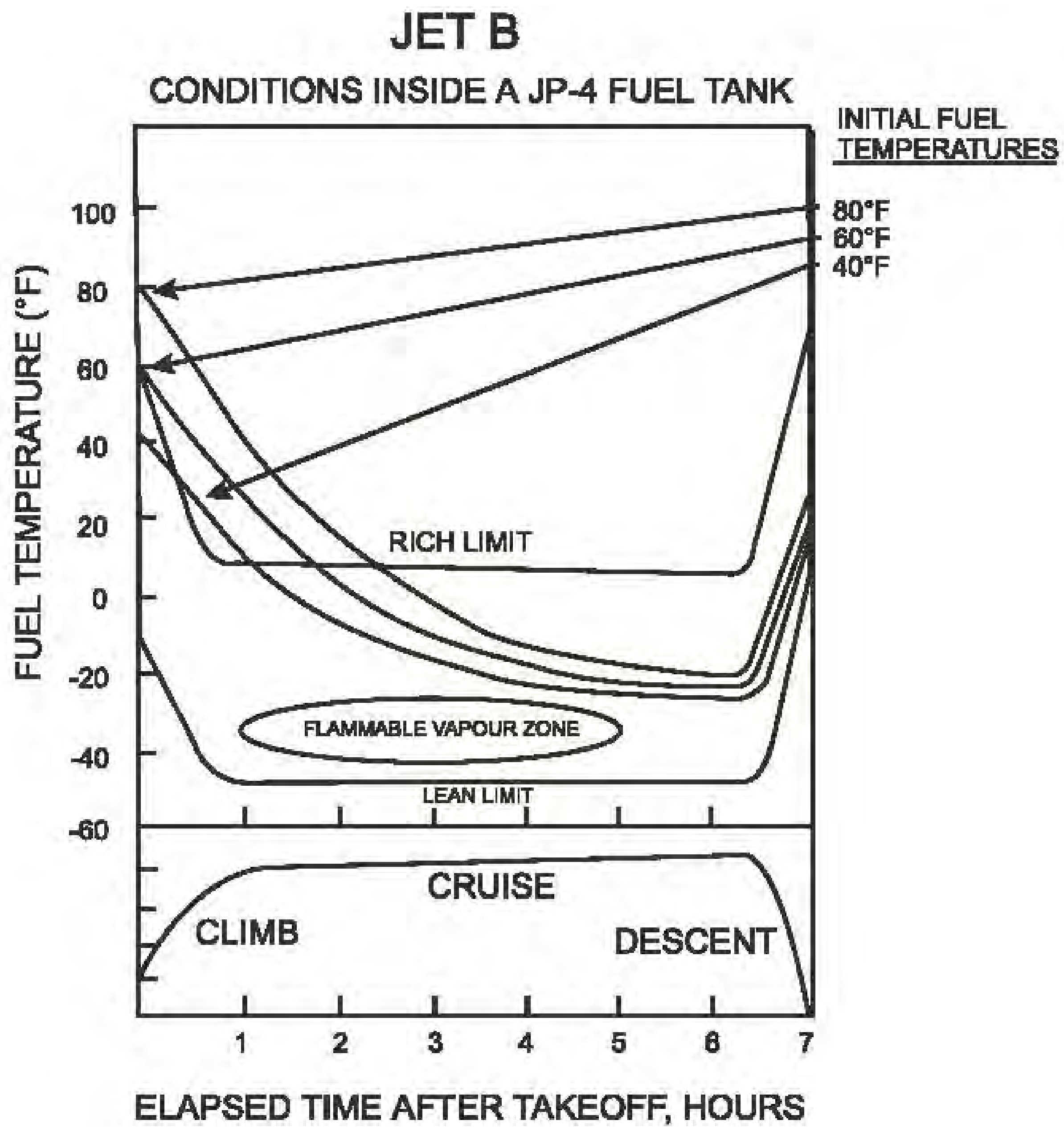


Figure 70: Typical time evolution of fuel temperature in flight, and ensuing risk situations for Jet–B.

3.2.9 DESCRIPTION OF CHEMISTRY

$$C_{10}H_{22} + 15,5\,O_2 \rightarrow 10\,CO_2 + 11\,H_2O + Q_R$$

- **GENERAL FORM:**
  - **FOR ELEMENTARY REACTION STEPS:**

$$\sum_{i=1}^{N} \nu_i' \mathrm{M}_i \rightarrow \sum_{i=1}^{N} \nu_i'' \mathrm{M}_i$$

  - **FOR REVERSIBLE REACTIONS:**

$$\sum_{i=1}^{N} \nu_i' \mathrm{M}_i \leftrightharpoons \sum_{i=1}^{N} \nu_i'' \mathrm{M}_i$$

- **DESCRIPTION LEVELS:**
  - **COMBUSTION "*MIXED IS BURNT*"**
  - **COMBUSTION IN CHEMICAL EQUILIBRIUM**
  - **COMBUSTION WITH FINITE-RATE CHEMISTRY**

3.2.10 COMBUSTION "MIXED IS BURNT"

- **EXAMPLE: KEROSENE/AIR COMBUSTION**
- **KEROSENE ~ 89% *n*–DECANE $C_{10}H_{22}$, 11% TOLUENE C_7H_8 (IN MASS) $\longrightarrow \frac{n_{C_{10}H_{22}}}{n_{C_7H_8}} \simeq 5{,}24$**
- **AIR ~ 79% N_2, 21% O_2 (IN VOL.) $\longrightarrow \frac{n_{N_2}}{n_{O_2}} \simeq 3{,}76$**
- **FOR STOICHIOMETRIC COMBUSTION (φ=1):**

$$C_7H_8 + 5,24 \cdot C_{10}H_{22} + 90,22\,(O_2 + 3,76 \cdot N_2) \longrightarrow$$
$$\longrightarrow\; 59,4 \cdot CO_2 + 61,64 \cdot H_2O + 339,23 \cdot N_2$$

- **FOR RICH COMBUSTION ($\varphi > 1$):**

$$C_7H_8 + 5,24 \cdot C_{10}H_{22} + \frac{90,22}{\varphi}(O_2 + 3,76 \cdot N_2) \rightarrow$$
$$\frac{59,4}{\varphi} \cdot CO_2 + \frac{61,64}{\varphi} \cdot H_2O + (1 - \frac{1}{\varphi}) \cdot (C_7H_8 + 5,24 \cdot C_{10}H_{22}) + \frac{339,23}{\varphi} \cdot N_2$$

- **FOR LEAN COMBUSTION ($\varphi < 1$):**

$$C_7H_8 + 5,24 \cdot C_{10}H_{22} + \frac{90,22}{\varphi}(O_2 + 3,76 \cdot N_2) \rightarrow$$
$$\rightarrow\; 59,4 \cdot CO_2 + 61,64 \cdot H_2O + 90,22 \cdot \left(\frac{1}{\varphi} - 1\right) \cdot O_2 + \frac{339,23}{\varphi} \cdot N_2$$

3.2.11 COMBUSTION IN CHEMICAL EQUILIBRIUM

- **PARTIAL PRESSURE OF SPECIES i**

$$p_i = X_i \, p$$

- **EXAMPLE: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$**

$$K_{p,H_2O}(T) = \frac{p_{H_2O}}{p_{H_2} \, (p_{O_2})^{1/2}}$$

$$\frac{X_{H_2O}}{X_{H_2} \, (X_{O_2})^{1/2}} = K_{p,H_2O}(T) \cdot p^{1/2} = K_{X,H_2O}(T, p)$$

- **IN GENERAL $K_p(T) = \prod_{i=1}^{N} p_i^{\Delta \nu_i}$, WITH $\Delta \nu_i = \nu_i'' - \nu_i'$**
- **p ESPRESSED IN UNITS OF REFERENCE p_0 (1 atm, 100 kPa)**
- **CODE STANJAN,**
  my.fit.edu/˜dkirk/4262/Lectures
- **CODE CEA,**
  www.grc.nasa.gov/WWW/CEAWeb/ceaguiDownload-win.htm
- **CEA DATA FILES ON**
  dma.dima.uniroma1.it:8080/STAFF2/lentini.html

3.2.12 DERIVATION OF EQUILIBRIUM CONSTANT K_p

- **REACTION** $\sum_{i=1}^{N} \nu_i' \, \mathrm{M}_i \leftrightharpoons \sum_{i=1}^{N} \nu_i'' \, \mathrm{M}_i$

- **GIBBS FUNCTION** $G = H - T\,S$ **UNCHANGED**

$$\sum_{i=1}^{N} \Delta\nu_i \, \hat{g}_i = \sum_{i=1}^{N} \Delta\nu_i \, (\hat{h}_i - T\,\hat{s}_i) = 0$$

- $\hat{g}_i$, $\hat{h}_i$, $\hat{s}_i$ **RELATIVE TO MOLAR UNIT**

- $d\hat{s}_i = \hat{c}_{p,i} \dfrac{dT}{T} - \mathcal{R} \dfrac{dp_i}{p_i} \implies \hat{s}_i = \hat{s}_{0,i}(p_0, T) - \mathcal{R} \log \dfrac{p_i}{p_0}$

$$\sum_{i=1}^{N} \Delta\nu_i \left[\hat{h}_i - T \left(\hat{s}_{0,i} - \mathcal{R} \log \frac{p_i}{p_0}\right)\right] = 0$$

$$\sum_{i=1}^{N} \Delta\nu_i \left(\hat{h}_i - T\,\hat{s}_{0,i}\right) = -\mathcal{R}\,T \sum_{i=1}^{N} \Delta\nu_i \log \frac{p_i}{p_0}$$

$$\exp\left[-\frac{1}{\mathcal{R}\,T} \sum_{i=1}^{N} \Delta\nu_i \left(\hat{h}_i - T\,\hat{s}_{0,i}\right)\right] = \prod_{i=1}^{N} \left(\frac{p_i}{p_0}\right)^{\Delta\nu_i} = K_p(T)$$

3.2.13 ABSOLUTE ENTHALPY

- **FOR EACH CHEMICAL SPECIES, A *FORMATION ENTHALPY* IS DEFINED**
- **e.g., $H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \hat{Q}_{f,H_2O}$**
- **$\hat{Q}_f$ HEAT OF FORMATION = - $\Delta \hat{h}_{f,H_2O}$**
- **FOR ELEMENTS IN MOLECULAR FORM IN THEIR STANDARD STATE $\Delta \hat{h}_{f,i} = 0$**
- **e.g., $H_2(g)$, $O_2(g)$, C(s), Hg(l), ...**

- **PER UNIT MASS $\Delta h_{f,i} = \Delta \hat{h}_{f,i} / \mathcal{M}_i$**
- **$\Delta h_{f,i}$ TABULATED FOR $T_0 = 298{,}15$ K, $p_0 = 100$ kPa (OR 1 atm)**

- **ABSOLUTE ENTHALPY: $h_i = \Delta h_{f,i} + \int_{T_0}^{T} c_{p,i}(T') \, dT'$**

- **ENTHALPY OF A MIXTURE:**

PER UNIT MASS: $$h = \sum_{i=1}^{N} Y_i h_i(T)$$

PER MOLAR UNIT: $$\hat{h} = \sum_{i=1}^{N} X_i \hat{h}_i(T)$$

3.2.14 FINITE–RATE CHEMISTRY COMBUSTION (SINGLE REACTION)

$$\frac{\partial \rho Y_i}{\partial t}+\frac{\partial \rho u_l Y_i}{\partial x_l} = \frac{\partial}{\partial x_l}\left(\rho D_i \frac{\partial Y_i}{\partial x_l}\right)+w_i, \quad i=1,2,...,N$$

- w_i **PRODUCTION RATE** i**–th CHEMICAL SPECIES** $[\mathrm{kg/(m^3s)}]$**: FROM LAW OF MASS ACTION**

$$w_i = \mathcal{M}_i \,\Delta\nu_i \left\{ k_f \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu'_j} \right\}, \quad i = 1,2,...,N$$

* $\{\cdots\}$ **REACTION RATE** $[\mathrm{no.\ reacts./(}N_A\mathrm{m^3s)}]$:

$$[\mathrm{M}_j] = \frac{n_j}{V} = \frac{m_j/\mathcal{M}_j}{V} = \frac{Y_j\, m/\mathcal{M}_j}{V} = \frac{\rho Y_j}{\mathcal{M}_j}$$

- k_f **'CONSTANT' OF FORWARD REACTION:**

$$k_f = B\, T^{\alpha} \exp\left(-\frac{E}{\mathcal{R}T}\right)$$

- B **FREQUENCY FACTOR,** E **ACTIVATION ENERGY**
- $m = \sum_i \nu'_i$ **MOLECULARITY OF REACTION**

$$w_i = \mathcal{M}_i \,\Delta\nu_i\, \rho^m\, B\, T^{\alpha} \exp\left(-\frac{E}{\mathcal{R}T}\right) \prod_{j=1}^{N}\left(\frac{Y_j}{\mathcal{M}_j}\right)^{\nu'_j}, \quad i=1,...,N$$

3.2.15 FINITE–RATE CHEMISTRY COMBUSTION (M REACTIONS)

- **IN PRESENCE OF M REACTIONS ($m_k = \sum_i \nu'_{i,k}$):**

$$w_i = \mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k}\, \rho^{m_k} B_k T^{\alpha_k} \exp\left(-\frac{E_k}{\mathcal{R}T}\right) \prod_{j=1}^{N} \left(\frac{Y_j}{\mathcal{M}_j}\right)^{\nu'_{j,k}}, \quad i = 1, \ldots, N$$

$$\Delta\nu_{i,k} = \nu''_{i,k} - \nu'_{i,k}$$

- **ARRHENIUS EXPRESSION**
- **B_k FREQUENCY FACTOR, E_k ACTIVATION ENERGY (T_k ACTIVATION TEMPERATURE) OF k–th REACTON**
- **EXPRESSED IN UNITS cm, g, s, mol → CONVERT**
- **FINITE–RATE CHEMISTRY SOMETIMES CALLED ‘NONEQUILIBRIUM CHEMISTRY’ (IMPROPERLY)**

3.2.16 FINITE–RATE CHEMISTRY: RELATIONSHIP AMONG k_f, k_b, K_p

- **FOR REVERSIBLE REACTIONS**

$$w_i = \mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k} \left\{ k_{f,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu'_{j,k}} - k_{b,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu''_{j,k}} \right\} = \ldots$$

- **AT EQUILIBRIUM (0–D, STEADY–STATE SYSTEMS):**

$$k_{f,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu'_{j,k}} = k_{b,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu''_{j,k}} \Longrightarrow \frac{k_{f,k}}{k_{b,k}} = \prod_{j=1}^{N} [\mathrm{M}_j]^{\Delta\nu_{j,k}}$$

$$[\mathrm{M}_j] = \frac{n_j}{V} = \frac{p_j}{\mathcal{R}\,T} = \frac{p_j/p_0}{\mathcal{R}\,T/p_0}$$

$$\frac{k_{f,k}}{k_{b,k}} = K_{p,k}(T)\,(\mathcal{R}\,T/p_0)^{-\sum_j \Delta\nu_{j,k}} = \frac{K_{p,k}(T)}{(\mathcal{R}\,T/p_0)^{n_k - m_k}}$$

- **MOLECULARITY FORWARD/BACKWARD STEPS:** $m_k = \sum_i \nu'_{i,k}$, $n_k = \sum_i \nu''_{i,k}$

- **w_i CAN BE EXPRESSED AS**

$$w_i = \mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k}\, k_{f,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu'_{j,k}} \left\{ 1 - \frac{k_{b,k}}{k_{f,k}} \prod_{l=1}^{N} [\mathrm{M}_l]^{\Delta\nu_{l,k}} \right\} =$$

$$\mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k}\, k_{f,k} \prod_{j=1}^{N} [\mathrm{M}_j]^{\nu'_{j,k}} \left\{ 1 - \frac{(\mathcal{R}\,T/p_0)^{n_k - m_k}}{K_{p,k}} \prod_{l=1}^{N} [\mathrm{M}_l]^{\Delta\nu_{l,k}} \right\} = \cdots$$

3.2.17 EQUILIBRIUM PRODUCTION RATE

$$w_i = \mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k} \rho^{m_k} B_{f,k} T^{\alpha_k} \exp\left(-\frac{E_k}{\mathcal{R}T}\right) \prod_{j=1}^{N} \left(\frac{Y_j}{\mathcal{M}_j}\right)^{\nu'_{j,k}} \cdot$$

$$\cdot \left\{ 1 - \frac{(\rho \mathcal{R} T / p_0)^{n_k - m_k}}{K_{p,k}} \prod_{l=1}^{N} \left(\frac{Y_l}{\mathcal{M}_l}\right)^{\Delta\nu_{l,k}} \right\}$$

- $\{\cdots\} = 0$, BUT AT EQUILIBRIUM $B_{f,k} \to \infty$

$\to w_i = \infty \cdot 0$ INDETERMINANT $\to$ ARRHENIUS NOT APPLICABLE

- IN GENERAL $w_i \neq 0$ AT EQUILIBRIUM; ATEQUILIBRIUM,STATEQUANTITIESEXPRESSED AS A FUNCTION OF 2 QUANTITIES, e.g., (p, T), (p, h), (h, s), ...

$$w_i = \frac{\partial \rho(p,T)\, Y_i(p,T)}{\partial t} + \frac{\partial\, \rho(p,T)\, u_l\, Y_i(p,T)}{\partial x_l} - \frac{\partial}{\partial x_l}\left[\rho(p,T)\, D_i \frac{\partial Y_i(p,T)}{\partial x_l}\right]$$

$\neq 0$ UNLESS: $\partial/\partial x_k = 0$ (0–D),
$\partial/\partial t = 0$ (STEADY STATE)

- NO REAL SYSTEM AT EQUILIBRIUM, BUT IT CAN BE APPROACHED IF $t_s \gg t_c$
  t_s STAY TIME,
  t_c REACTION CHARACTERISTIC TIME

3.2.18 *BE* AND *DR* REACTIONS

- ***BINARY EXCHANGE*** **REACTIONS:** $m_k = n_k$

  e.g., $\mathrm{H} + \mathrm{O_2} \rightleftharpoons \mathrm{OH} + \mathrm{O}$

- ***DISSOCIATION–RECOMBINATION*** **REACTIONS:** $m_k \neq n_k$

  e.g., $\mathrm{O_2} + \mathrm{M} \rightleftharpoons 2\ \mathrm{O} + \mathrm{M}$

  REQUIRE PRESENCE THIRD–BODY TO SATISFY EQS. MOMENTUM AND ENERGY

  THIRD–BODY (OR *CHAPERON*) EFFICIENCY
  e.g., FORWARD STEP $\mathrm{O_2} + \mathrm{M} \rightarrow 2\,\mathrm{O} + \mathrm{M}$

$$w_O = 2\,\mathcal{M}_O\,\rho^2\,B_f\,T^{\alpha_f}\,\exp\left(-\frac{E_f}{\mathcal{R}\,T}\right)\frac{Y_{O_2}}{\mathcal{M}_{O_2}}\sum_{i=1}^{N}\frac{\varepsilon_i\,Y_i}{\mathcal{M}_i}$$

M_i	ε_i
O_2	0,4
N_2	0,4
H_2O	6,54
CO_2	1,5
CO	0,75

3.2.19 CHEMICAL KINETICS MECHANISMS FOR FINITE–RATE CHEMISTRY

- **DIFFERENT LEVELS OF APPROXIMATION:**
  - **DETAILED**
  - **REDUCED/SIMPLIFIED**
  - **SEMI–GLOBAL**
  - **GLOBAL**

3.2.20 EXAMPLE: HYDROGEN/OXYGEN CHEMISTR

- **DETAILED MECH (N = 8 SPECIES, M = 37 REACT**

Mechanism of the Hydrogen-Oxygen Reaction

	A	β	E_a
1. $O_2 + H \rightarrow OH + O$	2.00×10^{14}	0.00	70.30
2. $OH + O \rightarrow O_2 + H$	1.46×10^{13}	0.00	2.08
3. $H_2 + O \rightarrow OH + H$	5.06×10^{4}	2.67	26.30
4. $OH + H \rightarrow H_2 + O$	2.24×10^{4}	2.67	18.40
5. $H_2 + OH \rightarrow H_2O + H$	1.00×10^{8}	1.60	13.80
6. $H_2O + H \rightarrow H_2 + OH$	4.45×10^{8}	1.60	77.13
7. $OH + OH \rightarrow H_2O + O$	1.50×10^{9}	1.14	0.42
8. $H_2O + O \rightarrow OH + OH$	1.51×10^{10}	1.14	71.64
9. $H + H + M \rightarrow H_2 + M$	1.80×10^{18}	−1.00	0.00
10. $H_2 + M \rightarrow H + H + M$	6.99×10^{18}	−1.00	436.08
11. $H + OH + M \rightarrow H_2O + M$	2.20×10^{22}	−2.00	0.00
12. $H_2O + M \rightarrow H + OH + M$	3.80×10^{21}	−2.00	499.41
13. $O + O + M \rightarrow O_2 + M$	2.90×10^{17}	−1.00	0.00
14. $O_2 + M \rightarrow O + O + M$	6.81×10^{18}	−1.00	496.41
15. $H + O_2 + M \rightarrow HO_2 + M$	2.30×10^{18}	−0.80	0.00
16. $HO_2 + M \rightarrow H + O_2 + M$	3.26×10^{18}	−0.80	195.88
17. $HO_2 + H \rightarrow OH + OH$	1.50×10^{14}	0.00	4.20
18. $OH + OH \rightarrow HO_2 + H$	1.33×10^{13}	0.00	168.30
19. $HO_2 + H \rightarrow H_2 + O_2$	2.50×10^{13}	0.00	2.90
20. $H_2 + O_2 \rightarrow HO_2 + H$	6.84×10^{13}	0.00	243.10
21. $HO_2 + H \rightarrow H_2O + O$	3.00×10^{13}	0.00	7.20
22. $H_2O + O \rightarrow HO_2 + H$	2.67×10^{13}	0.00	242.52
23. $HO_2 + O \rightarrow OH + O_2$	1.80×10^{13}	0.00	−1.70
24. $OH + O_2 \rightarrow HO_2 + O$	2.18×10^{13}	0.00	230.61
25. $HO_2 + OH \rightarrow H_2O + O_2$	6.00×10^{13}	0.00	0.00
26. $H_2O + O_2 \rightarrow HO_2 + OH$	7.31×10^{14}	0.00	303.53
27. $HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	2.50×10^{11}	0.00	−5.20
28. $OH + OH + M \rightarrow H_2O_2 + M$	3.25×10^{22}	−2.00	0.00
29. $H_2O_2 + M \rightarrow OH + OH + M$	2.10×10^{24}	−2.00	206.80
30. $H_2O_2 + H \rightarrow H_2 + HO_2$	1.70×10^{12}	0.00	15.70
31. $H_2 + HO_2 \rightarrow H_2O_2 + H$	1.15×10^{12}	0.00	80.88
32. $H_2O_2 + H \rightarrow H_2O + OH$	1.00×10^{13}	0.00	15.00
33. $H_2O + OH \rightarrow H_2O_2 + H$	2.67×10^{12}	0.00	307.51
34. $H_2O_2 + O \rightarrow OH + HO_2$	2.80×10^{13}	0.00	26.80
35. $OH + HO_2 \rightarrow H_2O_2 + O$	8.40×10^{12}	0.00	84.09
36. $H_2O_2 + OH \rightarrow H_2O + HO_2$	5.40×10^{12}	0.00	4.20
37. $H_2O + HO_2 \rightarrow H_2O_2 + OH$	1.63×10^{13}	0.00	132.71

A has units of cm mole s; E_A has units of kJ mole^{-1}; $k = AT^{\beta} \exp(-E_A/RT)$.
Collision efficiences in reactions with M: $f_{H_2} = 1.00$; $f_{O_2} = 0.35$; $f_{H_2O} = 6.50$; $f_{N_2} = 0.5$.

- **SIMPLIFIED MECHANISM (N = 7, M = 7):**

Reaction		A^a	n	T_a [K]
1. $H + O_2 \rightleftharpoons OH + O$		3.52×10^{16}	−0.7	8590
2. $H_2 + O \rightleftharpoons OH + H$		5.06×10^{4}	2.67	3166
3. $H_2 + OH \rightleftharpoons H_2O + H$		1.17×10^{9}	1.3	1829
4f. $H + O_2 + M \rightarrow HO_2 + M^b$	k_0	5.75×10^{19}	−1.4	0
	k_∞	4.65×10^{12}	0.44	0
5f. $HO_2 + H \rightarrow OH + OH$		7.08×10^{13}	0	148
6f. $HO_2 + H \rightarrow H_2 + O_2$		1.66×10^{13}	0	414
7f. $HO_2 + OH \rightarrow H_2O + O_2$		2.89×10^{13}	0	−250

[a] Units are mol, s, cm^3, and K.
[b] Chaperon efficiencies are 2.5 for H_2, 16.0 for H_2O, and 1.0 for all other species; Troe falloff with $F_c = 0.5$ [16].

- **SEMI–GLOBAL MECHANISM (N = 5, M = 2):**

$$3H_2 + O_2 \overset{I}{\rightleftharpoons} 2H_2O + 2H$$
$$H + H + M \overset{II}{\rightleftharpoons} H_2 + M,$$

- **GLOBAL MECHANISM (N = 3, M = 1):**

$$2H_2 + O_2 \rightarrow 2H_2O$$

3.2.21 HYDROCARBON/AIR CHEMISTRY

- **DETAILED MECHANISM (N = 1200 CHEMICAL SPECIES, M = 7000 REACTIONS):**
- **SIMPLIFIED MECHANISM (N = 100, M = 500):**
- **SEMI–GLOBAL MECHANISM (N = 11, M = 22):**

$$C_nH_{2m} + \frac{n}{2} O_2 = nCO + mH_2.$$

TABLE V

Reaction mechanism used in quasi-global mechanism for CO–H_2–O_2 system. Reverse rates computed from relevant equilibrium constants. Same units as Table I

Reaction	A	n	E_a
$H+O_2=O+OH$	2.2×10^{14}	0.0	16.8
$H_2+O=H+OH$	1.8×10^{10}	1.0	8.9
$O+H_2O=OH+OH$	6.8×10^{13}	0.0	18.4
$OH+H_2=H+H_2O$	2.2×10^{13}	0.0	5.1
$H+O_2+M=HO_2+M$	1.5×10^{15}	0.0	−1.0
$O+HO_2=O_2+OH$	5.0×10^{13}	0.0	1.0
$H+HO_2=OH+OH$	2.5×10^{14}	0.0	1.9
$H+HO_2=H_2+O_2$	2.5×10^{13}	0.0	0.7
$OH+HO_2=H_2O+O_2$	5.0×10^{13}	0.0	1.0
$HO_2+HO_2=H_2O_2+O_2$	1.0×10^{13}	0.0	1.0
H_2O_2+M $=OH+OH+M$	1.2×10^{17}	0.0	45.5
$HO_2+H_2=H_2O_2+H$	7.3×10^{11}	0.0	18.7
$H_2O_2+OH=H_2O+HO_2$	1.0×10^{13}	0.0	1.8
$CO+OH=CO_2+H$	1.5×10^{7}	1.3	−0.8
$CO+O_2=CO_2+O$	3.1×10^{11}	0.0	37.6
$CO+O+M=CO_2+M$	5.9×10^{15}	0.0	4.1
$CO+HO_2=CO_2+OH$	1.5×10^{14}	0.0	23.7
$OH+M=O+H+M$	8.0×10^{19}	−1.0	103.7
$O_2+M=O+O+M$	5.1×10^{15}	0.0	115.0
$H_2+M=H+H+M$	2.2×10^{14}	0.0	96.0
$H_2O+M=H+OH+M$	2.2×10^{16}	0.0	105.0

- **GLOBAL MECHANISM (N = 4, M = 1):**

$$w = B\,T^{\alpha}\,\exp\left(-\frac{E_A}{\mathcal{R}T}\right)\,[C_{10}H_{22}]^{0,25}[O_2]^{1,5}$$

3.2.22 ADIABATIC COMBUSTION

- ***ALL*** **REACTION HEAT ASSUMED TO INCREASE TEMPERATURE OF PRODUCTS**

$\rightarrow$ **GLOBALLY** $\boldsymbol{\Delta Q = 0 \leftrightarrows \Delta h = 0}$

- **FOR <u>EQUILIBRIUM</u> COMBUSTION, COMPUTATION AT** $\boldsymbol{(p,\, h)}$ **GIVEN**

$\rightarrow$ $\boldsymbol{T_{af}}$ **ADIABATIC FLAME TEMPERATURE**

3.2.23 ADIABATIC COMBUSTION TEMPERATURE vs. φ

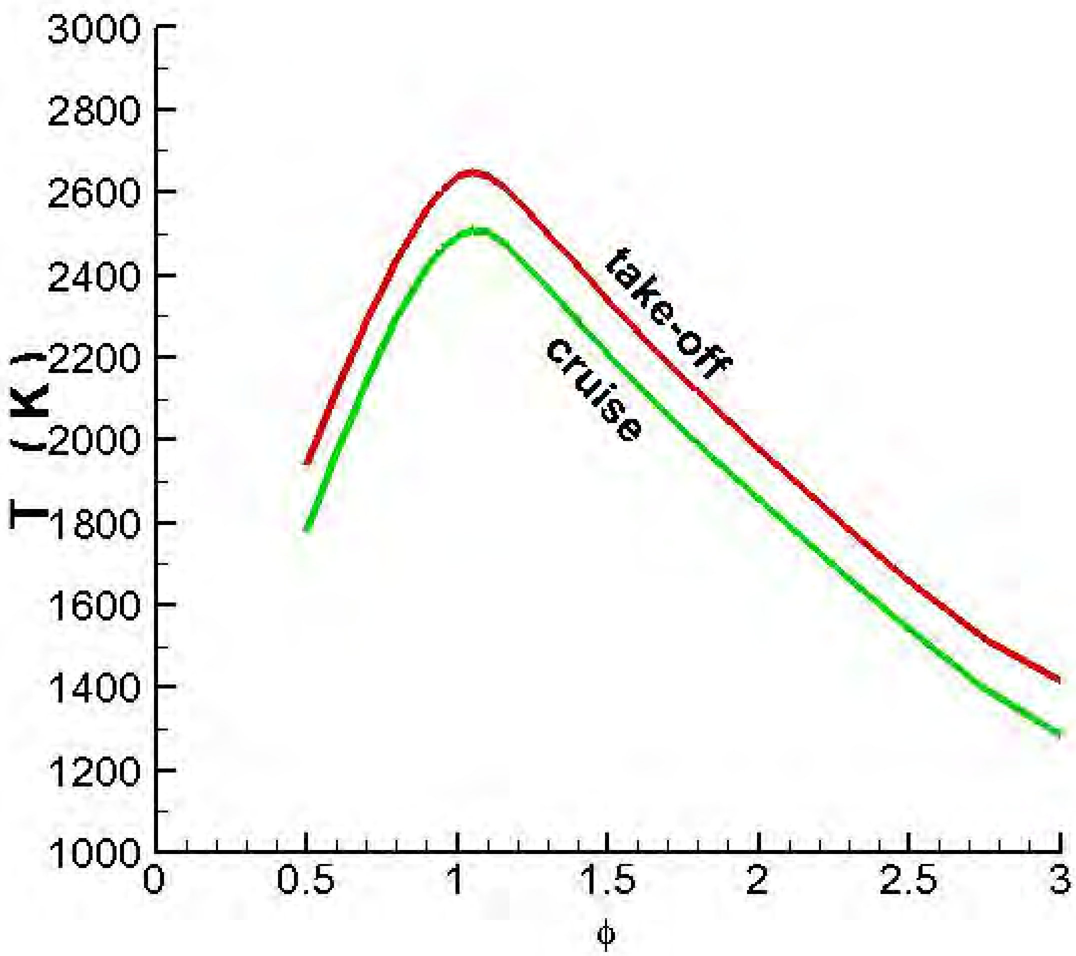


Figure 71: Adiabatic combustion temperature (in chemical equilibrium) of a kerosene/air mixture.

3.2.24 EQUILIBRIUM CONDITIONS

- **AT EQUILIBRIUM, PROPERTIES OF THE REACTING MIXTURE DETERMINED ONCE ARE SPECIFIED:**

  a. TWO STATE VARIABLES
  e.g., (p, T), (p, h), (h, s), (p, Y_{H_2O}), ...

  b. THE PROPORTIONS OF REACTANTS
  e.g., X_i, Y_i, n_i, ... (OF CHEMICAL SPECIES)
  [OR THE *ATOM* MOLES]

3.2.25 KEROSENE/AIR COMBUSTION

$$C_7H_8 + 5,24 \cdot C_{10}H_{22} + \frac{90,22}{\varphi}(O_2 + 3,76 \cdot N_2) \rightarrow \textit{PRODUCTS}$$

- **NO. OF *ATOMS* OF INDIVIDUAL ELEMENTS:**
  - $n_C = 7 + 5{,}24 \cdot 10 = 59{,}4$
  - $n_H = 8 + 5{,}24 \cdot 22 = 123{,}28$
  - $n_O = 2 \cdot 90{,}22/\varphi = 180{,}44/\varphi$
  - $n_N = 2 \cdot 3{,}76 \cdot 90{,}22/\varphi = 678{,}46/\varphi$

$$\left(\frac{F}{O}\right)_{st} = \frac{\mathcal{M}_{C_7H_8} + 5,24 \cdot \mathcal{M}_{C_{10}H_{22}}}{90,22\,(\mathcal{M}_{O_2} + 3,76 \cdot \mathcal{M}_{N_2})} = 0,0676$$

- **NUMBER OF ATOMS UNIVOCALLY DETERMINES ABUNDANCE OF REACTANTS:**
- **e.g., TAKING INTO ACCOUNT C_7H_{16}, C_8H_{18} TOO:**

$$C_7H_8 + \alpha\, C_7H_{16} + \beta\, C_8H_{18} + \gamma\, C_{10}H_{22}$$

$$n_C = 7 + 7\alpha + 8\beta + 10\gamma = 59,4$$

$$n_H = 8 + 16\alpha + 18\beta + 22\gamma = 123,28$$

- **SOLUTION:** $0{,}6\,\alpha + 0{,}4\,\beta = 0 \Longrightarrow \alpha = \beta = 0$

3.2.26 EXAMPLE: KEROSENE/AIR ADIABATIC COMBUSTION, $A/F = 50$ ($\rightarrow$ f=0,02)

- **CF6–50 CONDITIONS AT TAKE–OFF:**

  * $T_f \simeq 298{,}15$ K, $T_o \simeq 850$ K
  * $p \simeq 3$ MPa = 30 bar
  * $A/F = 50 \rightarrow f = \dfrac{1}{A/F} \rightarrow \varphi = \dfrac{f}{f_{st}} = \dfrac{1/50}{0,0676} \simeq 0{,}3$

- $h = Y_f \; h_f(T_f) + Y_o \; h_o(T_o)$

- $Y_f = \dfrac{1}{1 + A/F} = 0{,}0196$; $Y_o = 1 - Y_f = 0{,}9804$

- **FOR EQUILIBRIUM COMPUTATION WITH CEA, USE FILES ON dma.dima.uniroma1.it:8080/STAFF2/lentini.html:**

  * thermo.inp, thermo.lib (OVERWRITE)
  * jetaair.inp

3.2.27 CEA INPUT FILE jetaair.inp

```
!  EXAMPLE Jet-A/air:
!     (a)  Combustion or assigned-enthalpy-and-pressure problem (hp).
!     (b)  Fuel is surrogate kerosene 89% C10H22, 11% C7H8 at 298.15 K
!          The oxidant is air at 850 K.
!     (c)  A single value of the oxidant-to-fuel weight ratio is assigned.
!          Weight fractions are fractions of fuel relative to total fuel and
!          fractions of oxidant relative to total oxidant.
!     (d)  Mixture enthalpy is calculated from reactant values given in
!          thermo.lib. This is because data for these species are given in
!          thermo.lib and the species names match exactly.
!     (e)  Only some 50 species are included in the product data base ('only' dat
!          Note:  these species names must match those used in thermo.lib.
!     (f)  Assigned pressures is 30 bar.
!     (g)  Mixture properties are to be printed in SI units (siunits).
!     (h)  Mole fractions > 1.e-15 are to be in e-format (trace=1.e-15).
reac oxid Air                wtfrac= 1      t(k) = 850.
     fuel C10H22(L),n-dec    wtfrac= 0.89   t(k) = 298.15
     fuel C7H8(L)            wtfrac= 0.11   t(k) = 298.15
prob   case=Jet-A/air,   hp,  p(bar)=30.,    o/f  = 50.
output siunits,  trace=1.e-15
only H2               H                O2               O
     OH               H2O              HO2              H2O2
     N2               Ar               CO               CO2
     CH               CH2              CH3              CH4
     C2H              C2H2,acetylene   C2H3,vinyl       C2H4
     C2H5             C2H6             C3H3,1-propynl   C3H4,propyne
     C3H6,propylene   C3H7,i-propyl    C3H7,n-propyl    C4H4,1,3-cyclo-
     C4H6,butadiene   C4H8,1-butene    C4H9,n-butyl     C5H6,1,3cyclo-
     C5H11,pentyl     C6H5,phenyl      C6H6             C6H13,n-hexyl
     C7H8             C7H15,n-heptyl   C10H21,n-decyl   HCO
     CH2OH            CH3O             CH3OH            HCCO
     CH2CO,ketene     C6H5O,phenoxy    C6H5OH,phenol
!    N                NO               N2O               NO2
```

3.2.28 CEA OUTPUT FILE jetaair.out (1/2)

```
        THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED PRESSURES

CASE = Jet-A/air,

            REACTANT                     WT FRACTION      ENERGY      TEMP
                                          (SEE NOTE)     KJ/KG-MOL      K
OXIDANT     Air                           1.0000000      16645.137    850.000
FUEL        C10H22(L),n-dec               0.8900000    -249500.000    298.150
FUEL        C7H8(L)                       0.1100000      12179.997    298.150

O/F= 50.00000  %FUEL= 1.960784  R,EQ.RATIO= 0.298911  PHI,EQ.RATIO= 0.297843

THERMODYNAMIC PROPERTIES

P, BAR            30.000
T, K             1541.23
RHO, KG/CU M    6.7722 0
H, KJ/KG          533.08
U, KJ/KG          90.089
G, KJ/KG        -11476.5
S, KJ/(KG)(K)     7.7922

M, (1/n)          28.928
(dLV/dLP)t      -1.00000
(dLV/dLT)p        1.0001
Cp, KJ/(KG)(K)    1.2657
GAMMAs            1.2939
SON VEL,M/SEC      757.1
```

3.2.29 CEA OUTPUT FILE jetaair.out (2/2)

```
MOLE FRACTIONS

*Ar             9.1695-3
*CO             1.7396-7
*CO2            4.0532-2
*H              1.3277-9
HO2             3.0847-7
*H2             6.4868-8
H2O             4.1720-2
H2O2            2.2937-8
*N2             7.6454-1
*O              4.8465-7
*OH             3.2749-5
*O2             1.4401-1

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

   PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS
   WERE LESS THAN 1.000000E-15 FOR ALL ASSIGNED CONDITIONS

*CH             CH2             CH3             CH2OH           CH3O
CH4             CH3OH           C2H             C2H2,acetylene  CH2CO,ketene
C2H3,vinyl      C2H4            C2H5            C2H6            C3H3,1-propynl
C3H4,propyne    C3H6,propylene  C3H7,n-propyl   C3H7,i-propyl   C4H4,1,3-cyclo-
C4H6,butadiene  C4H8,1-butene   C4H9,n-butyl    C5H6,1,3cyclo-  C5H11,pentyl
C6H5,phenyl     C6H5O,phenoxy   C6H6            C6H5OH,phenol   C6H13,n-hexyl
C7H8            C7H15,n-heptyl  C10H21,n-decyl  HCO             HCCO
```

3.2.30 UNBURNT SPECIES (*IN EQUILIBRIUM*)

- **FOR $A/F = 50$ ($\varphi \simeq 0{,}3$):**
  - $T_{af} = 1541{,}23$ K
  - $\sum Y_{unburnt} = Y_{OH} + Y_{HO_2} + Y_{CO} + Y_{H_2} + Y_H + \cdots < 0{,}00002 = 0{,}002$ %
- **FOR $\varphi = 1$:**
  - $T_{af} = 2637{,}84$ K
  - $\sum Y_{unburnt} \simeq 0{,}019 = 1{,}9$ %
- **THIS HOLDS AT EQUILIBRIUM (IN ACTUALITY $Y_{unburnt}$ CERTAINLY LARGER)**

3.2.31 *EICO* GROSSLY UNDERESTIMATED IN EQUILIBRIUM

- **for $A/F = 50$:**

$$
\begin{aligned}
EICO_{\text{equilibrium}} &= 1000 \cdot \frac{Y_{\text{CO}}}{Y_{\text{fuel}}} \\
&= 1000 \cdot \frac{X_{\text{CO}}\, \mathcal{M}_{\text{CO}}/\mathcal{M}}{Y_{\text{fuel}}} \\
&= 1000 \cdot \frac{1.74 \cdot 10^{-7} \cdot 28/28.9}{0.0196} \\
&= 0.0085\, \frac{\text{g}_{\text{CO}}}{\text{kg}_{\text{fuel}}}
\end{aligned}
$$

- **MEASURED VALUE: $EICO = 0.14\, \frac{\text{g}_{\text{CO}}}{\text{kg}_{\text{fuel}}}$**

- **SAME FOR *EIUHC* (STRONGLY CORRELATED TO *EICO*)**

3.2.32 CEA INPUT FILE jetaairN.inp – WITH N CHEMISTRY

```
!  EXAMPLE Jet-A/air with N chemistry:
!     (a)  Combustion or assigned-enthalpy-and-pressure problem (hp).
!     (b)  Fuel is surrogate kerosene 89% C10H22, 11% C7H8 at 298.15 K
!          The oxidant is air at 850 K.
!     (c)  A single value of the oxidant-to-fuel weight ratio is assigned.
!          Weight fractions are fractions of fuel relative to total fuel and
!          fractions of oxidant relative to total oxidant.
!     (d)  Mixture enthalpy is calculated from reactant values given in
!          thermo.lib. This is because data for these species are given in
!          thermo.lib and the species names match exactly.
!     (e)  Only some 50 species are included in the product data base ('only' dat
!          Note:  these species names must match those used in thermo.lib.
!     (f)  Assigned pressures is 30 bar.
!     (g)  Mixture properties are to be printed in SI units (siunits).
!     (h)  Mole fractions > 1.e-15 are to be in e-format (trace=1.e-15).
reac oxid Air                wtfrac= 1      t(k) = 850.
     fuel C10H22(L),n-dec    wtfrac= 0.89   t(k) = 298.15
     fuel C7H8(L)            wtfrac= 0.11   t(k) = 298.15
prob   case=Jet-A/air+N,   hp,  p(bar)=30.,    o/f  = 50.
output siunits,  trace=1.e-15
only H2               H                O2               O
     OH               H2O              HO2              H2O2
     N2               Ar               CO               CO2
     CH               CH2              CH3              CH4
     C2H              C2H2,acetylene   C2H3,vinyl       C2H4
     C2H5             C2H6             C3H3,1-propynl   C3H4,propyne
     C3H6,propylene   C3H7,i-propyl    C3H7,n-propyl    C4H4,1,3-cyclo-
     C4H6,butadiene   C4H8,1-butene    C4H9,n-butyl     C5H6,1,3cyclo-
     C5H11,pentyl     C6H5,phenyl      C6H6             C6H13,n-hexyl
     C7H8             C7H15,n-heptyl   C10H21,n-decyl   HCO
     CH2OH            CH3O             CH3OH            HCCO
     CH2CO,ketene     C6H5O,phenoxy    C6H5OH,phenol
     N                NO               N2O               NO2
```

3.2.33 CEA OUTPUT FILE jetaairN.out – WITH N CHEMISTRY

```
        THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED PRESSURES
CASE = Jet-A/air+N,
.............................
O/F= 50.00000  %FUEL= 1.960784  R,EQ.RATIO= 0.298911  PHI,EQ.RATIO= 0.297843
THERMODYNAMIC PROPERTIES
P, BAR             30.000
T, K              1538.22
RHO, KG/CU M    6.7855 0
.............................
M, (1/n)           28.928
.............................
Cp, KJ/(KG)(K)     1.2829
GAMMAs             1.2887
SON VEL,M/SEC       754.8

MOLE FRACTIONS
*Ar              9.1696-3
*CO              1.6703-7
*CO2             4.0533-2
*H               1.2599-9
HO2              3.0129-7
*H2              6.2570-8
H2O              4.1721-2
H2O2             2.2512-8
*N               2.515-14
*NO              1.1946-3
NO2              2.6003-5
*N2              7.6394-1
N2O              3.9168-7
*O               4.6518-7
*OH              3.1921-5
*O2              1.4338-1
```

3.2.34 CONSIDERATIONS ON NITROGEN CHEMISTRY

- **WHEN INCLUDING N, NO, NO_2, N_2O:**
  - T_{af} **DECREASES ONLY 3 K (for $\varphi \simeq 0,3$)**
  - $X_{NO,eq}$ **= 0,12 % → $EINO_x \simeq$ 100 g/kg$_f$**

  - T_{af} **DECREASES 15 K (for $\varphi = 1$)**
  - $X_{NO,eq}$ **= 0,474 % → $EINO_x \simeq$ 120 g/kg$_f$**

  ($EINO_x$ IN TERMS OF NO_2)

- **HOWEVER, N CHEMISTRY SLOW ($t_c \gg t_s$) → EQUILIBRIUM <u>NOT</u> APPLICABLE**

3.2.35 $EINO_x$ GROSSLY OVERESTIMATED IN EQUILIBRIUM

- **for $A/F = 50$:**

$$EINO_{x,\text{equilibrium}} = 1000 \cdot \frac{Y_{NO_2}}{Y_{fuel}} = 1000 \cdot \frac{\mathcal{M}_{NO_2}}{\mathcal{M}_{NO}} \cdot \frac{Y_{NO}}{Y_{fuel}}$$

$$= 1000 \cdot \frac{\mathcal{M}_{NO_2}}{\mathcal{M}_{NO}} \cdot \frac{X_{NO}\, \mathcal{M}_{NO}/\mathcal{M}}{Y_{fuel}}$$

$$= 1000 \cdot \frac{X_{NO}\, \mathcal{M}_{NO_2}/\mathcal{M}}{Y_{fuel}}$$

$$= 1000 \cdot \frac{1.2 \cdot 10^{-3} \cdot 46/28.9}{0.0196}$$

$$= 97.5\ \frac{g_{NO_x}}{kg_{fuel}}$$

- **MEASURED VALUE: $EINO_x = 28\ \frac{g_{NO_x}}{kg_{fuel}}$**

3.2.36 PREMIXED LAMINAR FLAMES

- **(GASEOUS REACTANTS)**
- **LAMINAR FLAME PROPAGATION SPEED $S_L \simeq 0{,}43$ m/s ($\varphi = 1$, p ATMOSPHERIC)**
- **CONTROLLING FACTORS: CHEMICAL KINETICS AND HEAT CONDUCTION**
- **DEPENDS ON p, φ, T_{in}**
- **u FLOW SPEED:**
  - $u = S_L$ **STABLE COMBUSTION**
  - $u > S_L$ ***FLAMEOUT***
  - $u < S_L$ ***FLASHBACK***

3.2.37 PREMIXED *TURBULENT* FLAMES

- **TURBULENT FLAME PROPAGATION SPEED:**

$$S_T = \frac{\dot{m}_{burnt}}{\rho\, A}$$

- $S_T \gg S_L$ **BECAUSE FLAME FRONT IS WRINKLED**
- S_T **INCREASES WITH TURBULENCE *INTENSITY***
- ***INTENSITY*: $u'/\overline{u}$ = (RMS VELOCITY FLUCTUATIONS)/(MEAN VELOCITY)**

3.2.38 NONPREMIXED LAMINAR FLAMES

- **CONTROLLING FACTOR: SPECIES DIFFUSION**
- **INTRINSIC FLAME PROPAGATION SPEED DOES *NOT* EXIST (COMBUSTION MORE STABLE)**
  - **HOMOGENEOUS (GASEOUS REACTANTS – *JET FLAMES*)**
  - **HETEROGENEOUS (e.g., LIQUID FUEL, GASEOUS OXIDIZER)**

3.2.39 NONPREMIXED *TURBULENT* FLAMES

• TRANSITION FOR $Re_j \simeq 8000$

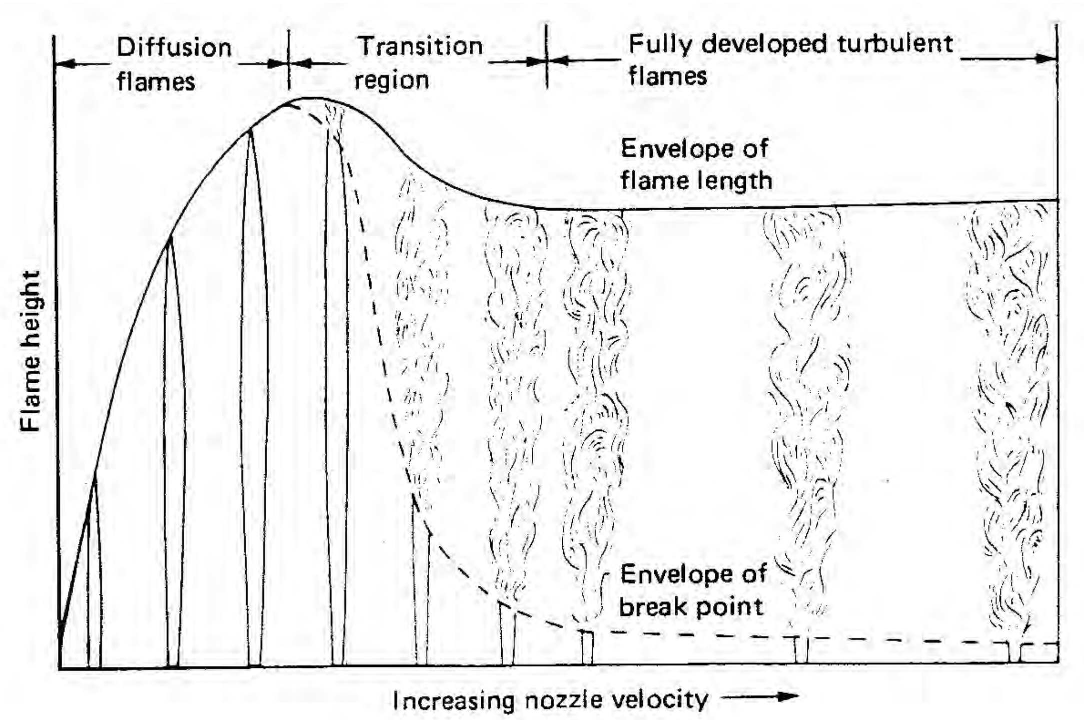


Figure 72: Aspect of a nonpremixed jet flame as the fuel jet velocity is increased.

3.2.40 HETEROGENEOUS FLAMES: EVAPORATION

- **EVAPORATION RELATED TO HEAT TRANSFER FROM COMBUSTION PRODUCTS TO DROPLETS**

→ T_d INCREASES, D_d DECREASES ($d = DROPLET$)

3.3.1 COMBUSTION CHAMBERS: COMBUSTION EFFICIENCY η_b

- **IN ORDER TO OBTAIN A HIGH $\eta_b \longrightarrow$**

$$t_s \geq t_e + t_m + t_c$$

  - t_s **STAY TIME IN THE CHAMBER**
  - t_e **EVAPORATION TIME**
  - t_m **MIXING TIME**
  - t_c **CHARACTERISTIC CHEMICAL TIME**

- **SELDOM $t_e \simeq t_m \simeq t_c$**
- **USUALLY ONE OF 3 TIMES $\gg$ OTHERS (CONTROLLING FACTOR)**
- ***WHICH ONE*** **OF 3 TIMES IS CONTROLLING DEPENDS UPON OPERATING CONDITIONS (START–UP, IDLE, TAKE–OFF, CLIMB, CRUISE)**
- **IN BORDERLINE SITUATIONS, 2 TIMES CAN BE $\simeq$, WHILE THIRD IS $\ll$**

3.3.2 EVAPORATION TIME

- **DEPENDS UPON DROPLET SIZE (SMD), TURBULENCE INTENSITY, p_3**
- SMD = **SAUTER MEAN DIAMETER** $= \sum_i n_i D_i^3 / \sum_i n_i D_i^2$
- n_i **NO. DROPLETS OF DIAMETER** D_i
- **THERMAL POWER TRANSFERRED FROM HOT GASES TO DROPLETS:**

$$\dot{Q}_t = \sum_i \mathsf{h}_c (T_g - T_d) \pi D_i^2 n_i$$

- **THERMAL ENERGY NEEDED TO FULLY VAPORIZE DROPLETS:**

$$E_{ev} = \sum_i \left[c (T_b - T_d) + \lambda_{ev}\right] \rho \pi \frac{D_i^3}{6} n_i$$

- **FRACTION OF DROPLETS VAPORIZED PER UNIT TIME:**

$$\mathsf{f}_{ev} = \frac{\dot{Q}_t}{E_{ev}} \propto \frac{\sum_i n_i D_i^2}{\sum_i n_i D_i^3} \propto \frac{1}{SMD}$$

3.3.3 EVAPORATION: EFFECT OF DIAMETER

→ FUEL MUST BE FINELY ATOMIZED

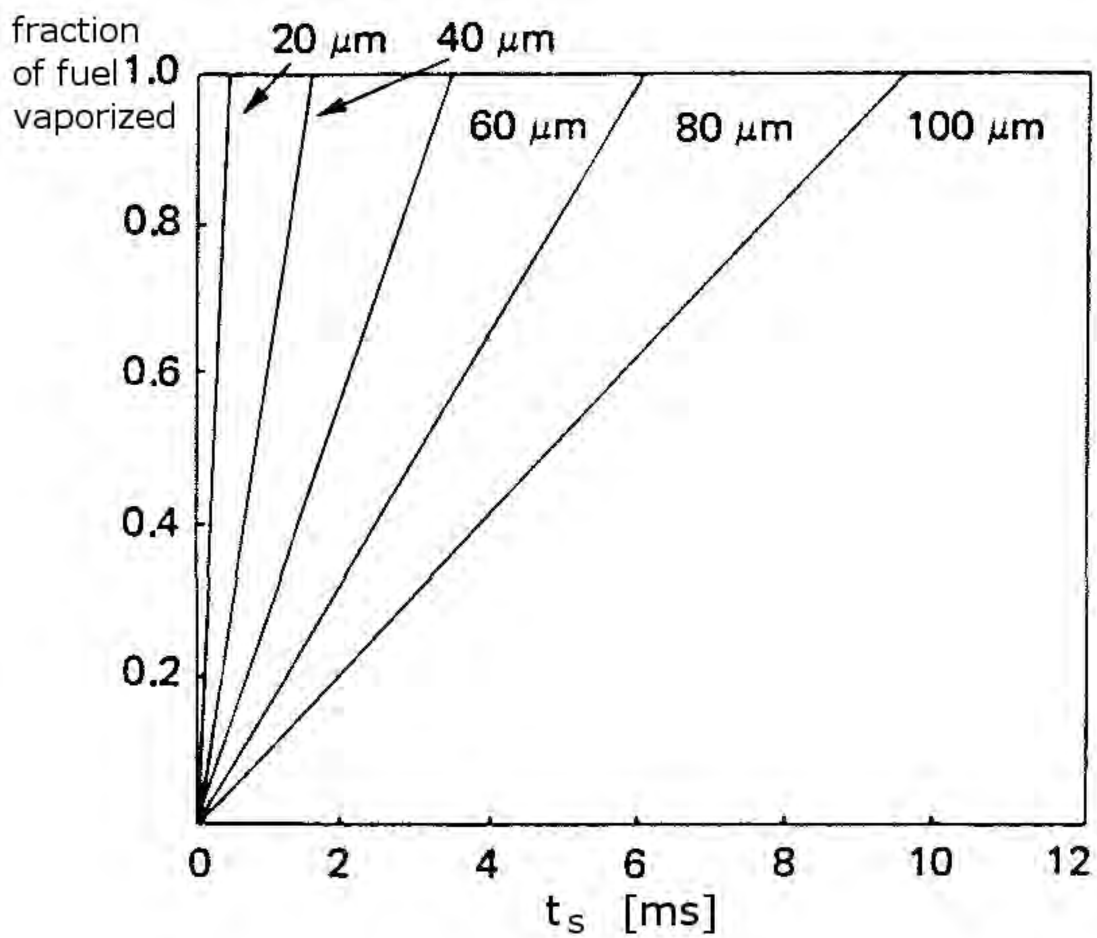


Figure 73: Fraction of (diesel) fuel vaporized, as a function of stay time, for several values of Sauter mean diameter.

3.3.4 EVAPORATION: EFFECT OF TURBULENCE AND PRESSURE

- **CAN BECOME CONTROLLING FACTOR AT LOW p_3**

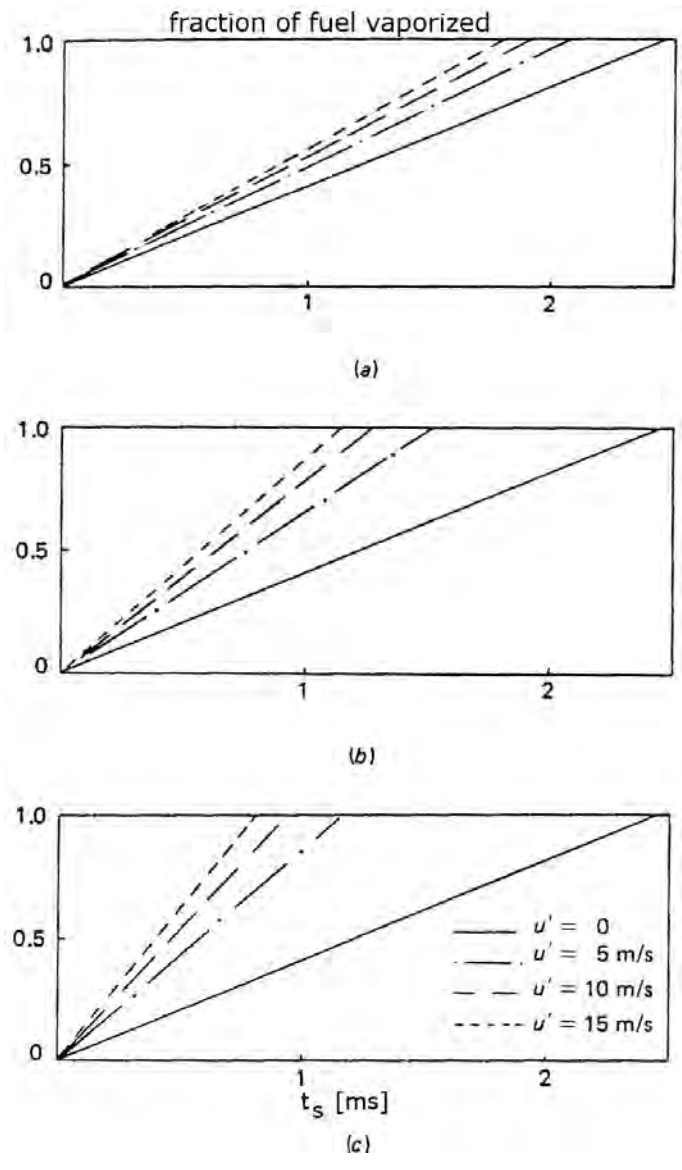


Figure 74: Fraction of fuel (kerosene) vaporized as a function of stay time, for SMD = 60 μm, for different pressure levels (a) 0,1 MPa, b) 1 MPa, c) 3 MPa), and different rms velocity.

3.3.5 MIXING TIME

- **INVERSELY PROPORTNL TO *MIXING RATE*** $\dot{m}_{mix}$ **(kg/s OF REACTANTS BEING MIXED)**

$$\dot{m}_{mix} \propto [\text{DIFFUSIVITY}] \cdot [\text{AREA}] \cdot [\text{CONCENTR. GRAD.}]$$

$$\propto \; [\rho\, u_j\, l] \cdot [l^2] \cdot [1/l] \;=\; \rho\, u_j\, l^2$$

*** NOTE: *TURBULENT* [DIFFUSIVITY]**

* $\rho = \rho_3 = p_3/(R\,T_3)$

* $u_j \simeq (2\,\Delta p_{liner}/\rho)^{1/2}$ **AIR JET SPEED (BERNOUILLI)**

* l **CHARACTERISTIC CHAMBER SIZE**

$$\dot{m}_{mix} \propto \rho \sqrt{\frac{\Delta p_{liner}}{\rho}}\, l^2 = \sqrt{\rho \Delta p_{liner}}\, l^2 = \sqrt{\frac{p_3}{R T_3}} \sqrt{\Delta p_{liner}}\, l^2$$

$$\propto \frac{p_3}{\sqrt{T_3}} \sqrt{\frac{\Delta p_{liner}}{p_3}}\, l^2$$

- **GIVEN** l, T_3, $\Delta p_{liner}/p_3 \rightarrow \dot{m}_{mix} \propto p_3$

$$\Longrightarrow t_m \propto \frac{1}{p_3}$$

3.3.6 CHARACTERISTIC CHEMICAL TIME

- **INVERSELY PROPORTIONAL TO PRODUCTION RATE w_i [e.g., kg/(m^{3}s) OF FUEL BEING BURNED]**
- **MOLECULARITY OF MOST REACTIONS $m_k = 2$**
- **IF CHEMICAL KINETICS IS CONTROLLING → BACKWARD RATE ≃ NEGLIGIBLE**

$$w_i = \mathcal{M}_i \sum_{k=1}^{M} \Delta\nu_{i,k}\, \rho^{m_k}\, B_k\, T^{\alpha_k} \exp\left(-\frac{E_k}{\mathcal{R}T}\right) \prod_{j=1}^{N} \left(\frac{Y_j}{\mathcal{M}_j}\right)^{\nu'_{j,k}}$$

- **GIVEN TEMPERATURE AND CONCENTRATIONS →**

$$w_i \propto \rho^2 \propto p_3^2$$

- **EXPERIMENTAL DATA: $w_i \propto p_3^{1,75} \div p_3^{1,8}$**

$$\Longrightarrow t_c \propto \frac{1}{p_3^{1,75}}$$

3.3.7 t_c, t_m AS A FUNCTION OF PRESSURE p_3

- **TYPICALLY FOR $p_3 < 100$ kPa: $t_c \gg t_m, t_e$**
- **TYPICALLY FOR $p_3 > 300$ kPa: $t_m \gg t_c, t_e$**
- **FOR 100 kPa $\leq p_3 \leq$ 300 kPa: $t_c \sim t_m \gg t_e$**

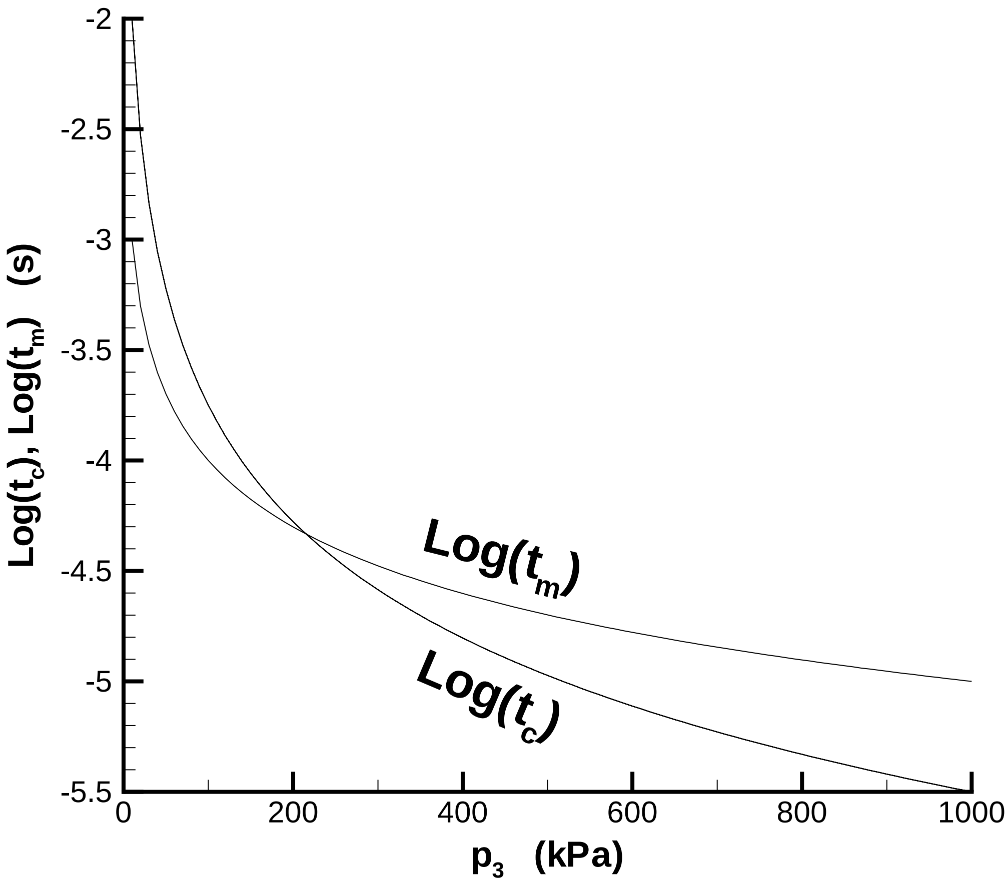


Figure 75: Typical trend of mixing and characteristic chemical times as a function of chamber pressure.

3.3.8 THEORETICAL TREND OF η_b vs. $p_3^{1,75}$

- **GIVEN $t_s \rightarrow \eta_b \propto \dfrac{1}{\max(t_e, t_m, t_c)}$**
- **WHEN PLOTTING η_b vs. $p_3^{1,75} \rightarrow$ STRAIGHT LINE FOR $p_3 < 100$ kPa, CURVE $\propto p_3 = (p_3^{1,75})^{1/1,75} = (p_3^{1,75})^{0,57}$ FOR $p_3 > 300$ kPa**
- **$p_3^{1,75}$ LOAD PARAMETER $\theta \propto$ HEAT RELEASE (MAY INCLUDE DEPENDENCE UPON T_3, $\dot{m}_a$, SIZE)**

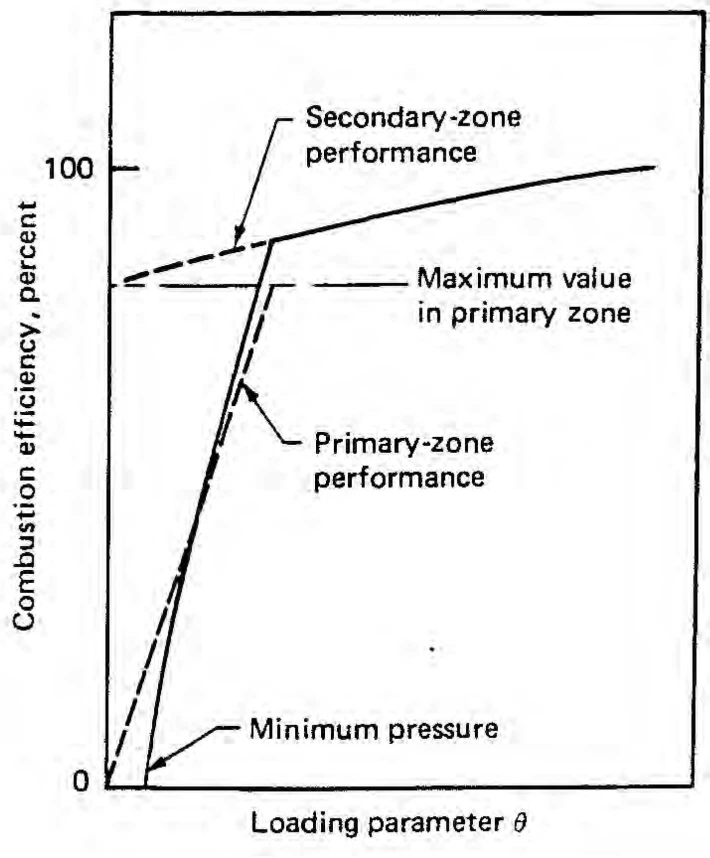


Figure 76: Theoretical trend of combustion efficiency.

- **BUT THE ACTUAL CURVE DOES NOT REACH DOWN TO $p_3 = 0$**

3.3.9 ACTUAL TREND OF η_b vs. θ

- **ACTUAL CURVE DOES NOT REACH DOWN TO $p_3 = 0$ BECAUSE OF:**
  - **FLAMMABILITY LIMITS**
  - **HEAT TRANSFER (GREATER WEIGHT AT LOW p_3)**
  - **ATOMIZATION (t_e LONGER AT LOW p_3)**

→ RELIGHT DIFFICULT AT ALTITUDE

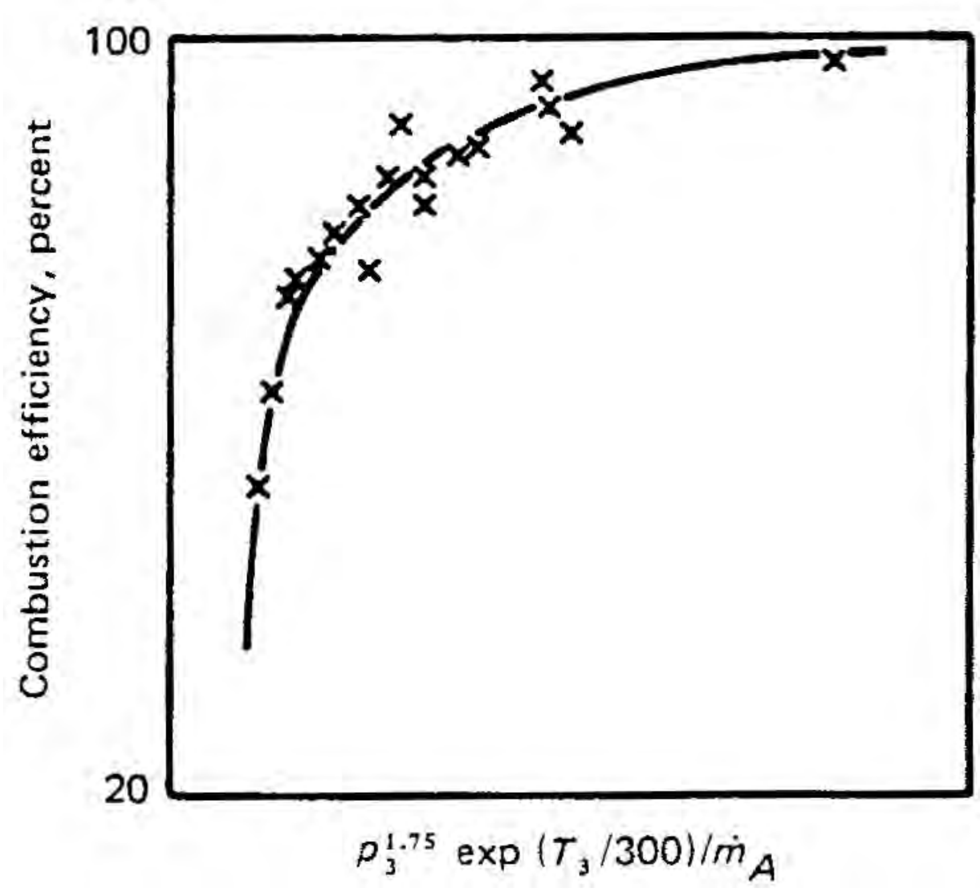


Figure 77: Actual curve of combustion efficiency.

3.3.10 IN ORDER TO OBTAIN A HIGH η_b

- **LARGER VOLUME CHAMBER TO INCREASE t_s (BUT WEIGHT INCREASES TOO ...)**
- **REDUCE t_e, t_m, t_c (ATOMIZATION, TURBULENCE, PRESSURE)**
- **REDUCE AIR SHARE DEVOTED TO WALL COOLING (FUEL DOES NOT FULLY BURN AT LOW T)**

$\rightarrow$ **TRANSPIRATION COOLING**

3.4.1 COMBUSTION CHAMBERS: FUELS

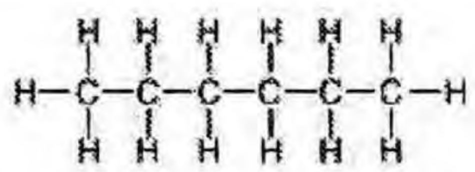
- **ORIGIN OF FOSSIL FUELS:**
- **PHOTOSYNTHESIS REACTION:**

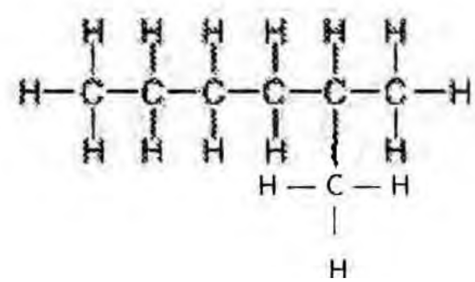
$$\mathrm{n\,CO_2 + n\,H_2O} + \textbf{sunlight} \longrightarrow \mathrm{(CH_2O)_n + n\,O_2}$$

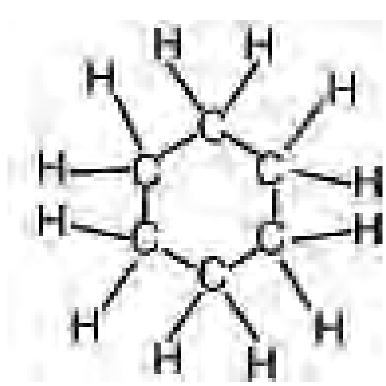
- **$(\mathbf{CH_2O})_\mathrm{n}$ CARBOHYDRATES:**
  - **CELLULOSE**
  - **SUGARS**
- **CONVERTED INTO FATS $(\mathbf{CH_2})_\mathrm{n}\mathbf{O}_\mathrm{m}$ BY PLANTS (SEEDS) AND ANIMALS**
- **$\mathbf{m \ll n \rightarrow (CH_2)_\mathrm{n}O_\mathrm{m} \sim (CH_2)_\mathrm{n},\ H/C \sim 2}$**

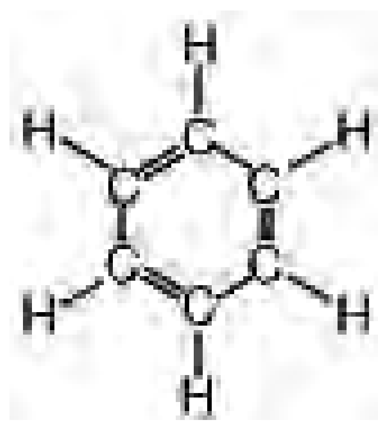
3.4.2 CLASSIFICATION OF HYDROCARBONS

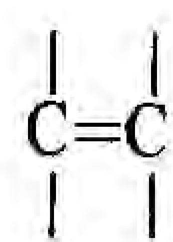
1. **PARAFFINS (ALIPHATICS) C_nH_{2n+2} (METHANE CH_4, ETHANE C_2H_6, PROPANE C_3H_8, *n*–BUTANE C_4H_{10}, ..., *n*–EPTANE C_7H_{16}, *n*–OCTANE C_8H_{18}, ..., *n*–DECANE $C_{10}H_{22}$, ...)**
2. **ISOPARAFFINS (ISOALIPHATICS) C_nH_{2n+2}, n $\geq$ 3 (*i*–BUTANE C_4H_{10}, ...)**
3. **CYCLOPARAFFINS (CYCLOALIPHATICS, NAPHTHENS) C_nH_{2n} (CYCLOPROPANE C_3H_6, ...)**
4. **AROMATICS C_nH_{2n-6} (BENZENE C_6H_6, TOLUENE C_7H_8,...)**
5. **OLEFINS C_nH_{2n} (ETHYLENE C_2H_4, ...; AFTER *CRACKING*)**











3.4.3 TYPICAL KEROSENE COMPOSITION

- **DEPENDS UPON SOURCE, AND TREATMENT:**
  - **$\sim$ 60% PARAFFINS (HIGH H/C, NO COKE, LITTLE SOOT)**
  - **$\sim$ 20% CYCLOPARAFFINS (HIGH H/C, NO COKE, LITTLE SOOT)**
  - **$\sim$ 20% AROMATICS (LOW H/C, MUCH SOOT, HYGROSCOPIC, RUBBER SOLVENT)**

3.4.4 PROPERTIES OF SOME HYDROCARBONS

	MOLAR MASS kg/kmol	VAPORIZ HEAT MJ/kg	HEATING VALUE MJ/kg	STOICH MIXTURE (F/O)	FLAMMAB LIMITS φ	IGNIT TEMPER STOICH C	ADIAB FLAME TEMPER STOICH K
METHANE CH_4	16,0	0,509	50	0,0583	0,435 – 1,76	900	2232
n–BUTANE C_4H_{10}	58,1	0,386	45,7	0,0650	0,530 – 3,56	700	2238
TOLUENE C_7H_8	92,1	0,363	40,9	0,0745	0,425 – 3,40	840	2327
n–OCTANE C_8H_{18}	114,2	0,300	44,8	0,0664	0,505 – 4,50	510	2279
n–DECANE $C_{10}H_{22}$	142,3	0,277	44,6	0,0667	0,445 – 3,69	495	2269

- $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 242{,}1\ \text{kJ/mol} = 120{,}1\ \frac{\text{MJ}}{\text{kg } H_2}$

- $C + O_2 \rightarrow CO_2 + 393{,}5\ \text{kJ/mol} = 32{,}75\ \frac{\text{MJ}}{\text{kg C}}$

- $C + \frac{1}{2}O_2 \rightarrow CO + 110{,}5\ \text{kJ/mol} = 9{,}2\ \frac{\text{MJ}}{\text{kg C}}$

$\Longrightarrow$ **LOW H/C RATIO $\leftrightarrow$ LOW Q_f**

3.4.5 FUEL CONTAMINANTS

- **RUBBERS (UNDER ACTION OXYGEN, LIGHT, METAL CATALYSTS Cu Zn)**
- **WATER (DISSOLVED, EMULSIONATED, FREE)**
- **SULPHUR (CORROSIVE, POLLUTING)**
- **SODIUM (FROM SEA NaCl → HCl CORROSIVE)**
- **VANADIUM (BLADE DEPOSITS BELOW 922 K)**
- **(SEDIMENTS, ASH)**

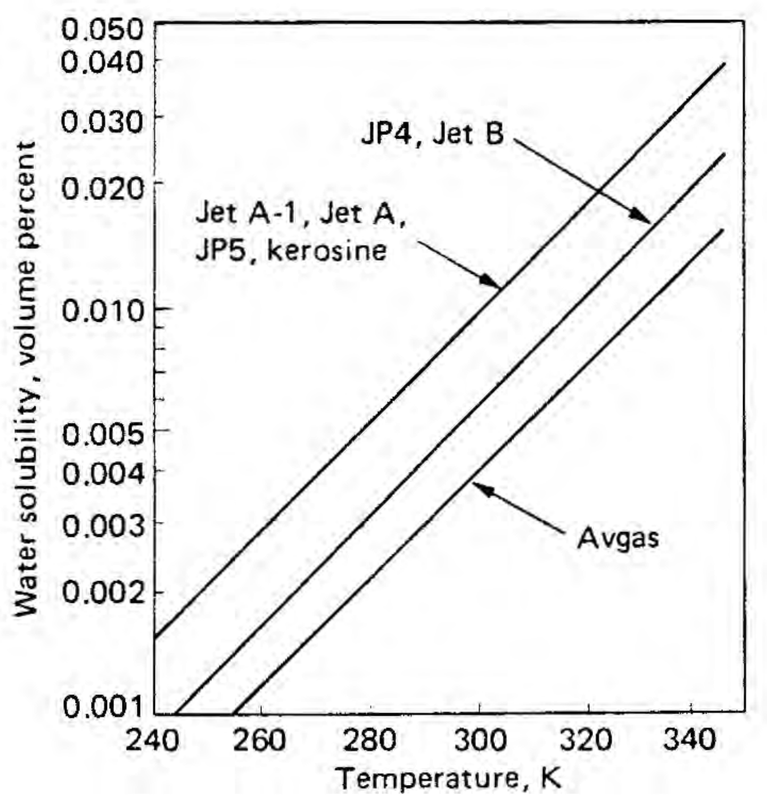


Figure 78: Water solubility in different aeronautical fuels.

3.4.6 ADDITIVES

- **RUBBER PREVENTION (ANTIOXIDANTS, METAL DEACTIVATORS, CATALYTIC PASSIVANTS)**
- **ANTIRUST (HYDROCARBONS WITH AFFINITY TO METALS)**
- **ANTI–ICE:**
  - **GLICEROL: HOWEVER, CAN FORM GEL → ADDED WHEN REFUELLING (MILITARY A/Cs)**
  - **HEATERS ON FUEL LINES AND FILTERS (CIVIL A/Cs)**
- **ANTISTATICS (Stadis 450)**
- **LUBRICANTS (NATURALLY PRESENT IN FUELS, CAN BE DESTROYED BY H)**
- **BIOCIDES (TOXIC)**
- **{ANTISMOKE} (ORGANIC COMPOUNDS OF Ba, Mn, Fe; BETTER TO ACT ON φ)**

3.4.7 AVIATION FUELS

- **SPECIFICATIONS: FREEZING POINT, FLASH POINT, VOLATILITY, FLUIDITY, CORROSIVITY, STABILITY, CONTAMINANT CONTENT, ...**
- **JET–A1, JP–5, JP–8 (KEROSENE)**

FUEL	USE	FREEZING	FLASH
JET–A	USA	-40 ºC	38 ºC
JET–A1	INTERNATIONAL	-47 ºC	38 ºC
JP–5	AIRCRAFT CARRIERS	-46 ºC	60 ºC
JP–6	XB–70	-54 ºC	...
JP–7	SR–71	-43 ºC	60 ºC
JP–8	MILITARY	-47 ºC	38 ºC

- **JET–B, JP–4 (MIXTURE GASOLINE–KEROSENE; UNDER REPLACEMENT)**

FUEL	USE	FREEZING	FLASH
JET–B	CANADA, ALASKA	-51 ºC	(-29 ºC)
JP–4	MILITARY	-72 ºC	(-29 ºC)

3.4.8 VAPOUR PRESSURE

- **AFFECTS *FLASH POINT***

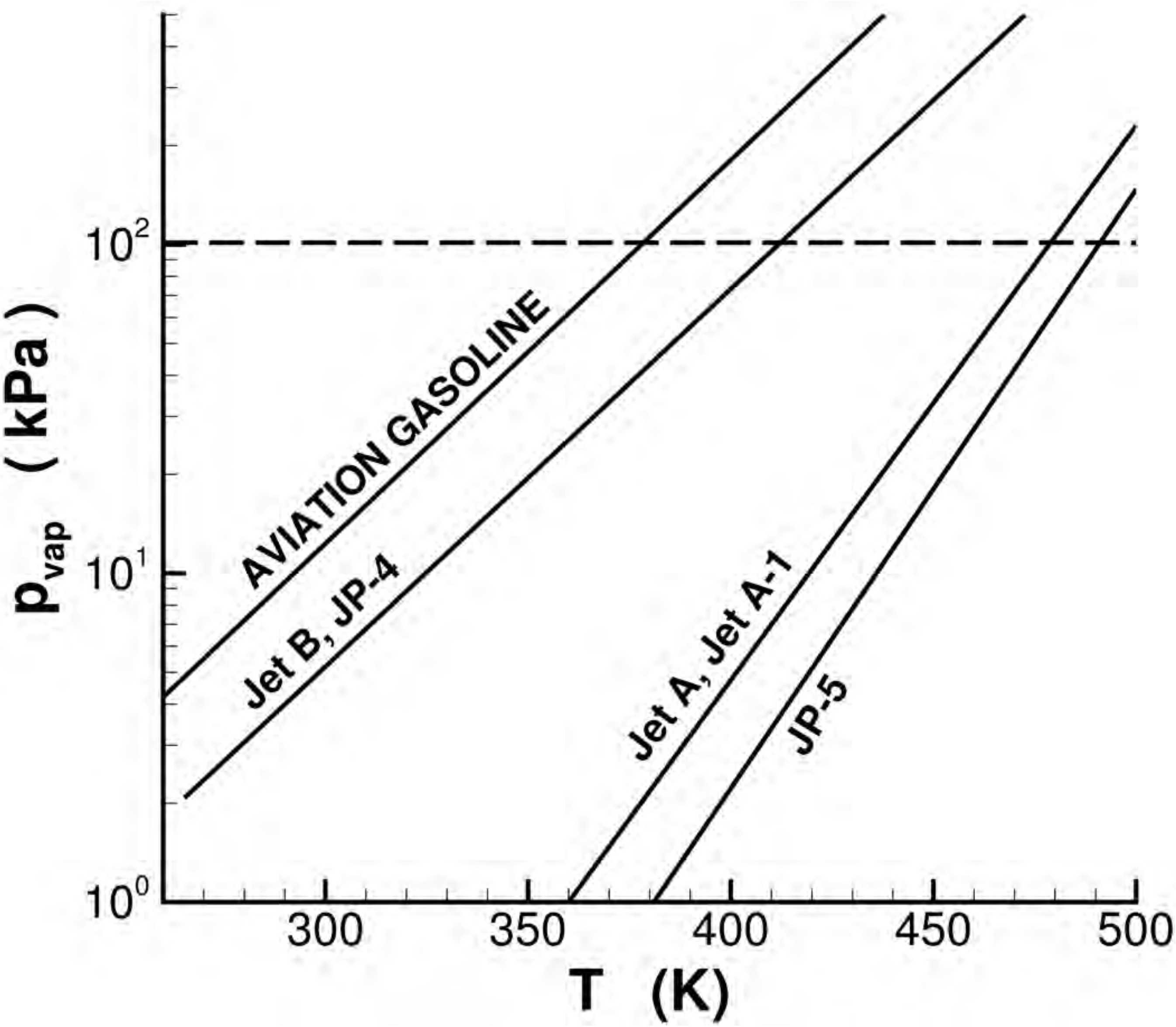


Figure 79: Vapour pressure of different aeronautical fuels as a function of temperature.

3.4.9 BOILING/FREEZING FRACTIONAL DISTILLATION

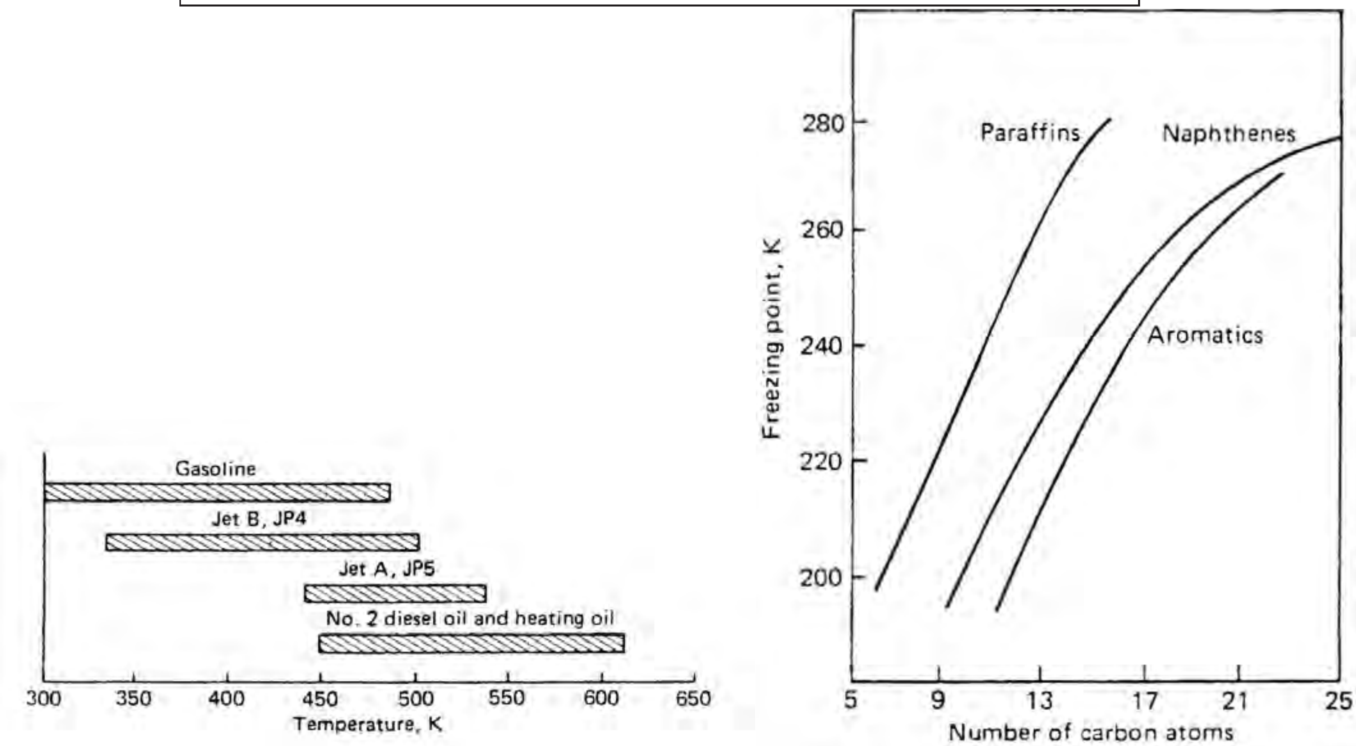


Figure 80: Boiling range of different aviation fuels (left); freezing point of different hydrocarbons as a function of the number of carbon atoms in the molecule (right).

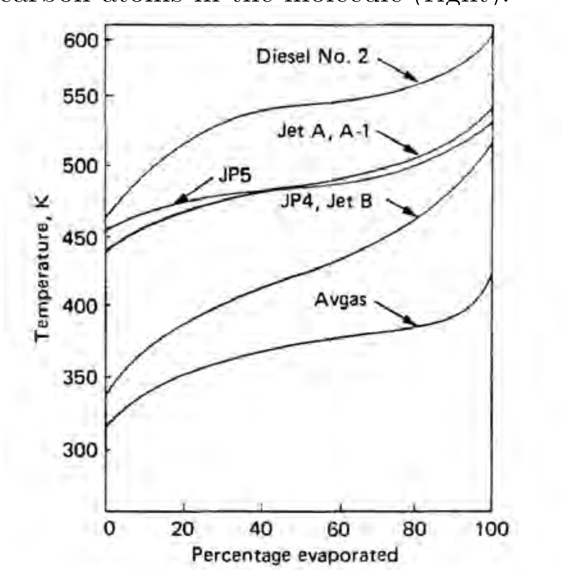


Figure 81: Distillation curves of different fuels.

4.1 POLLUTANT FORMATION AND EMISSION CONTROL

- **POLLUTION:**
  - **NEAR AIRPORTS**
  - **AFTER EMISSIONS AT ALTITUDE**
- **SMOKE (SOOT – PARTICULATE)**
- **UHC, VOC**
- **SO_x**
- **NO_x**
- **CO**
- **CO_2, H_2O (CONTAMINANTS)**

4.2 STRATEGIES FOR EMISSION CONTROL

- **CONTROL (IN GENERAL):**
  - **PRE–TREATMENT OF FUEL**
  - **MODIFICATIONS OF COMBUSTION PROCESS**
  - **POST–TREATMENT OF EXHAUST GASES**
- **(DISPERSION)**

4.3.1 PARTICULATE

- **TERMINOLOGY:**
  - **AEROSOL (MOST GENERAL, LIQUID OR SOLID DISPERSED IN ATMOSPHERE)**
  - **DUST (SOLID PARTICLES FROM GRINDING/CRUSHING)**
  - **SMOKE (SOLID PARTICLES FROM VAPOUR CONDENSATION. IF C → *SOOT*)**
  - **FOG (LIQUID PARTICLES SUSPENDED IN ATMOSPHERE)**
  - **SMOG (PARTICLES OF DIAMETER ∼ WAVELENGTH OF LIGHT)**
- **PRIMARY PARTICULATE (COMBUST. PRODUCT)**
  - **SOOT**
  - **ASH (IN COAL COMBUSTION: OXIDES OF Si, Ca, Al + TRACES OTHER MINERALS)**
- **SECONDARY PARTICULATE (PRODUCED BY REACTIONS IN ATMOSPHERE):**
  - **SMOG**

4.3.2 PRIMARY AND SECONDARY PARTICLES

- **PRIMARY:**
  - **PULVERIZED COAL (50 – 150 μm)**
  - **SOOT ($\sim$ 1 nm – 1 μm, GENERATED IN COMBUSTION OF ALL HCs):**
    - **PARTICULATE (SOLID)**
    - **CENOSPHERES (HOLLOW)**
  - **ASHES (COAL COMBUSTION): FLY, BOTTOM**
- **SECONDARY:**
  - **FORMED IN THE PRESENCE OF HCs, NO_x, SO_x, NH_3**

4.3.3 SIZE AND CHARACTERISTICS OF SUSPENDED PARTICLES

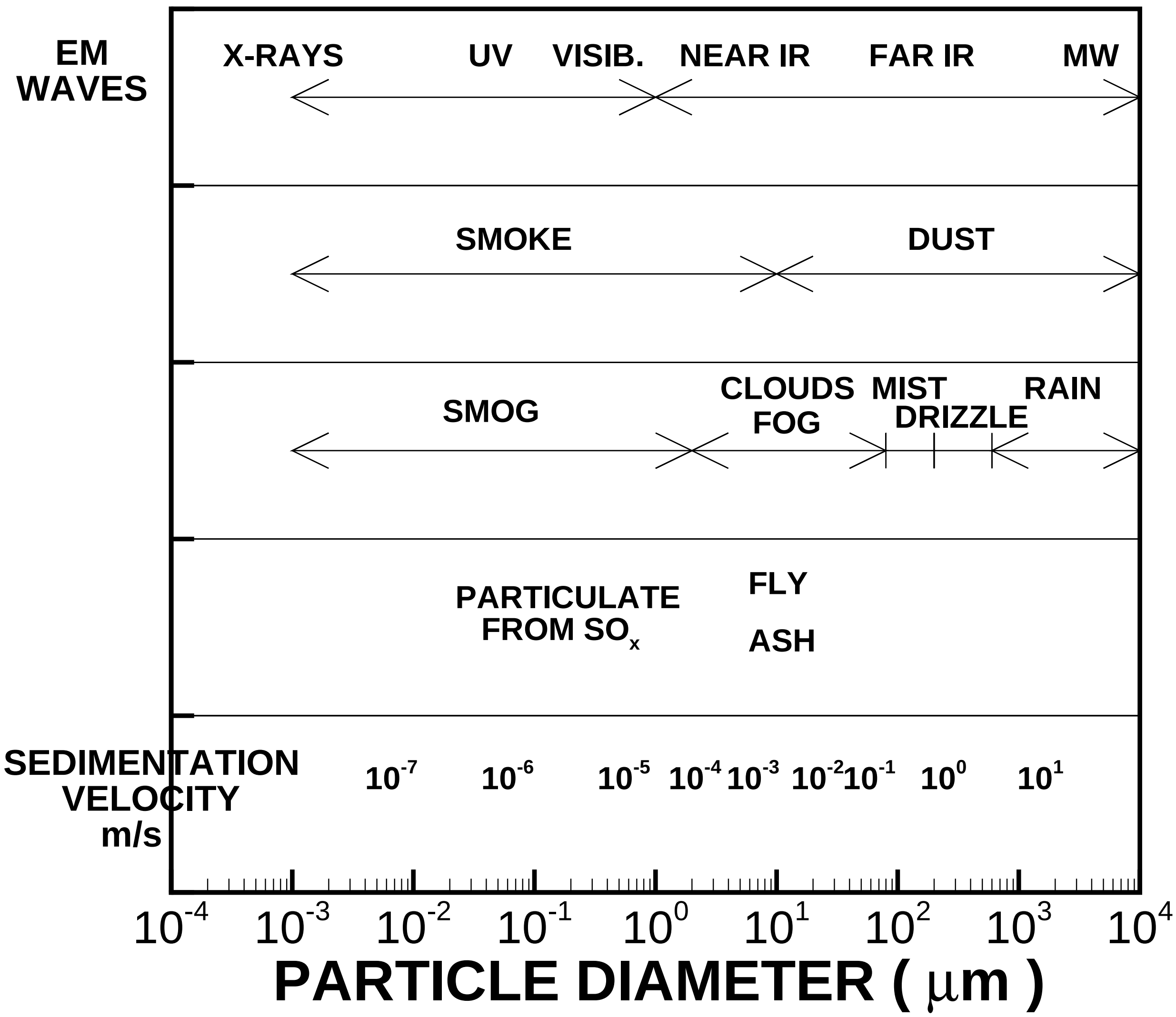


Figure 82: Size and characteristics of suspended particles: EM electromagnetic, UV ultraviolet, IR infrared, MW microwave.

4.3.4 FINE PARTICLES

- **PM10: PARTICLES DIAMETER $< 10\ \mu$m (STANDARD 1987)**
- **PM2,5: PARTICLES DIAMETER $< 2{,}5\ \mu$m (STANDARD 1997, MORE REPRESENTATIVE)**

- **PARTICLES DIAMETER $> 10\ \mu$m FILTERED BY NOSE AND THROAT**
- **PARTICLES DIAMETER $5 - 10\ \mu$m REMOVED BY TRACHEA AND BRONCHI**

- **INHALABLE PARTICLES: DIAMETER $< 10\ \mu$m**
- **FINE PARTICLES: DIAMETER $< 2{,}5\ \mu$m**

- **PARTICLES HARMFUL TO LUNGS: DIAMETER $0{,}5 - 5\ \mu$m**
- **BUT ALSO $< 0{,}1\ \mu$m (NANOPARTICLES)**
- **MOST FINE PARTICLES IN AIR ARE SECONDARY**

4.3.5 SOOT

- **VISIBLE AS SMOKE**
- **FORMED IN COMBUSTION OF ALL HCs**
- **SOLID PARTICLES CONTAINING C ($\sim$ 96% IN MASS), H**
- **MAKES FLAME YELLOW AND LUMINOUS (THERMAL RADIATION)**
- **AMOUNTS TO UNBURNT FUEL**

4.3.6 SOOT FORMATION (1/2)

- **FORMATION FOSTERED IN PRESENCE OF HCs WITH LOW H/C RATIO (AROMATICS)**
- **(METHANE CH_4 FORMS VERY LITTLE SOOT)**

a) **HC SPLITS UNTIL CH IS FORMED, THEN C_2H_2, C_3H_3, n–C_4H_3, n–C_4H_5 → *FORMATION FIRST AROMATIC RING* BY REACTIONS:**

$$n\text{–}C_4H_3 + C_2H_2 \rightarrow C_6H_5$$

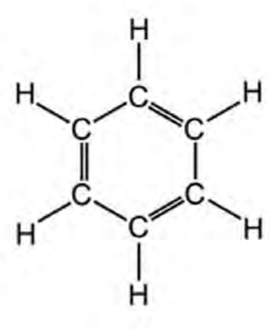
$$C_3H_3 + C_3H_3 \rightarrow C_6H_6$$

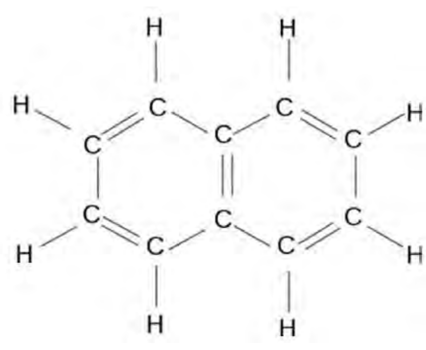
b) **HACA MECHANISM (H–ABSTRACTION, C_2H_2 ADDITION) LEADS TO FORMATION OF PAHs:**

$$C_6H_6 + H \rightarrow C_6H_5 + H_2$$

$$C_6H_5 + C_2H_2 \rightarrow C_8H_7$$

$$C_8H_7 + C_2H_2 \rightarrow C_{10}H_8 + H$$





benzene **naphthalene**

4.3.7 SOOT FORMATION (2/2)

- **... AND SO ON TO BIGGER PAHs**
- **D INITIAL PARTICLES $\sim$ 1 nm, THEN AGGLOMERATION UP TO $\sim$ 1 μm (BY VAN DER WAALS AND ELECTROSTATIC FORCES)**
- **GROWTH HAMPERED BY OXIDATION BY O_2 AND OH**

$\rightarrow$ **MOST SOOT FORMED IN PRIMARY ZONE, THEN CONSUMED IN INTERMEDIATE AND DILUTION ZONES**

- **FORMATION CONTROLLED MORE BY *PHYSICAL* PROCESSES (ATOMIZATION, MIXING THAN *CHEMICAL* ONES**

4.3.8 EFFECT OF φ, p ON CONVERSION C → SOOT

- **SOOT FORMS ONLY FOR $\varphi > 1{,}2 - 1{,}3$**
- ***ALWAYS*** **FORMED IN NONPREMIXED COMBUSTION ($0 \le \varphi_{local} \le \infty$)**
- **IN PRINCIPLE, CAN BE TOTALLY ELIMINATED IN PREMIXED COMBUSTION...**
- **... BUT IN PRACTICE GTs CAN ONLY OPERATE WITH *PARTIALLY* PREMIXED COMBUSTION**

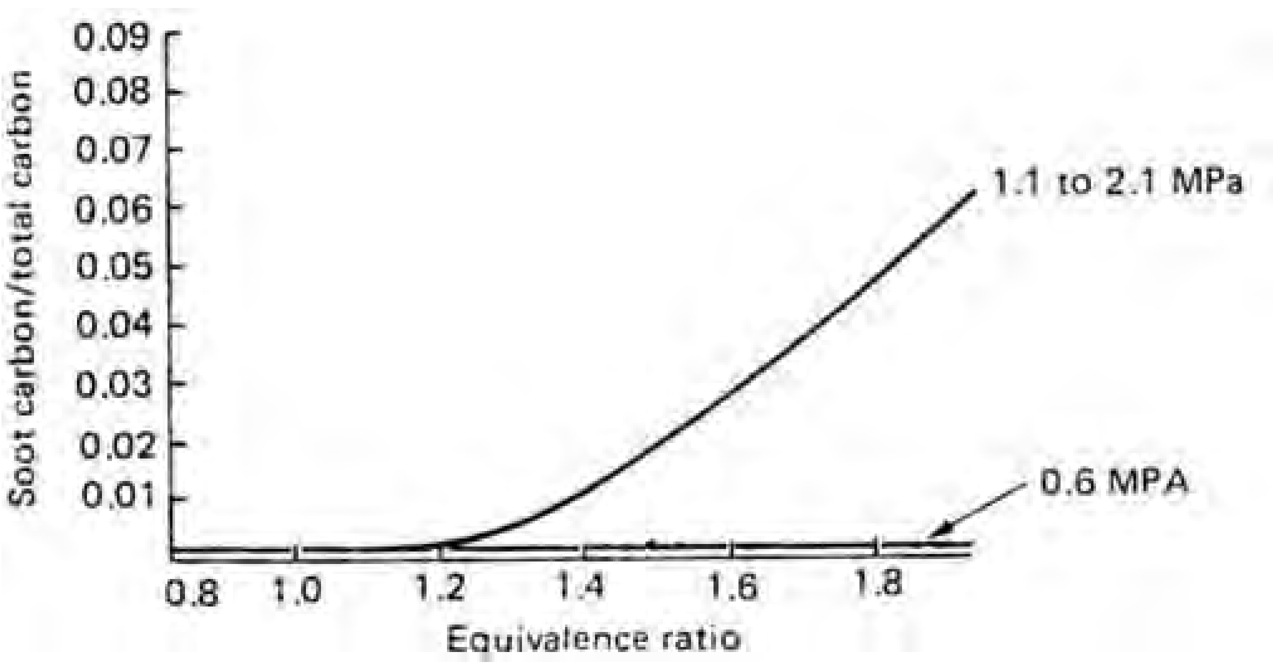


Figure 83: Formation of soot in premixed kerosene/air combustion.

4.3.9 EFFECT OF p ON SMOKE EMISSIONS

- **INCREASING p_3 WIDENS FLAMMABILITY LIMITS → COMBUSTION CAN TAKE PLACE EVEN FOR $\varphi \gg 1$ → SOOTING**
- **IN PRESSURE–SWIRL INJECTORS, REDUCED APERTURE SPRAY CONE (LOCAL φ HIGHER)**
- **AIRBLAST INJECTORS MUCH LESS SENSITIVE (AND ANYWAY PRODUCE LESS SOOT)**
- **...**

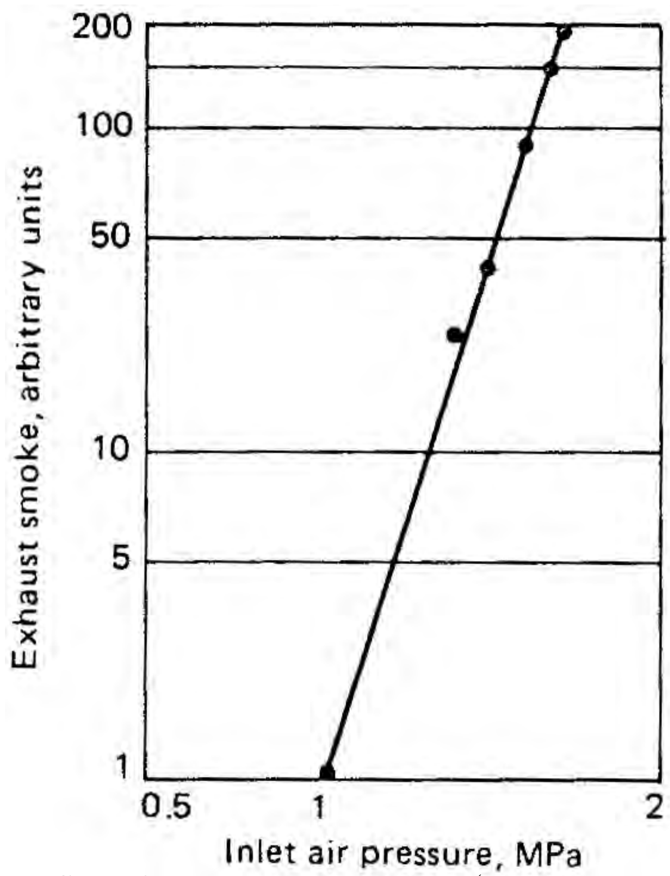


Figure 84: Effect of p_3 on smoke emissions (pressure–swirl injector).

4.3.10 CONTROL OF PRIMARY PARTICULATE

- **REMOVAL (IN GROUND PLANTS)**
- **MODIFICATION OF COMBUSTION PROCESS (φ)**

→ **INTERACTION WITH NO_x AND CO EMISSIONS**

- **FINER ATOMIZATION OF DROPLETS:**
  - **IF D_d SMALL, COMBUSTION LOCALLY ∼ PREMIXED**
  - **IF D_d LARGE, COMBUSTION LOCALLY NONPREMIXED ANYWAY**

4.3.11 REMOVAL OF PRIMARY PARTICULATE

- **IN GROUND PLANTS:**
  - **GRAVITY SETTLERS (GRAVITY)**
  - **CYCLONES (CENTRIFUGAL FORCE)**
  - **ELECTROSTATIC PRECIPITATORS (ESP – ELECTROSTATIC FORCE)**
  - **FILTERS**
  - **SCRUBBERS**
  - **VENTURI SCRUBBERS**
- **REMOVAL EFFICIENCY DEPENDS ON PARTICLE DIAMETER**

4.3.12 EFFECT OF FUEL DROPLET SIZE ON SOOT EMISSIONS

- **SMALLER DROPLET SIZE ALLOWS VAPORIZATION BEFORE IGNITION**

∼ LOCALLY PREMIXED COMBUSTION (LOW φ)

- **EFFECT CAN BE OPPOSITE IN PRESSURE–SWIRL DUE TO REDUCED PENETRATION**

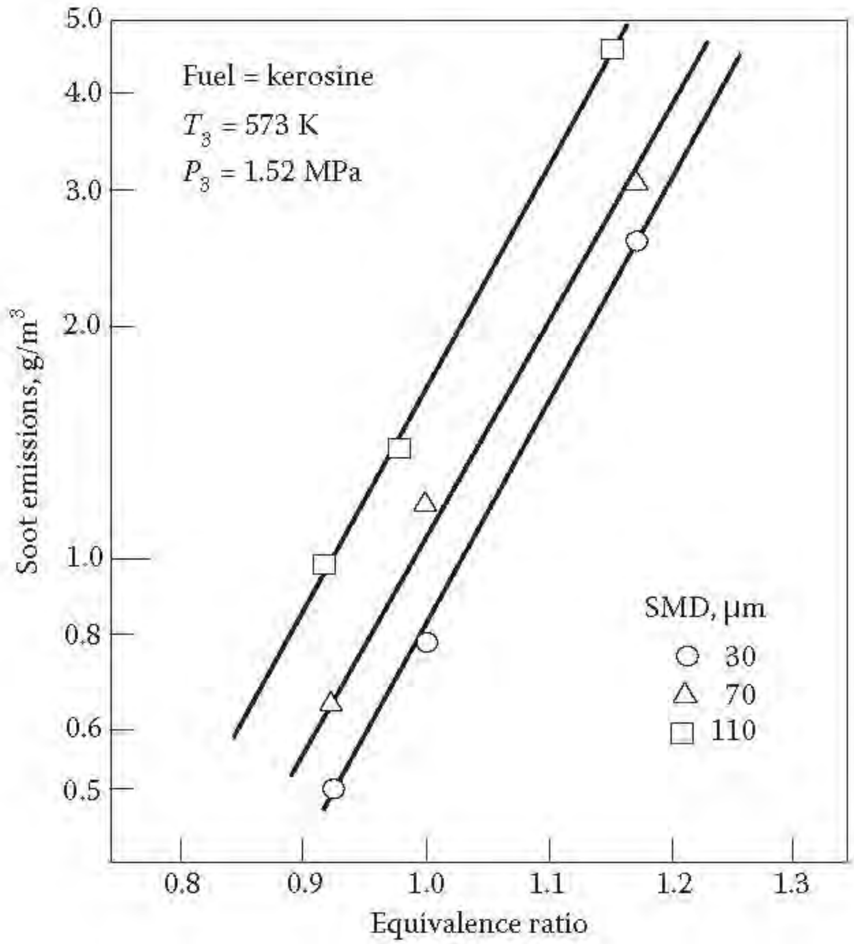
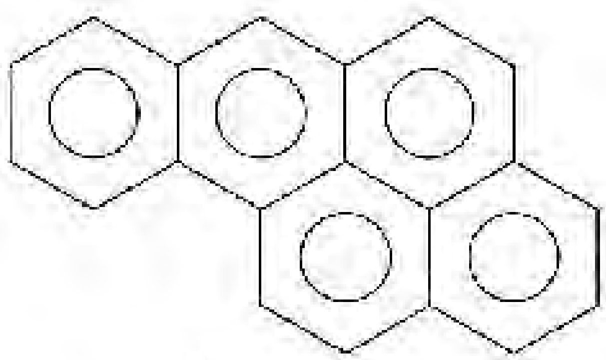


Figure 85: Effect of fuel droplet size on soot emissions (airblast injector).

4.4.1 VOLATILE ORGANIC COMPOUNDS (VOCs)

- **VOLATILE LIQUIDS OR SOLIDS CONTAINING ORGANIC CARBON (C BONDED TO C, H, N, S – *NOT* $CaCO_3$, CaC_2, CO, CO_2)**
- **SOME TOXIC, CARCINOGEN (BENZENE C_6H_6, PAH), BUT MOST NOT, OR MILDLY TOXIC**
- **TAKE PART IN FORMATION OF S/L OZONE, SMOG/SECONDARY PARTICULATE (FINE)**
- **SOME VOCs ARE ALSO GHGs**
- **METHANE CH_4 RELATIVELY LITTLE REACTIVE → NMVOCs (NON–METHANE VOCs)**
- **MAIN SOURCES: SOLVENTS, MOTOR VEHICLES**
- ***PAH* POLYCYCLIC AROMATIC HYDROCARBONS**



Benzopyrene
$C_{20}H_{12}$

4.4.2 FORMATION OF GROUND–LEVEL OZONE

- **NO FROM ENGINES OXIDIZED TO NO_2 IN ATMOSPHERE**
- **UNDER THE ACTION OF A PHOTON:**

$$\mathrm{NO_2} + h\nu \rightarrow \mathrm{NO} + \mathrm{O} \quad (1)$$
$$\mathrm{O_2} + \mathrm{O} + \mathrm{M} \rightarrow \mathrm{O_3} + \mathrm{M} \quad (2)$$
$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2} \quad (3)$$

- **REACTION (3) REMOVES NO AND OZONE**
- **REACTION (2) REQUIRES THIRD–BODY TO SATISFY ENERGY BALANCE; IN (1), ENERGY SUPPLIED BY PHOTON**
- **IN THE PRESENCE OF VOCs, ADDITIONAL REACTIONS ULTIMATELY RESULTING IN**

$$\mathrm{OH} + \mathrm{VOC} \rightarrow \mathrm{HO_2} + \ldots \quad (4)$$
$$\mathrm{NO} + \mathrm{HO_2} \rightarrow \mathrm{NO_2} + \mathrm{OH} \quad (5)$$

- **(5) REMOVES NO *WITHOUT* CONSUMING OZONE → X_{O_3} INCREASES**
- **e.g., IF (3) ASSUMED IN EQUILIBRIUM AS FIRST APPROXIMATION:**

$$K_{p,3}(T) = \frac{p_{NO_2}\, p_{O_2}}{p_{NO}\, p_{O_3}} = \frac{X_{NO_2}\, X_{O_2}}{X_{NO}\, X_{O_3}}$$

- **X_{NO_2} INCREASES, X_{NO} DROPS, $X_{O_2} \simeq$ const → X_{O_3} INCREASES**

4.4.3 FORMATION OF SECONDARY PARTICULATE

- **AS AN EFFECT OF PRESENCE OF NO_x, SO_x, VOC, NH_3**
- **NH_3 FROM BIOLOGICAL SOURCES (LIVESTOCK, AGRICULTURE)**
- **DUE TO ATMOSPHERIC HUMIDITY:**
  $NO_2 \rightarrow HNO_3$, $SO_3 \rightarrow H_2SO_4$
- **IN THE PRESENCE OF $NH_3 \rightarrow$**
  NH_4NO_3, $(NH_4)_2SO_4$ IN CONDENSED PHASE
- **SIMILARLY, OXIDATION OF VOCs IN ATMOSPHERE LEADS TO FORMATION OF LESS VOLATILE SPECIES, WHICH THEN CONDENSE**

4.4.4 VAPOUR PRESSURE BEHAVIOUR IN AN *OPEN* VESSEL

- $p_v < p_{atm} \rightarrow$ **SLOW EVAPORATION**
- $p_v = p_{atm} \rightarrow$ **BOILING, WITH RATE DEPENDING ON HEAT BEING SUPPLIED**
- $p_v > p_{atm} \rightarrow$ **VIGOROUS BOILING, COOLING DOWN TO** $T : p_v(T) = p_{atm}$

- $p_v = A - \dfrac{B}{T + C}$ **ANTOINE's LAW**

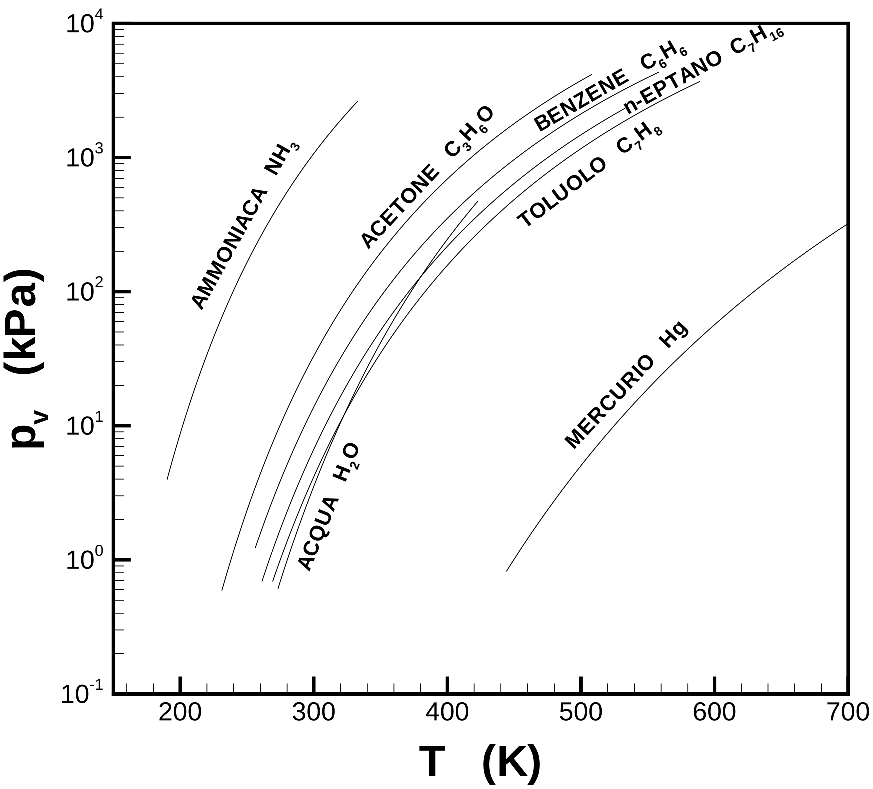


Figure 86: Vapour pressure of some chemical species as a function of temperature.

4.4.5 BEHAVIOUR OF SOME VOCs

- **ETHANE** C_2H_6, **PROPANE** C_3H_8, n–**BUTANE** C_4H_{10}: $p_v(T_{ambient}) > p_{atm}$
- [**Cd, Zn, As, Sb:** $p_v(T_{\mathrm{kiln}}) \sim p_{atm} \rightarrow$ **SUBSEQUENT CONDENSATION IN FINE *TOXIC* PARTICLES**]

4.4.6 DEFINITION OF VOC

- **ORGANIC LIQUIDS/SOLIDS SUCH THAT $T_b < 250$ °C at 1 atm**
- **MOST ORGANIC COMPOUNDS WITH LESS THAN 12 ATOMS C**

4.4.7 BEHAVIOUR IN A CLOSED VESSEL

- **VOLATILE LIQUID EVAPORATES UNTIL ITS PARTIAL PRESSURE $p_i = p_v(T)$**
- $p_i \; = \; X_i \, p$
- **IF T INCREASES, p_i INCREASES (THEN TOTAL p AS WELL)**

4.4.8 FILLING, BREATHING AND EMPTYING LOSSES

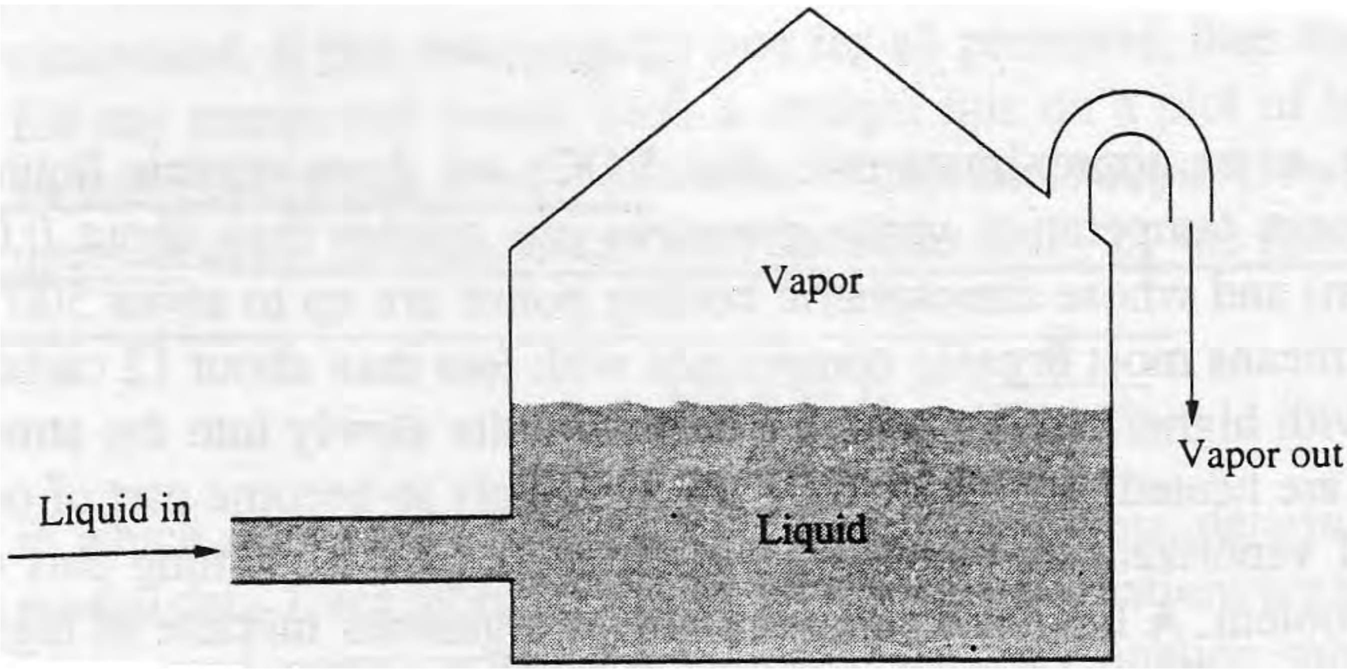


Figure 87: Mechanism of filling losses.

- **TANK VENTED TO AVOID OVER/UNDER–PRESSURE**
- **BREATHING LOSSES RELATED TO EXCURSIONS OF T_{ambient}**
- **VAPOUR CONSERVATION VALVES (OPEN BEYOND -0,043 $< \Delta p <$ 0,034 atm)**

4.4.9 FLOATING ROOF TANK

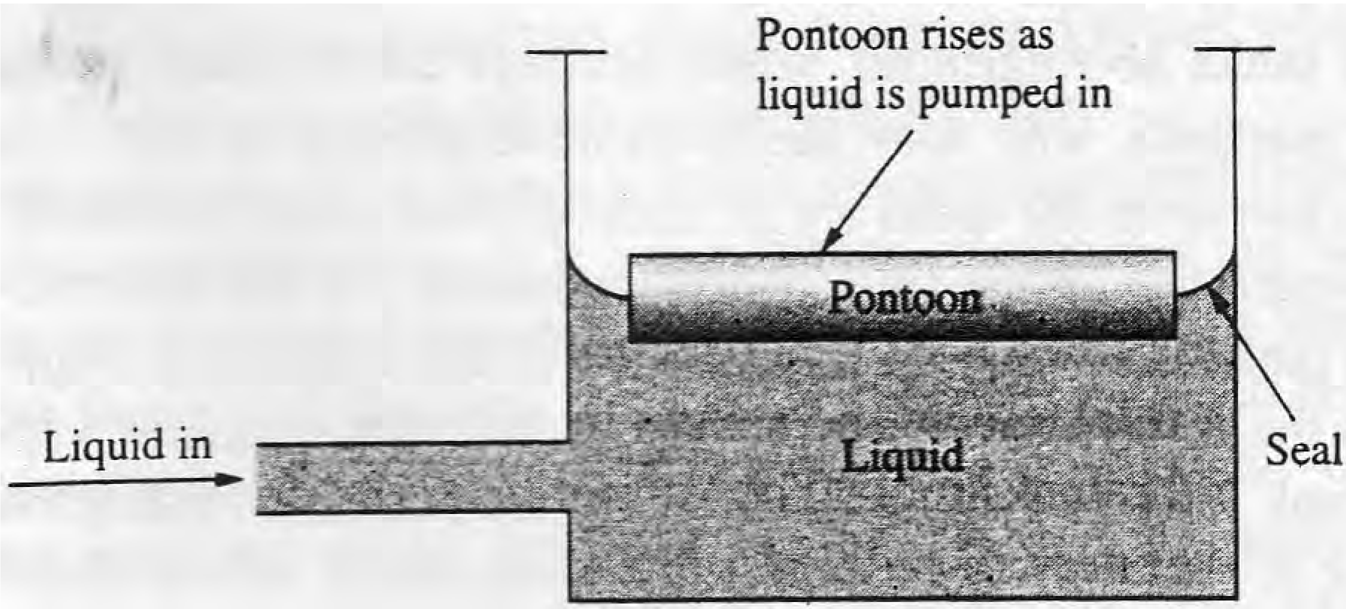
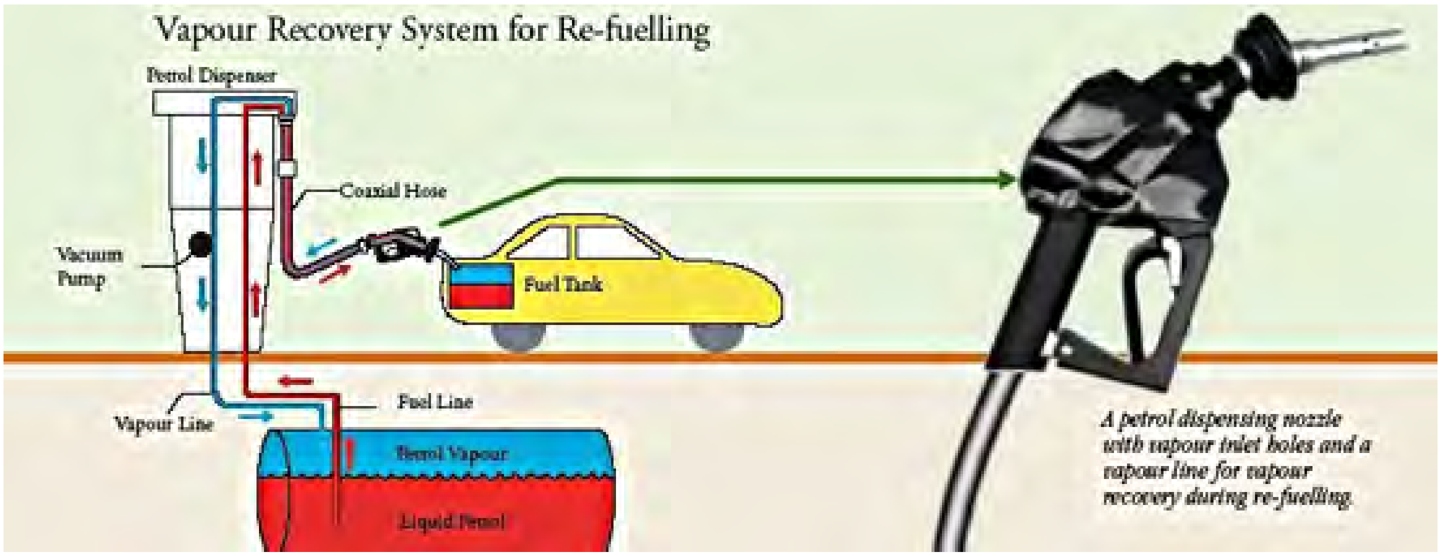


Figure 88: Floating roof tank.

4.4.10 CAR TANK REFUELLING



4.5.1 SULFUR OXIDES (SO_x)

- **RESPIRATORY IRRITANTS**
- **FORM SECONDARY PARTICLES**
- **CAUSE ACID RAIN**
- **RAISE DEW POINT OF FLUE GAS**

4.5.2 SULFUR CHEMISTRY

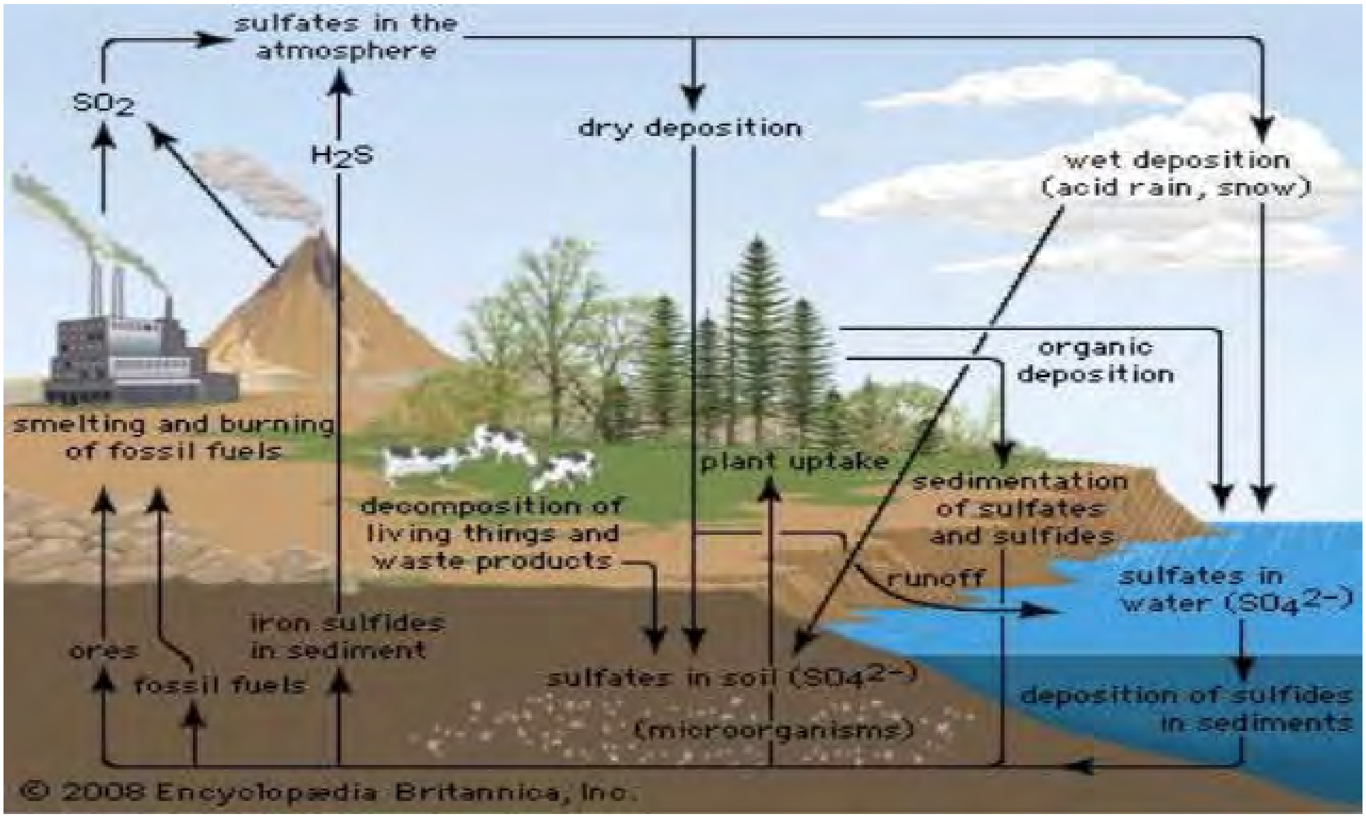
- **OXIDATION S (BY ATMOSPHERIC O_2) → SO_2 → SO_3**

  + ATMOSPHERIC MOISTURE → H_2SO_4

  + ATMOSPHERIC AMMONIA → SULFATE PARTICLES (0.1 – 1 μm → LIGHT SCATTERING)

- **REDUCTION S (BY HYDROGEN) → H_2S**
- **BACKGROUND CONCENTRATIONS:**
  - **SULFUR DIOXIDE SO_2 0,2 ppb**
  - **AMMONIA NH_3 10 ppb**

4.5.3 SULFUR CYCLE



4.5.4 EMISSION SOURCES

- **FUELS:**
  - **WOOD ∼ 0,1% S**
  - **GASOLINE ∼ 0,03% S**
  - **KEROSENE (JET FUEL) ∼ 0,05% S**
  - **HEAVY FUEL OIL ∼ 0,5 – 1% S**
  - **COAL ∼ 0,5 – 3% S**
- **SMELTING OF MINERALS:**
  - **CHALCOPYRITE:**
    $\mathbf{CuFeS_2 + 2{,}5\ O_2 \rightarrow Cu + FeO + 2\ SO_2}$

4.5.5 SO_x EMISSION CONTROL

- **LARGE GROUND PLANTS: EXHAUST GAS TREATMENT**
- **MOBILE SOURCES (CARS, AIRPLANES, ...): USE OF LOW–SULFUR FUELS**

4.5.6 DESULFURATION OF HYDROCARBONS

- **CATALYTIC HYDRODESULFURATION**
- **(HC + S) + H_2 → HC + H_2S**
- **CATALYST: Ni or Co, PROMOTED WITH Mo or W**
- **THEN H_2S + 0,5 O_2 → S + H_2O (IN ALKALINE ACQUEOUS SOLUTION)**
- **CONTROL O_2 FLOW TO AVOID REACTION H_2S + 1,5 O_2 → SO_2 + H_2O**

4.6.1 NITROGEN OXIDES (NO_x)

- **FORM SECONDARY PARTICULATE, AND INCREASE O_3 CONCENTRATION IN THE PRESENCE OF VOCs ($\sim$ HC)**
- **CAUSE ACID RAIN**
- **DEPLETE STRATOSPHERIC OZONE**
- **NO_2 RESPIRATORY IRRITANT ($\sim$ 1 ppb IN UNPOLLUTED AIR)**
- **N_2O GREENHOUSE GAS**

4.6.2 NITROGEN CYCLE

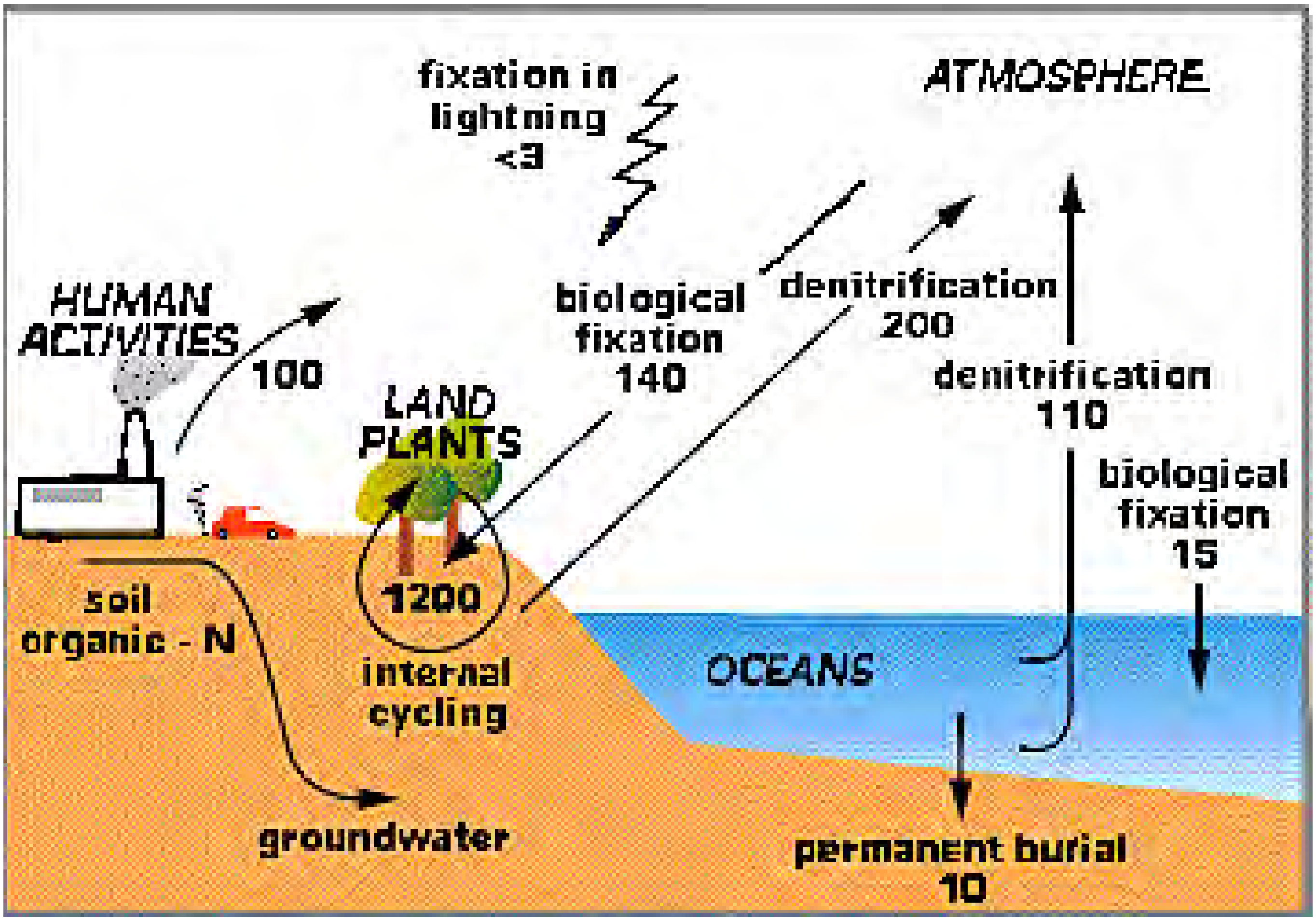


Figure 89: Nitrogen fluxes in Gt/year.

4.6.3 EMISSION SOURCES

- **VEHICLES (CARS, AIRPLANES,...)**
- **COMBUSTION PLANTS (COAL–FED IN PARTICULAR)**

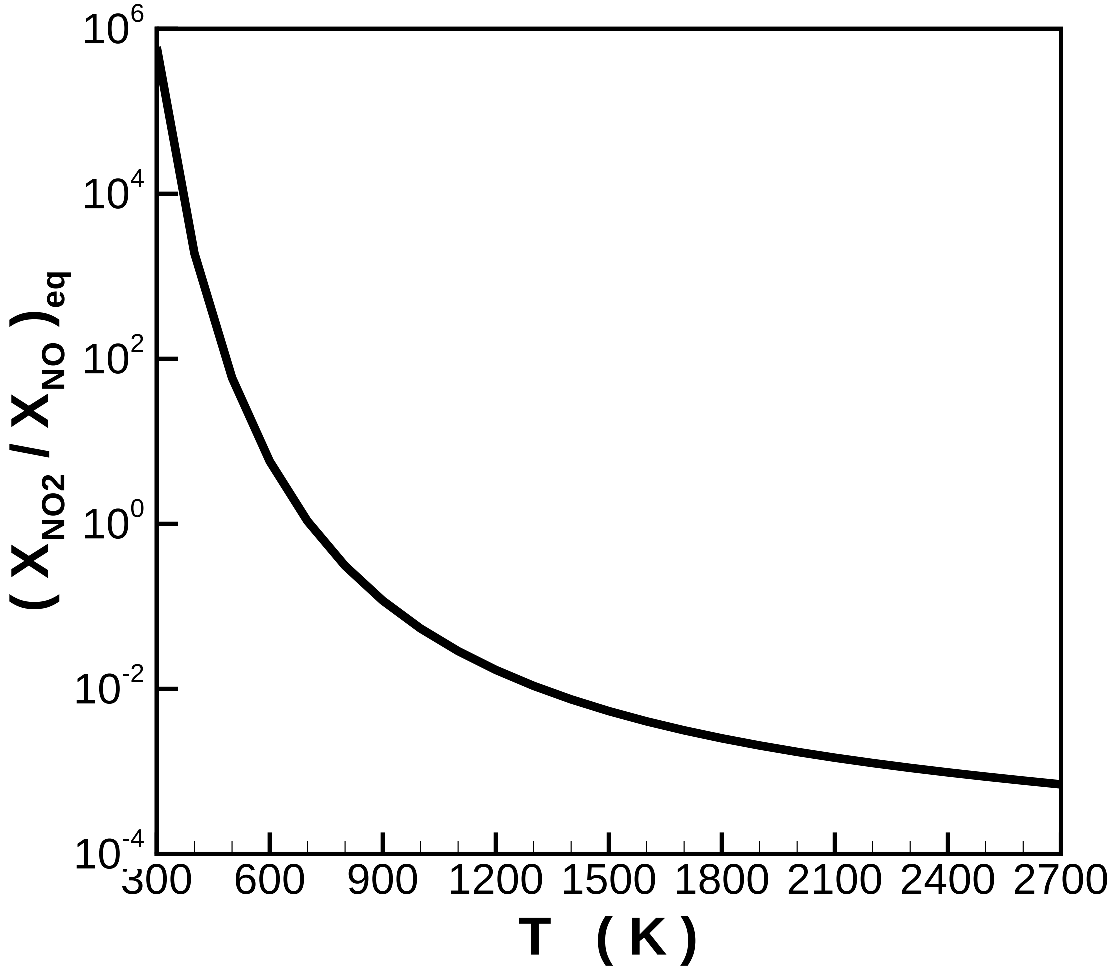
4.6.4 DIFFERENCES w.r.t. SO_x

- **SO_x FORMED FROM FUEL CONTAMINANTS, NO_x FROM ATMOSPHERIC N (MAINLY)**
- **MOTOR VEHICLES LARGE SOURCE OF NO_x, BUT SMALL OF SO_x**
- **NO_x FORMATION CAN BE CONTROLLED VIA T, t_s, X_{O_2} (SO_x CANNOT)**

4.6.5 ATMOSPHERIC REACTIONS

- **NITROGEN MONOXIDE NO COLOURLESS, LITTLE HARMFUL**
- **NITROGEN DIOXIDE NO_2 BROWN, IRRITANT**
- **NO_x EMITTED AS NO, CONVERTED TO NO_2 AT AMBIENT T**
- **OFTEN NO_x EXPRESSED AS NO_2**
- **$NO + HC + O_2 + \text{SUNLIGHT} \rightarrow NO_2 + O_3$**
- **OZONE O_3 STRONG IRRITANT**

4.6.6 EQUILIBRIUM NO/NO_2



4.6.7 *EQUILIBRIUM* CONCENTRATIONS OF NO AND NO_2

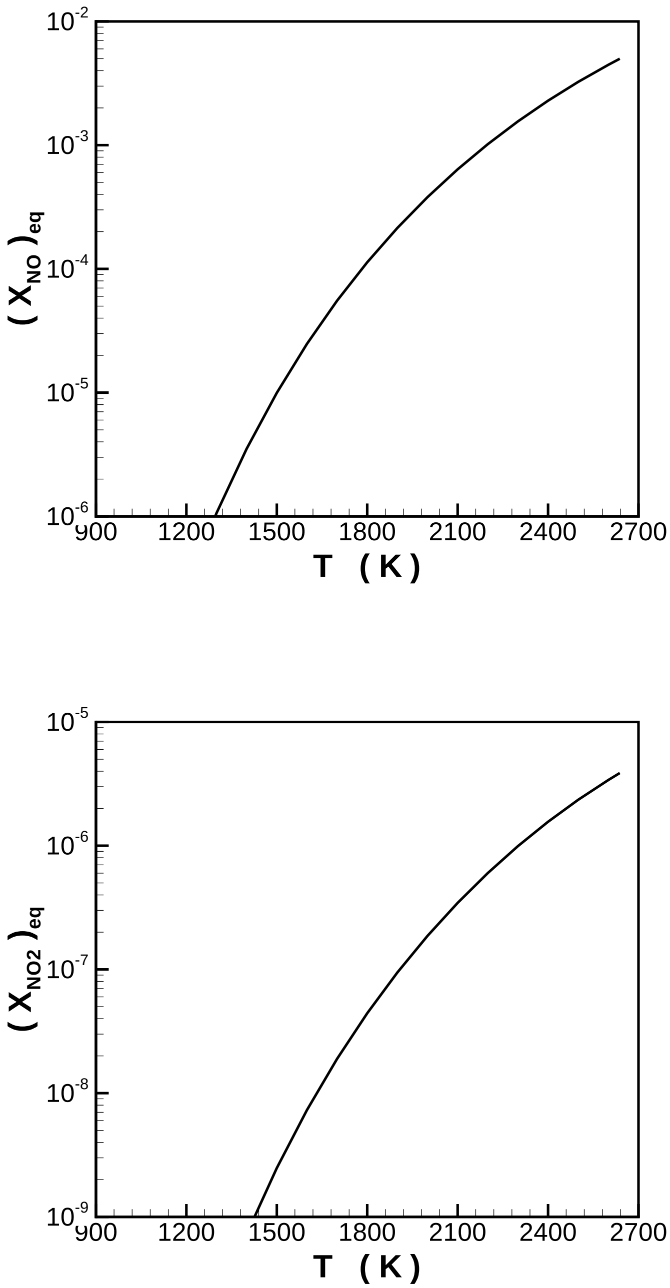


Figure 90: Equilibrium concentration of NO (top) and NO_2 (bottom), at atmospheric pressure.

4.6.8 NO_x FORMATION MECHANISMS

1. **THERMAL (ZEL'DOVICH)**
2. **PROMPT (FENIMORE)**
3. **FUEL–NITROGEN**
4. **NITROUS OXIDE N_2O**
5. **OTHERS (NNH, N_2H_3, NO_2,...)**

- **APPROXIMATE CONCISE EXPRESSION OF PRODUCTION RATE AVAILABLE FOR THERMAL MECHANISM ONLY**

4.6.9 THERMAL MECHANISM (ZEL'DOVICH)

1. $N_2 + O \rightleftharpoons NO + N$
2. $N + O_2 \rightleftharpoons NO + O$
3. $N + OH \rightleftharpoons NO + H$ (EXTENDED ZEL'DOVICH)

- 1. ***VERY*** **SLOW** ($\sim$ 0,02 s) $\rightarrow$ **CONTROLLING, NO FORMED DOWNSTREAM OF THE FLAME**
- **N BEING FORMED PRODUCES A SECOND NO MOLECULE *VIA* 2. OR 3. (FASTER)**
- **STEP 3. LESS IMPORTANT (OH CONCENTRATION RELATIVELY LOW)**
- **GLOBALLY,** $N_2 + O_2 \rightleftharpoons 2\,NO$;
  UNDER APPROPRIATE HPs:

$$w_{NO} = 2,44 \cdot 10^{10} \rho^2 \exp\left(-\frac{38\,370}{T}\right) Y_O Y_{N_2} \qquad (*)$$

- w_{NO} **IN** kg/(m^3 s), T **IN** K, ρ **IN** kg/m^3
- **<u>IF</u>** $O_2 + M \rightleftharpoons O + O + M$ **IN EQ. (M 3rd BODY)**

$$\rightarrow \quad w_{NO} = 7,75 \cdot 10^{12} \rho^{3/2}\, T^{-0,0675} \exp\left(-\frac{67\,915}{T}\right) \sqrt{Y_{O_2}} Y_{N_2}$$

- **MAX** w_{NO} **FOR** $\varphi \sim 0,8$ **(HIGH** T**, RELATIVELY HIGH** Y_{O_2}**)**
- **BUT** $Y_O \gg Y_{O,eq} \rightarrow$ **(*) MUCH MORE ACCURATE**

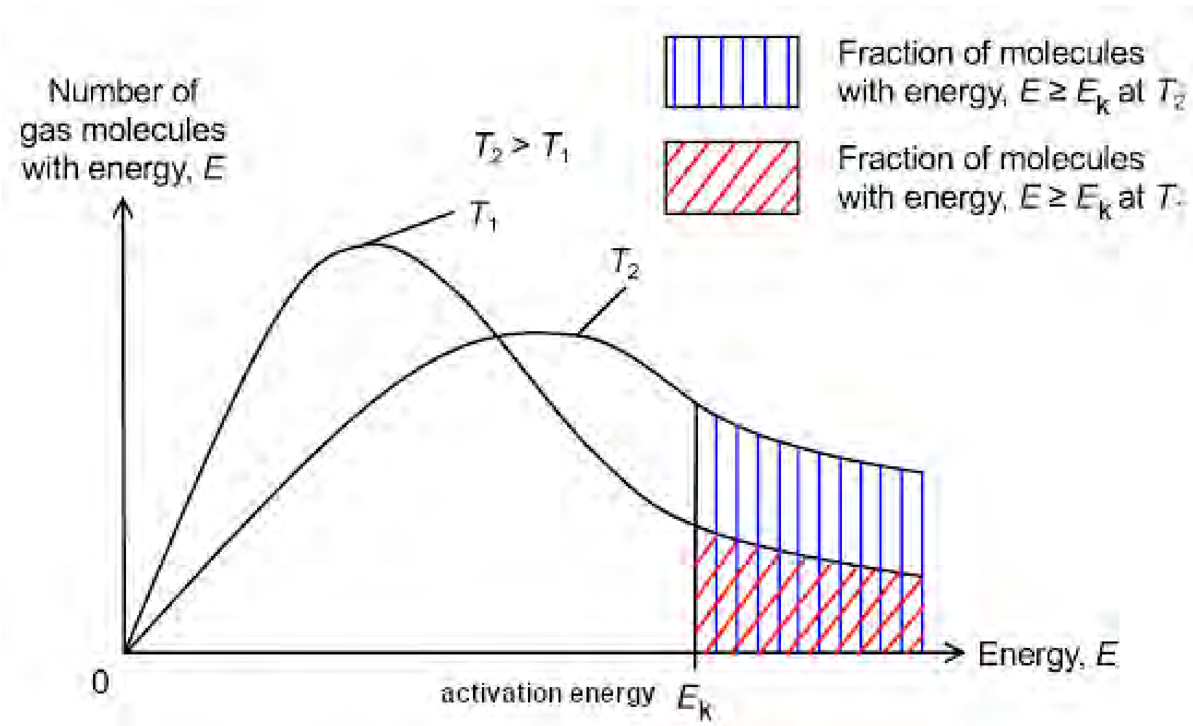
4.6.10 MAXWELL–BOLTZMANN ENERGY DISTRIBUTION AND ACTIVATION ENERGY

IF ACTIVATION ENERGY OF REACTION *VERY* HIGH

→ ONLY A *SMALL* FRACTION OF THE MOLECULES HAVE ENOUGH ENERGY TO TRIGGER REACTION

→ REACTION VERY *SLOW* (w_{NO} SMALL)

- **HOWEVER, FRACTION INCREASES WITH T**



4.6.11 EFFECT OF TEMPERATURE

0. $N_2 + M \rightleftharpoons 2\,N + M$ $\quad T_k = E_k/\mathcal{R} = 114\,000$ K

1. $N_2 + O \rightleftharpoons NO + N$ $\quad T_k = 38\,370$ K

2. $N + O_2 \rightleftharpoons NO + O$ $\quad T_k = 3\,500$ K

3. $N + OH \rightleftharpoons NO + H$ $\quad T_k = 69$ K

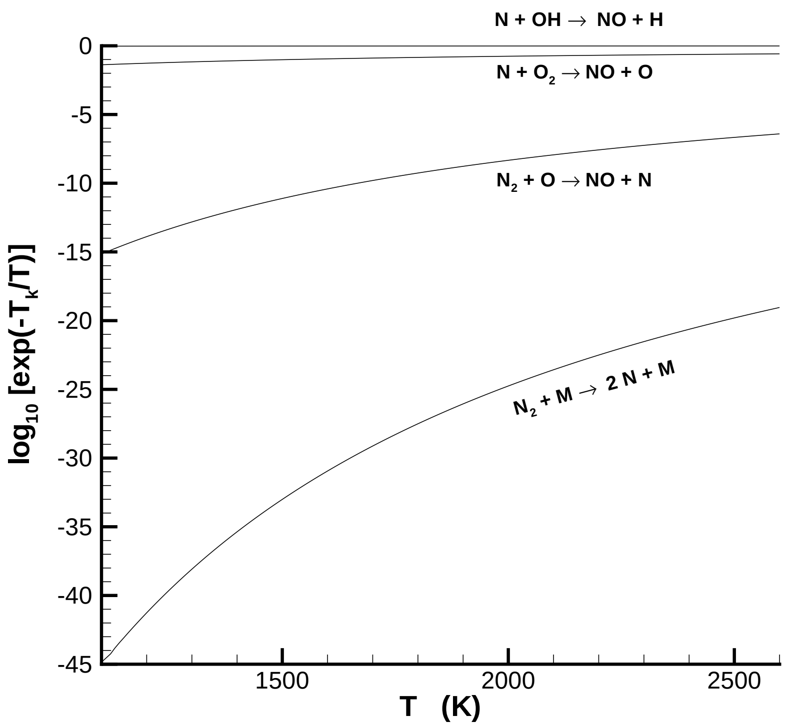


Figure 91: Effect of temperature on reactions potentially involved in Zel'dovich's mechanism.

4.6.12 GROWTH OF THERMAL NO

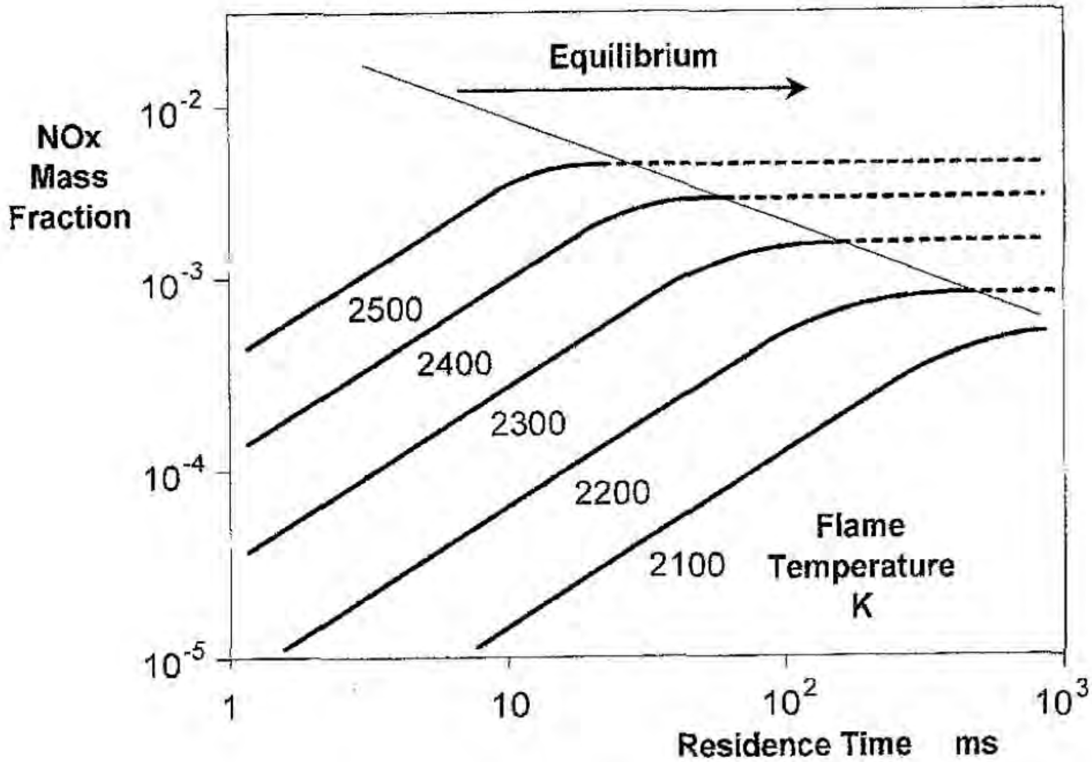


Figure 92: Growth of thermal NO concentration in products, as a function of residence time.

4.6.13 COMPARISON OF THERMAL NO EQUILIBRIUM/FINITE RATE

- **PRODUCTION RATE USUALLY $\ll$ EQUILIBRIUM**
- **NO CONCENTRATION 'FROZEN' AS T GOES DOWN (DUE TO SLOW CHEMISTRY)**

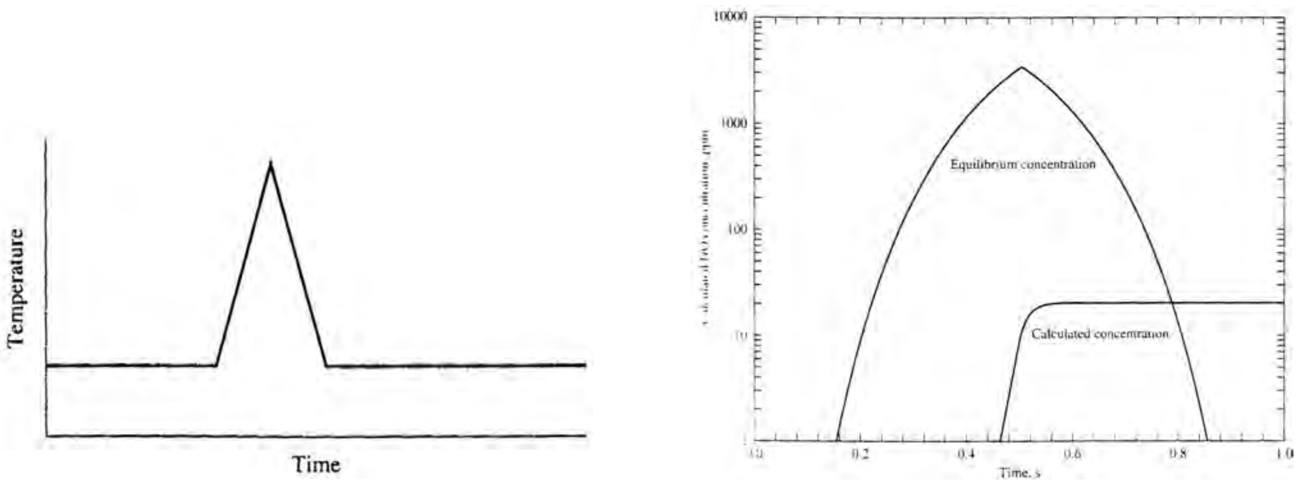
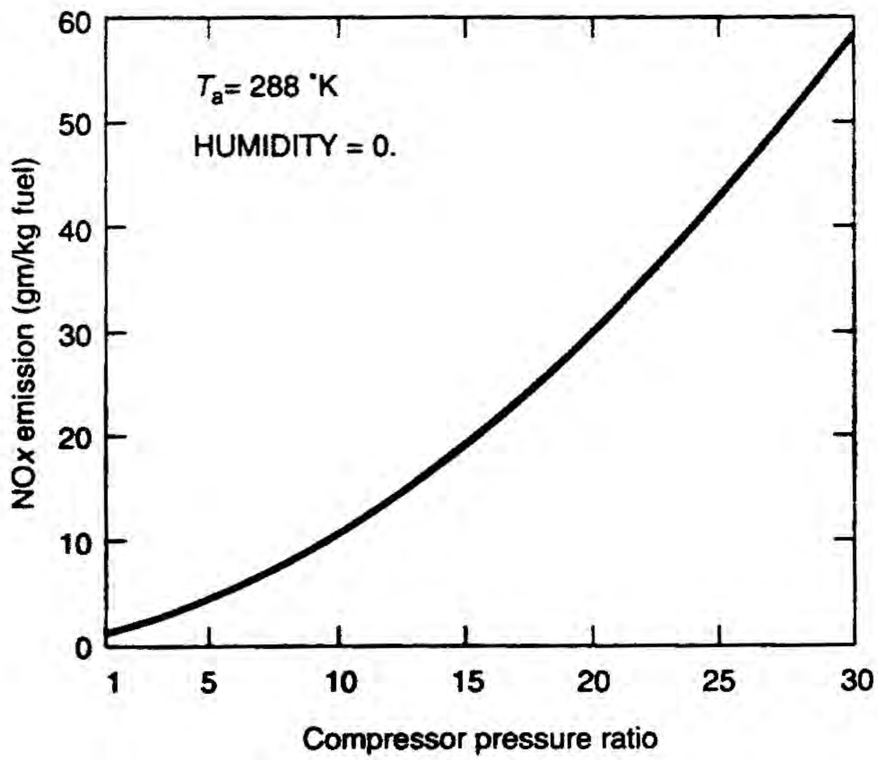


Figure 93: (left) Assumed temperature variation in time; (right) concentrations of NO computed in equilibrium and under finite–rate chemistry.

4.6.14 EFFECT OF PRESSURE



- **YET, APPROACH OF LIMITING p NOT FEASIBLE (~ SOOT)**

4.6.15 PROMPT MECHANISM (FENIMORE)

- **IMPLIES FORMATION OF HYDROGEN CYANIDE HCN**
- **IMPORTANT IN ALL HYDROCARBONS**
- **RELATIVELY FAST (NO FORMED IN FLAME ZONE)**

... $C_nH_m \rightleftharpoons CH_x$

4. $N_2 + CH_x \rightleftharpoons HCN + N + \cdots$

2. $N + O_2 \rightleftharpoons NO + O$

3. $N + OH \rightleftharpoons NO + H$

5. $N_2 + C_2 \rightleftharpoons CN + CN$

6. $N_2 + CH_2 \rightleftharpoons HCN + NH$

7. $HCN + O_2 \rightleftharpoons NO + \cdots$

...

- **ACTIVE IN RICH REGIONS**
- **IMPORTANT WHEN THERMAL IS DEPRESSED**
- **CONTRIBUTION DECREASES AS p RISES**

→ **RELATIVELY UNIMPORTANT IN GAS TURBINES**

4.6.16 FUEL–N MECHANISM

- **NITROGEN BOUND IN THE FORM OF NH_2, NH_3**
- **GASOLINE AND KEROSENE CONTAIN $<$ 0,05% BOUND NITROGEN**
- **HEAVY FUEL OIL FROM 0,5 UP TO A 1,8%**
- **COAL UP TO 2%**
- **IMPLIES FORMATION FROM HCN AND NH_3**

7. $HCN + O_2 \rightleftharpoons NO + \cdots$
8. $NH_3 + O_2 \rightleftharpoons NO + \cdots$

- **IN COMPETITION WITH**

9. $HCN + NO \rightleftharpoons N_2 + \cdots$
10. $NH_3 + NO_2 \rightleftharpoons N_2 + \cdots$

- **FASTER THAN THERMAL MECHANISM**
- **TIPICALLY FROM 20% TO 50% OF FUEL–N CONVERTED TO NO**
- **UNIMPORTANT IN AERO GAS TURBINES**

4.6.17 N_2O MECHANISM

11. $N_2O + M \rightleftharpoons N_2 + O + M$

12. $N_2O + O \rightleftharpoons NO + NO$

13. $N_2O + H \rightleftharpoons NO + NH$

14. $N_2O + H \rightleftharpoons N_2 + OH$

15. $N_2O + O \rightleftharpoons N_2 + O_2$

16. $N_2O + OH \rightleftharpoons N_2 + HO_2$

17. $N_2O + OH \rightleftharpoons NH + NO_2$

18. $N_2O + OH \rightleftharpoons NO + HNO$

19. $N_2O + H_2O \rightleftharpoons NH_2 + NO_2$

20. $N_2O + H_2O \rightleftharpoons HNO + HNO$

21. $N_2O + CO \rightleftharpoons NCO + NO$

- **N_2O PRODUCTION VIA REVERSE STEPS OF 11, 14–16**
- **CONVERSION TO NO VIA FORWARD STEPS OF 12, 13, 18, 21**
- **BOUND NITROGEN (NH_2, NH_3) DECOMPOSED IN NH, CONVERTED TO N_2O VIA REVERSE STEPS OF 13, 17, 19**
- **CONTRIBUTION INCREASES WITH p**
- **N_2O GHG, ODG**

4.6.18 COAL COMBUSTION

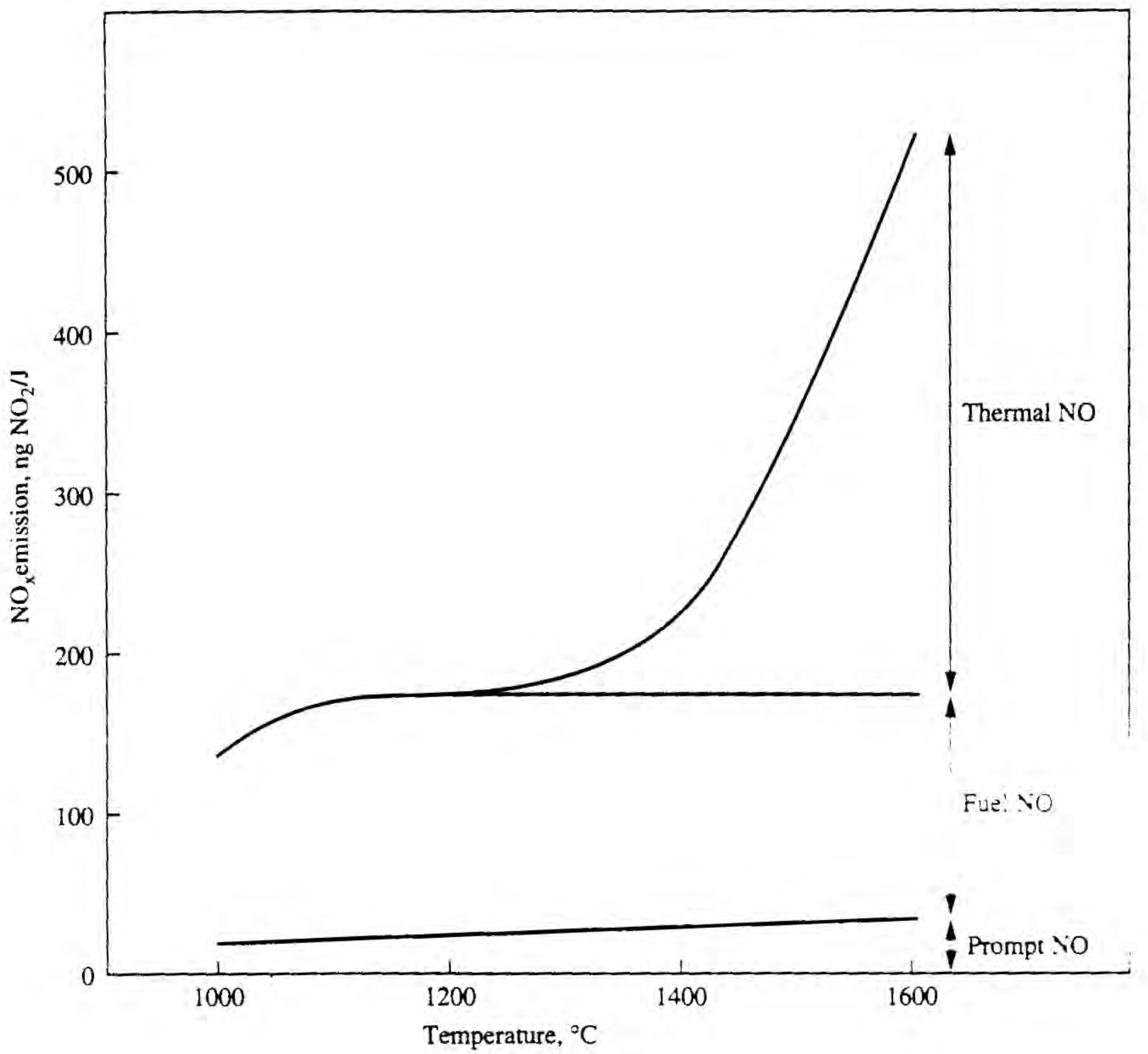


Figure 94: Contribution of the different mechanisms to NO formation, as a function of temperature.

4.6.19 COMBUSTION IN GAS TURBINES

- **THERMAL MECHANISM DOMINATING (HIGH T)**
- ***PROMPT* MECHANISM RELATIV. UNIMPORTANT**
- **N_2O MECHANISM $\sim$ 10 – 15 %**

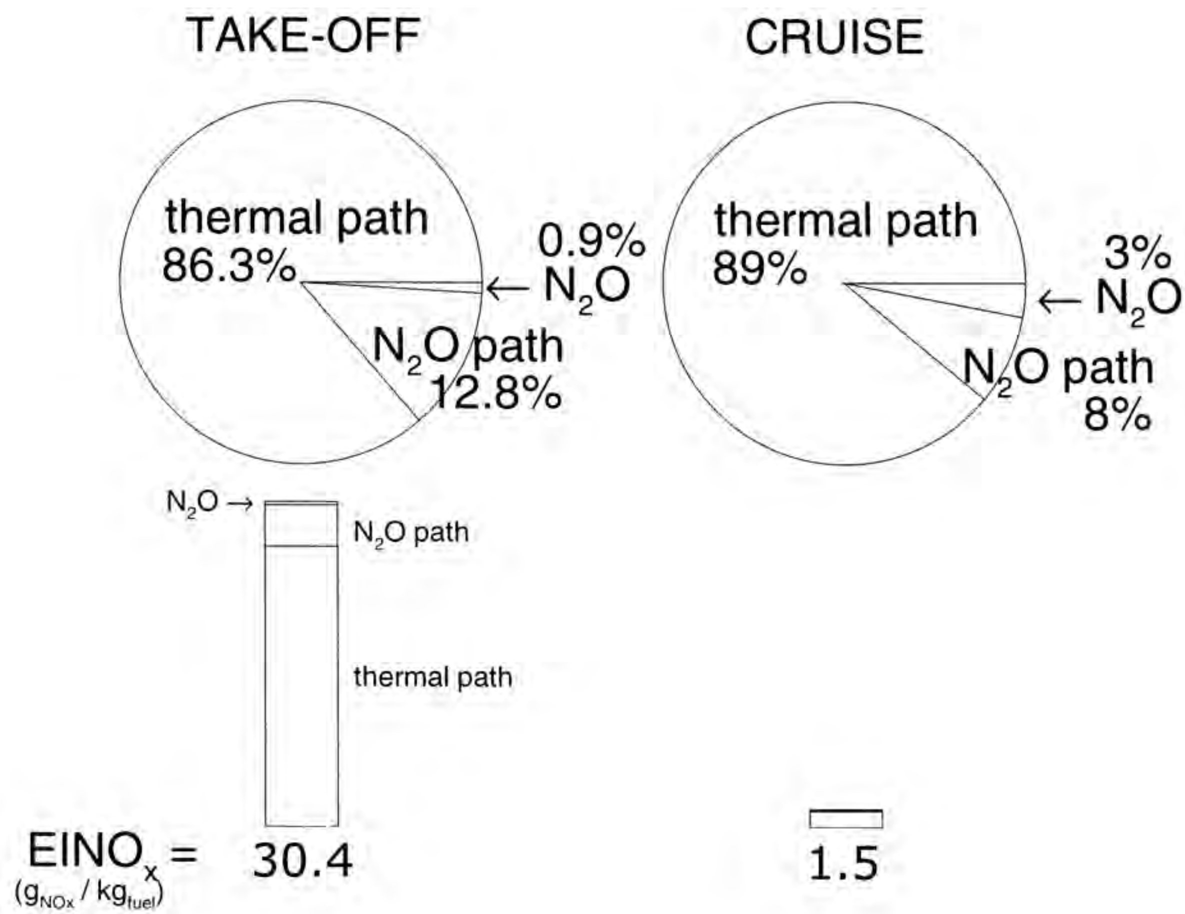


Figure 95: Contribution of different mechanisms to NO_x formation in an aeroengine, under take–off and cruise conditions.

4.6.20 CONTROL OF NO_x EMISSIONS

1. **FORMATION PREVENTION (BY ACTING ON COMBUSTION PROCESS)**
2. **EXHAUST GAS TREATMENT (IN GROUND PLANTS)**
   - **SCRUBBING HAMPERED BY EXTREMELY LOW SOLUBILITY**

4.6.21 TAKING ACTION ON COMBUSTION PROCESS

- **REDUCE T, t_s, TIME–AT–TEMPERATURE, X_{O_2}**
- **TWO–STAGE COMBUSTION (REBURNING)**
- **(FLUE GAS RECIRCULATION – FGR)**
- **(USE PURE O_2 AS OXIDIZER)**
- **NO_x REDUCTION GENERALLY IMPLIES INCREASE OF CO AND UHC**

4.7.1 CARBON MONOXIDE (CO)

- **MOSTLY PRODUCED BY MOTOR VEHICLES**
- **MAXIMUM CONCENTRATION IN TOWN**
- **NEAR AIRPORTS, 50% TO 80% EMITTED BY AIRCRAFTS (REST BY VEHICLE TRAFFIC)**
- **CO $\leftrightharpoons$ UNBURNT FUEL**

4.7.2 CO CHEMISTRY

- **OXIDATION OF HC CARBON TO CO FAST**
- **OXIDATION OF CO TO CO_2:**

  $CO + OH \rightleftharpoons CO_2 + H$
  (RELATIVELY SLOW AT LOW T BECAUSE, DESPITE VERY LOW T_k, CONCENTRATION [OH] STRONGLY DEPENDANT UPON T)
- **STRONG CORRELATION WITH EMISSIONS OF UNBURNT HYDROCARBONS (UHC)**

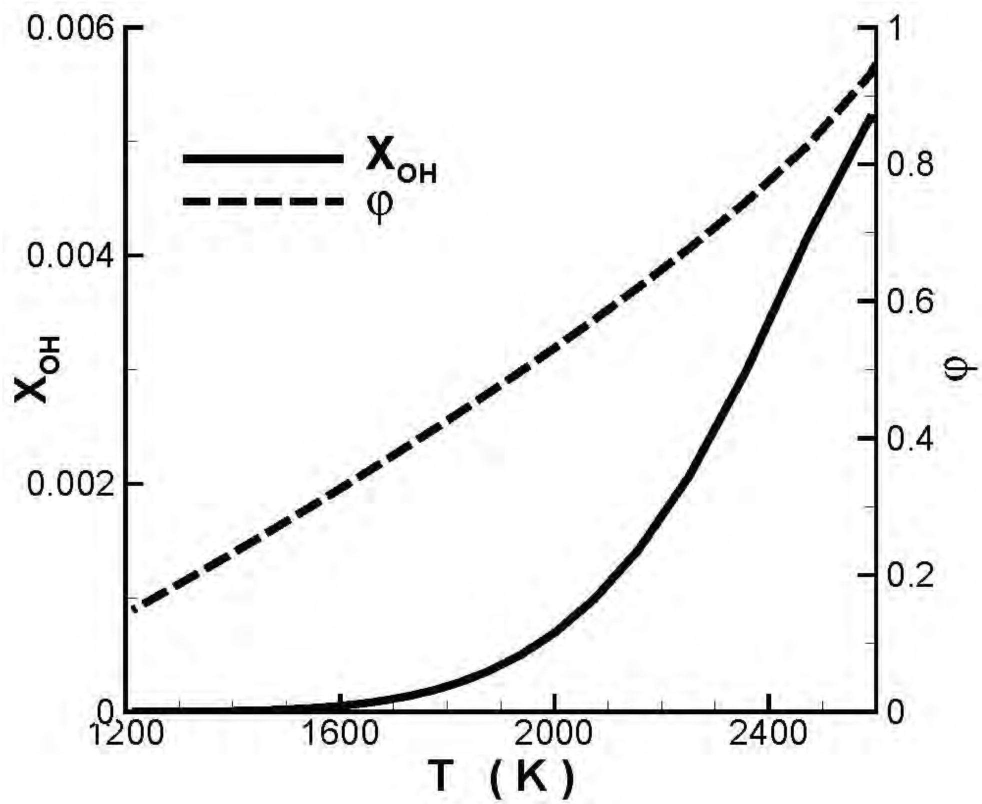


Figure 96: OH *equilibrium* concentration *vs.* temperature, and associated equivalence ratio, for a kerosene/air reacting mixture at $p = 3$ MPa, $T_{air} = 850$ K, $T_f = 298.15$ K.

4.7.3 CO EMISSIONS FROM GAS TURBINE COMBUSTORS EFFECT OF φ

- **MINIMUM FOR $\varphi \sim 0,8$**

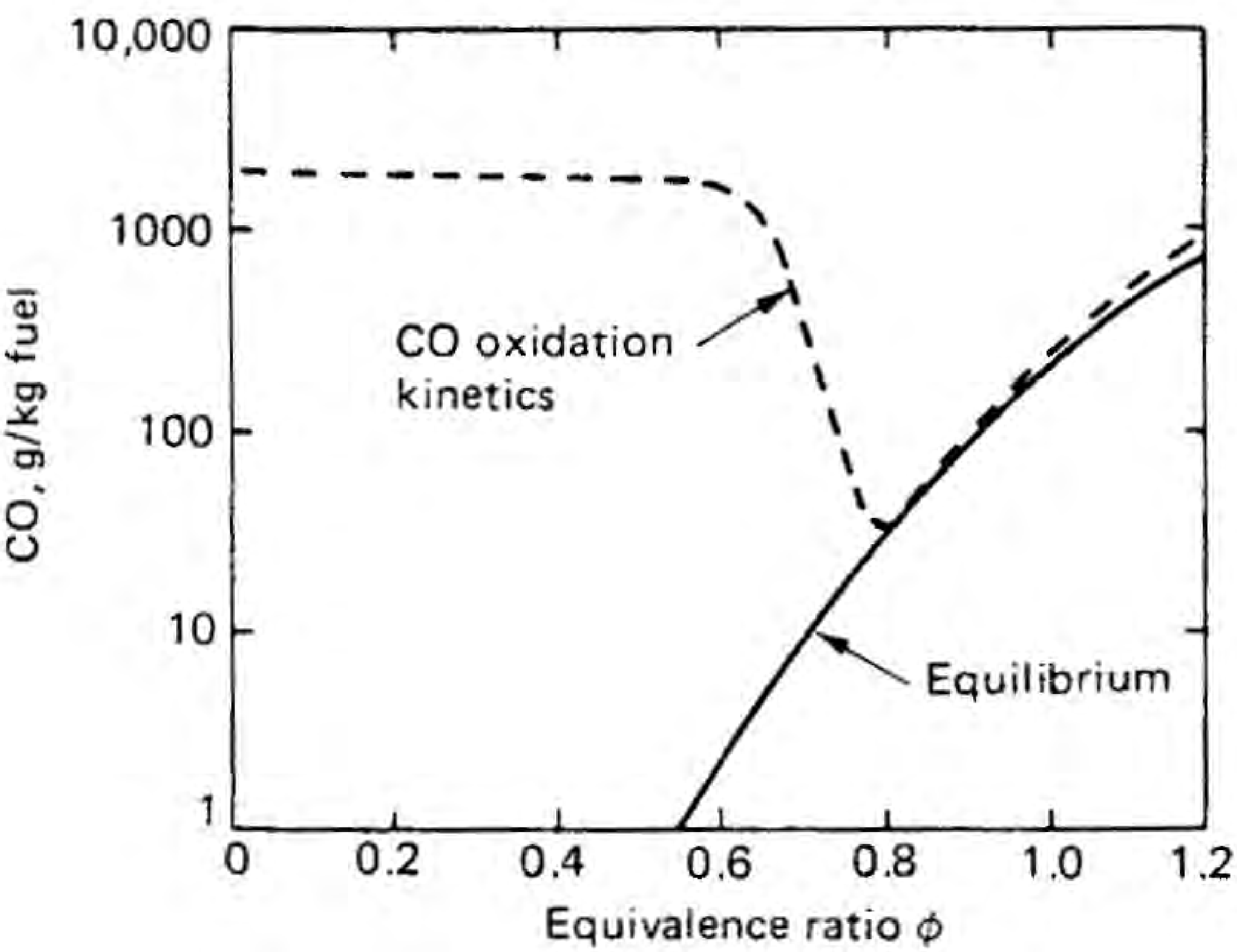


Figure 97: Typical trend of CO concentration as a function of equivalence ratio, under the assumption of either equilibrium or finite–rate chemistry.

4.7.4 CORRELATION BETWEEN CO AND UHC EMISSIONS FROM GAS TURBINE COMBUSTORS

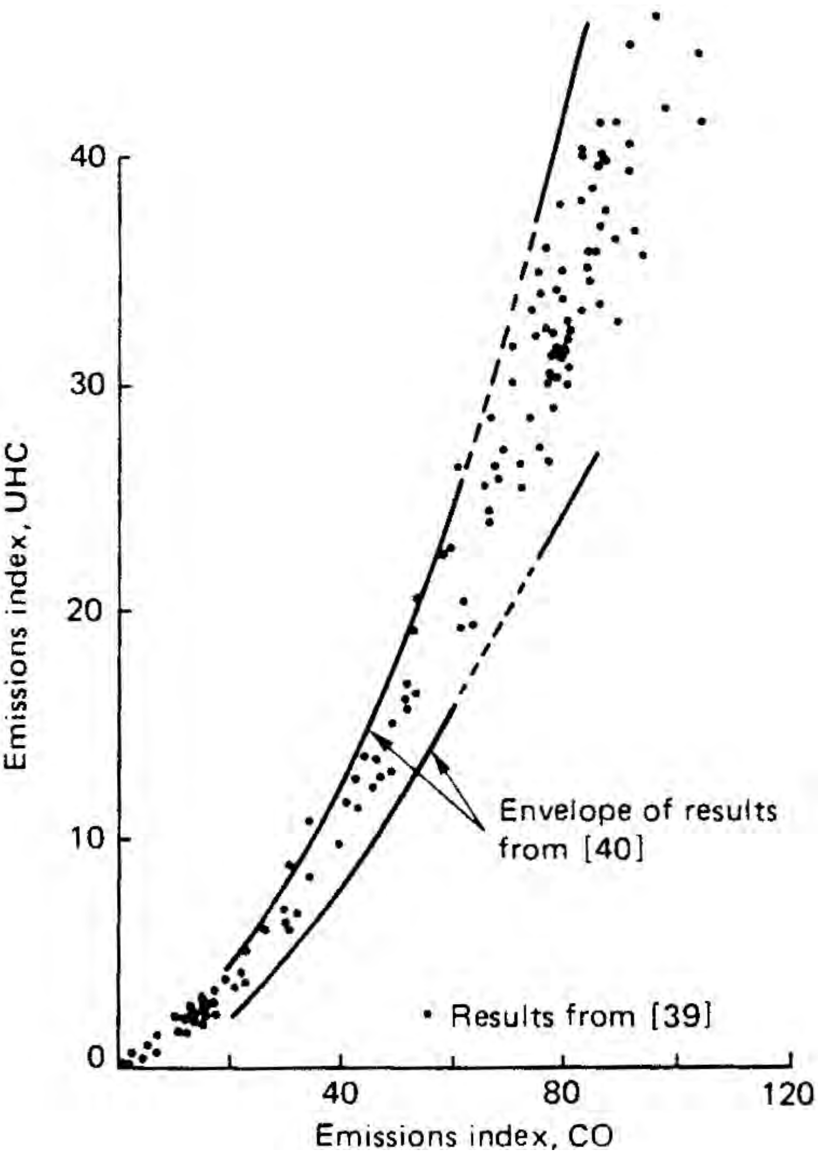


Figure 98: Correlation between CO and UHC emissions.

4.7.5 CORRELATION BETWEEN CO/UHC EMISSIONS AND COMBUSTION EFFICIENCY FOR GAS TURBINES

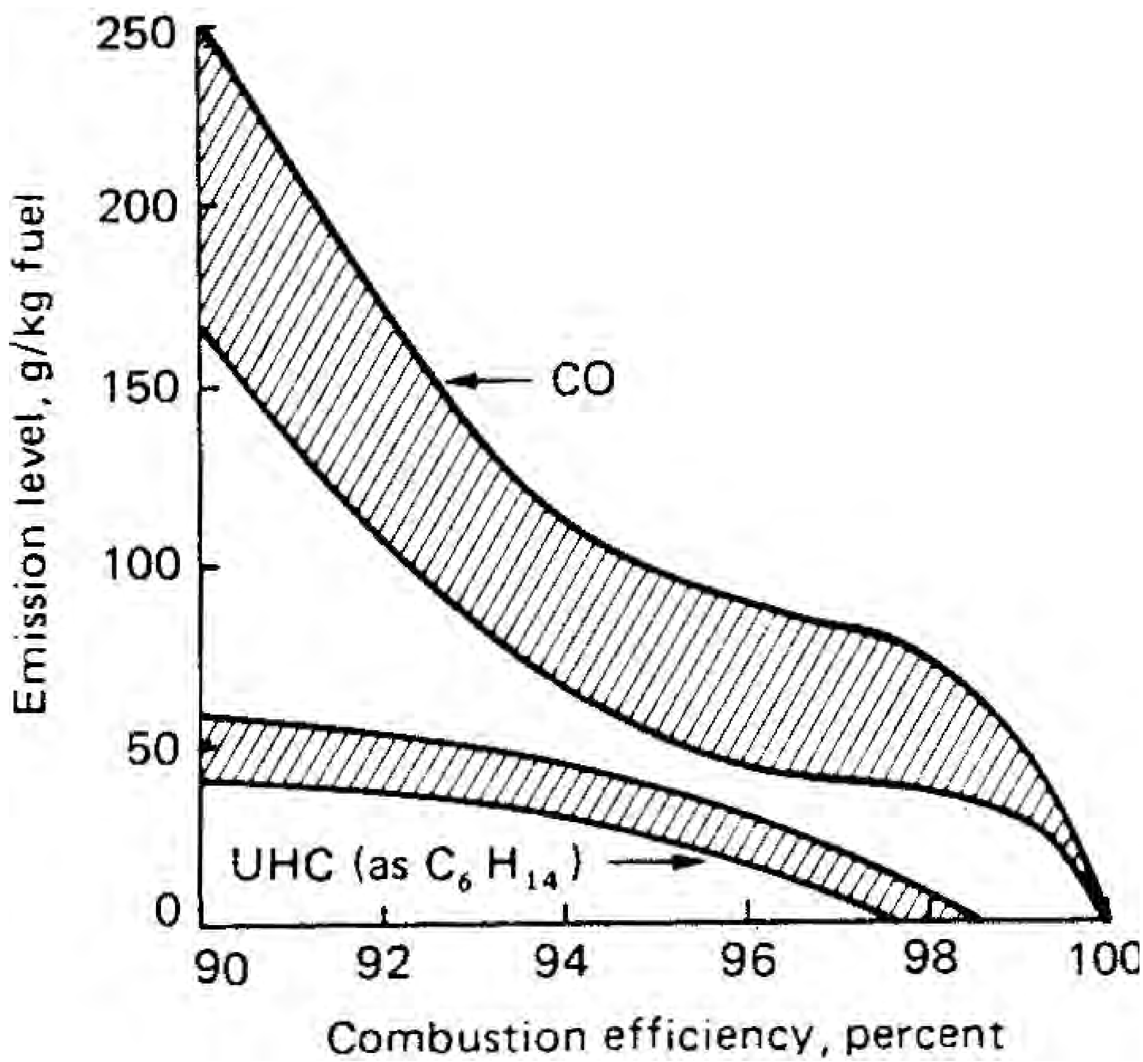


Figure 99: Correlations between CO/UHC emissions and combustion efficiency.

4.7.6 EFFECT OF p ON EMISSIONS FROM GAS TURBINE COMBUSTORS

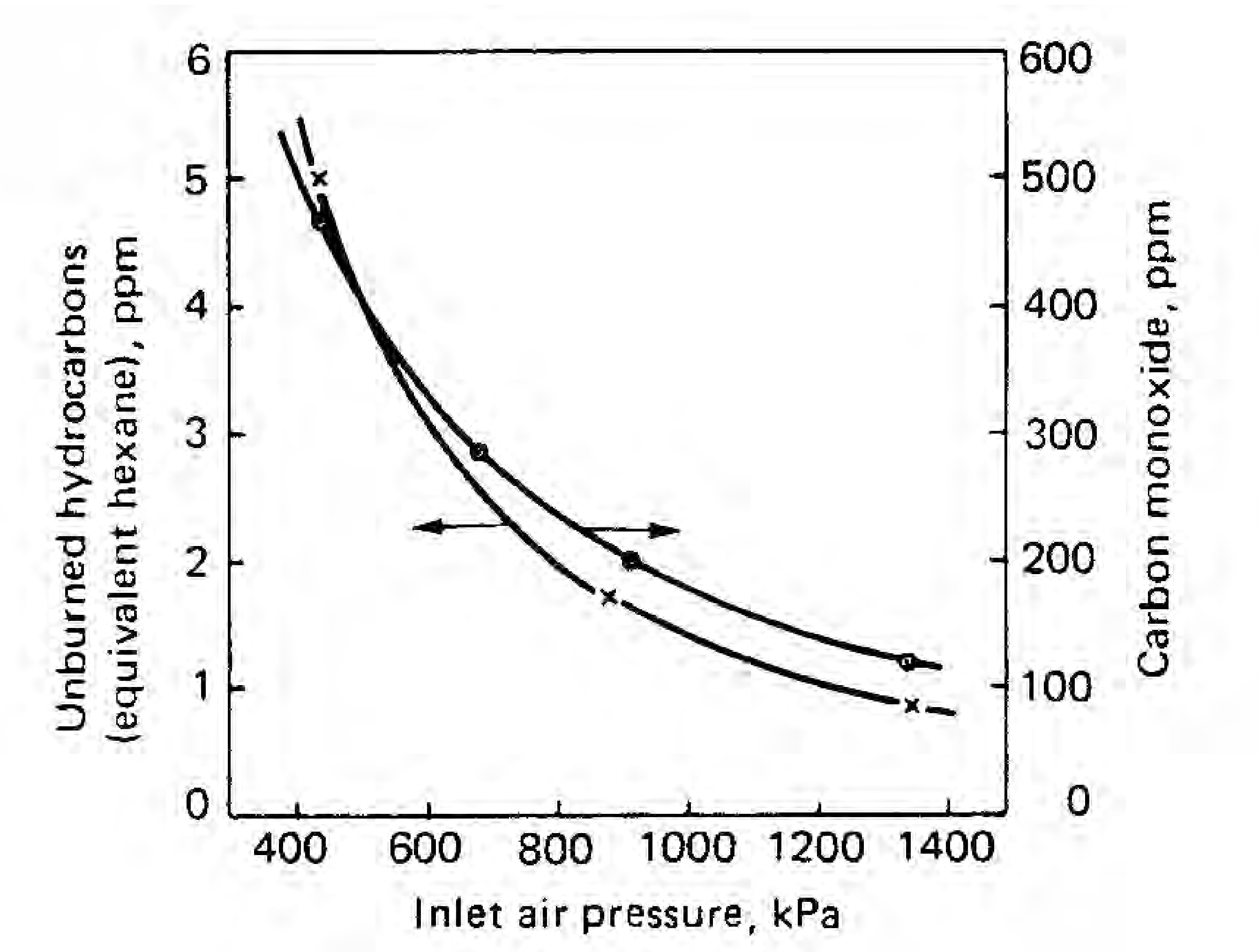


Figure 100: Effect of pressure on UHC/CO emissions from a gas turbine.

4.8.1 INTERRELATION AMONG EMISSIONS OF CO, UHC AND NO_x

- **CONTAINING NO_x EMISSIONS DICTATES MODERATE T, OXYGEN SHORTAGE, SHORT RESIDENCE TIMES**
- **CO OXIDATION TO CO_2 REQUIRES HIGH T, ABUNDANT OXYGEN, LONG RESIDENCE TIMES**
- **REDUCTION OF UHC EMISSIONS FOLLOWS SAME LINES AS CO**

$\Longrightarrow$ **CONFLICT**

4.8.2 CO AND NO_x EMISSIONS FROM RECIPROCATING ENGINES

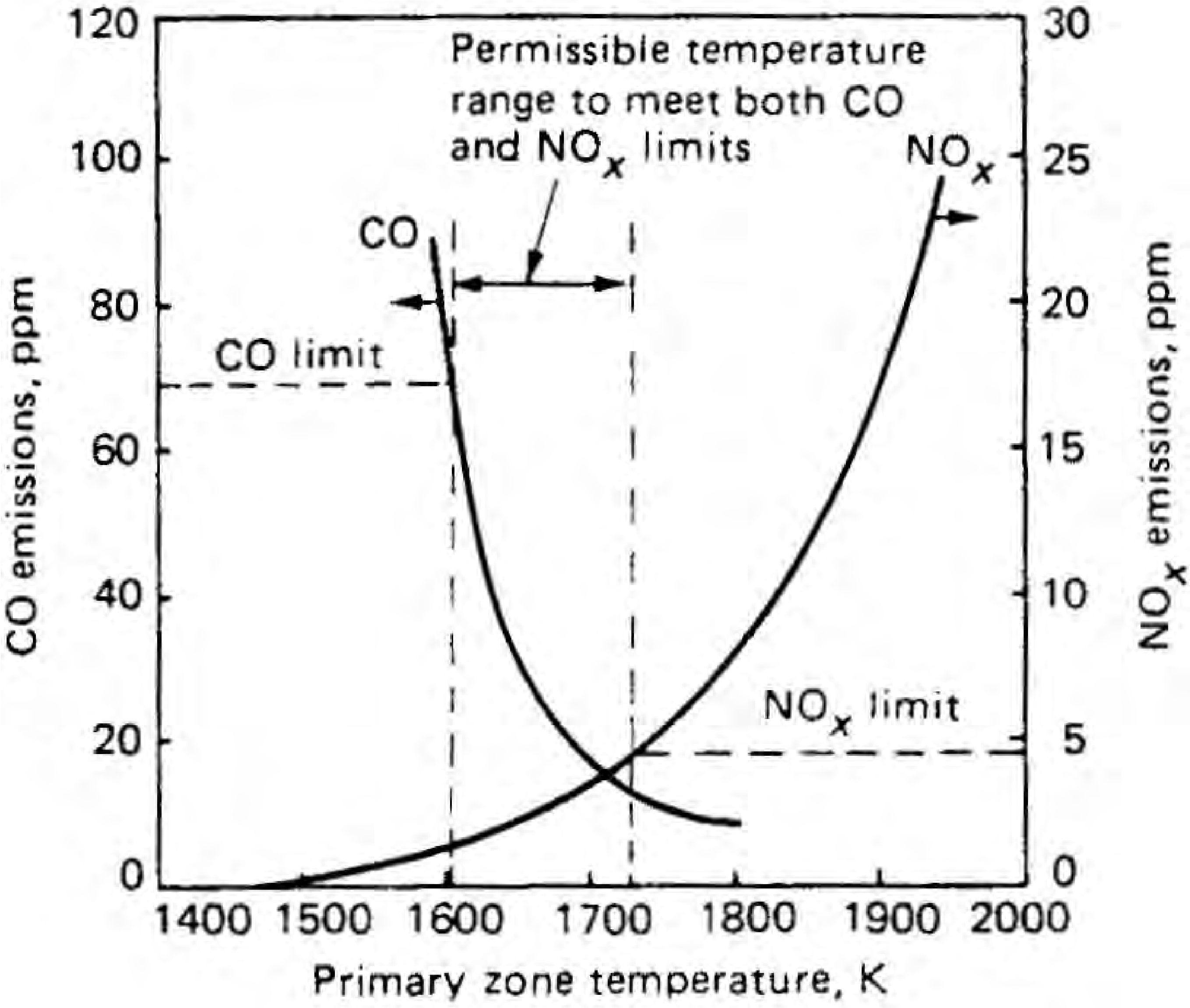


Figure 101: NO_x and CO emission indices of a reciprocating engine, as a function of temperature.

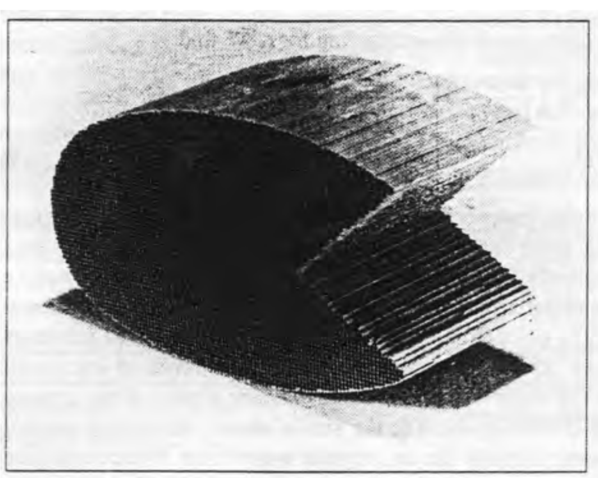
- **OPERATE IN A NARROW TEMPERATURE RANGE IN ORDER TO OBTAIN ACCEPTABLE EMISSIONS OF BOTH CO AND NO_x**

4.8.3 REDUCTION OF EMISSIONS FROM RECIPROCATING ENGINES

- **CHAMBERS $\sim$ SPHERICAL TO REDUCE EXTENSION OF LOW T ZONES**
- **ACCELERATED WARMUP (MOST PART EMISSIONS RELEASED AT START–UP$\rightarrow$ 1 – 2 min WARMING UP)**
- **CATALYTIC MUFFLERS**

4.8.4 CATALYTIC MUFFLER

- **$NO + CO + HC \rightarrow N_2 + CO_2 + H_2O$**
- **CATALYST Pt, Pd, Rh**
- ***A/F* CONTROLLED ON THE BASIS OF EXHAUST GAS OXYGEN CONTENT**



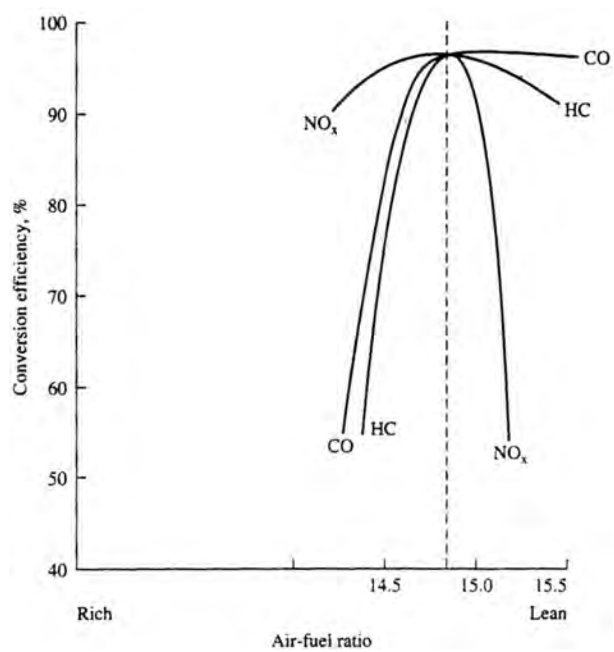


Figure 102: (left) Honeycomb structure of catalyst support; (right) conversion efficiencies as a function of A/F ratio.

4.8.5 CO AND NO_x EMISSIONS FROM GAS TURBINES

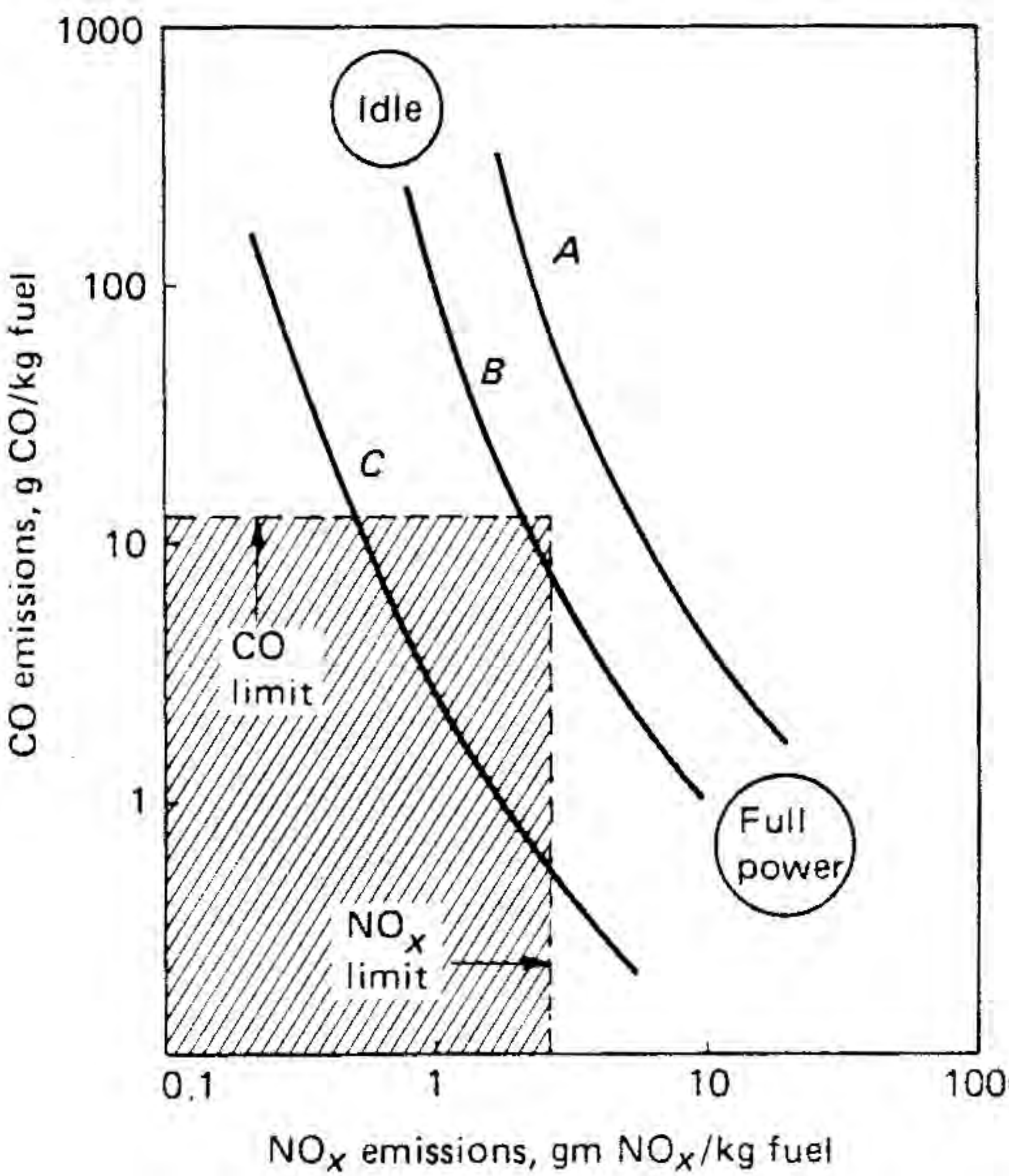


Figure 103: Emission indices of CO and NO_x from gas turbines for different operating conditions.

- **IDLE: LOW T → LOW EINO$_x$, HIGH EICO**
- **TAKE–OFF: HIGH T → HIGH EINO$_x$, LOW EICO**
- **CRUISE: INTERMEDIATE CONDITIONS**

4.8.6 CO, NO_x, UHC, SOOT EMISSIONS FROM GAS TURBINES

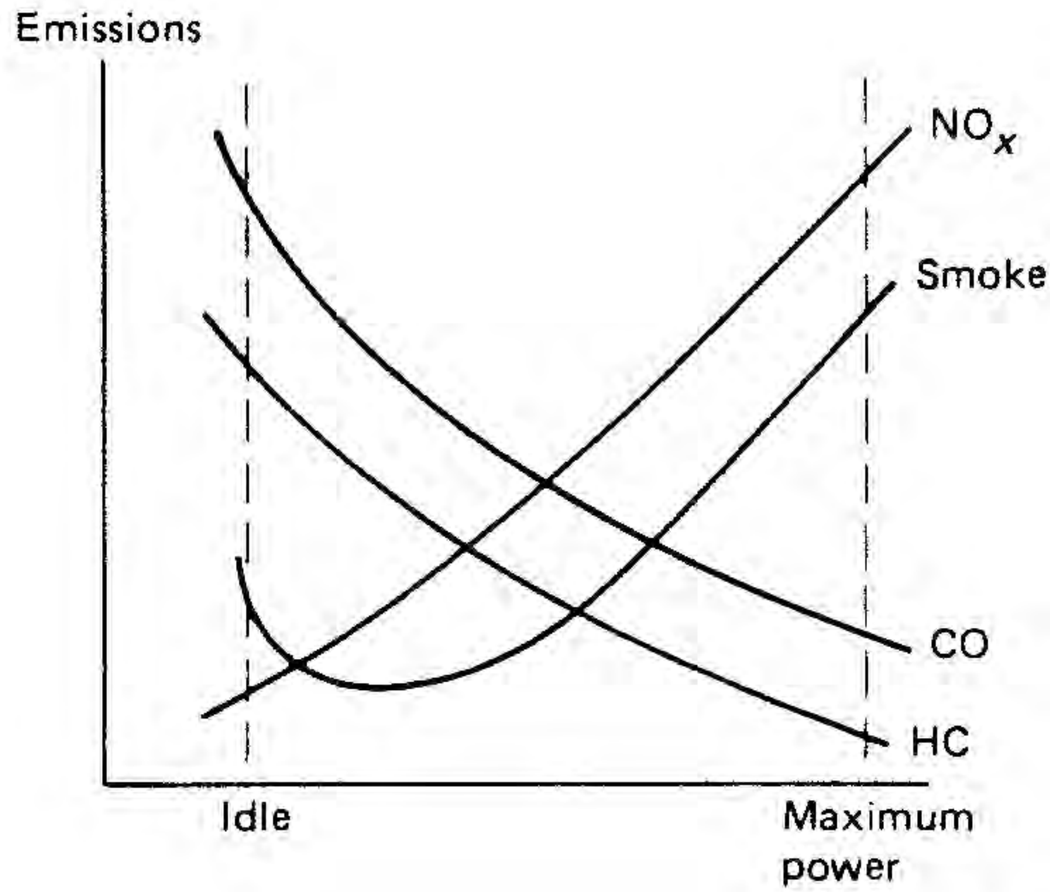


Figure 104: CO, UHC, NO_x and soot emissions from gas turbines for different operating conditions.

- **IDLE: LOW T → LOW $EINO_x$, HIGH EICO, EIUHC; LOW φ → LITTLE SOOT**
- **TAKE–OFF: HIGH T, HIGH $EINO_x$, LOW EICO, EIUHC; HIGH φ → MUCH SOOT**
- **CRUISE: INTERMEDIATE; RELATIVELY HIGH T, RELATIVELY LOW φ → VERY LITTLE SOOT**

4.8.7 REDUCTION OF EMISSIONS FROM GAS TURBINES

- (CATALYTIC DEVICE CANNOT BE USED DUE TO PRESSURE DROP, WEIGHT, SIZE)
- WALL CHAMBERS COOLED BY AIRFLOW
- TRY AND CONTAIN RATIO WALL AREA/CHAMBER VOLUME
- ANNULAR COMBUSTORS GIVE LOWER EMISSIONS AS COMPARED TO CAN COMBUSTORS (BUT MORE EXPENSIVE)
- MINIMIZE COOLING AIR FLOW RATE → TRANSPIRATION COOLING

4.8.8 STAGING

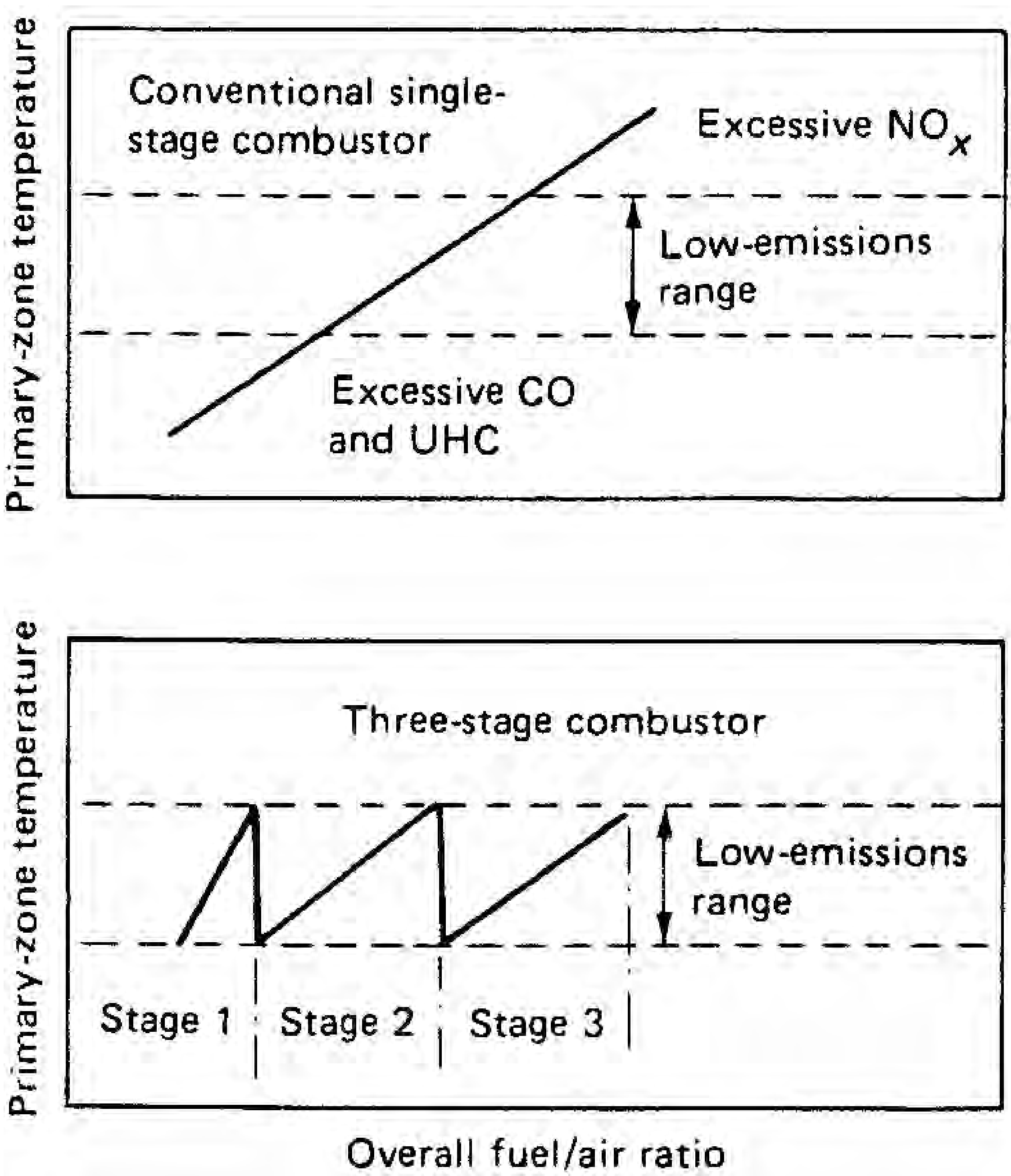


Figure 105: (top) Conventional combustor; (bottom) staged combustor.

4.8.9 φ CONTROL

- φ **DETERMINES EMISSIONS**
- **PREMIXED COMBUSTION IN PRINCIPLE ALLOWS RESTRICTING COMBUSTION TO VERY NARROW φ RANGE → LOWER EMISSIONS**
- **BUT PRESENCE PILOT FLAME (*PARTIALLY* PREMIXED COMBUSTION) REDUCES GAIN**
- **EVEN IF NOMINAL φ CHOSEN SO AS TO MINIMIZE EMISSIONS, DEPARTURES FROM IT CAN GIVE RISE TO STRONG INCREASE EMISSIONS**
- **DEPARTURES DUE TO:**
  - **INHOMOGENEITIES (→ IMPROVE ATOMIZATION AND MIXING)**
  - **TURBULENCE (NEEDED TO ACTIVATE MIXING...)**
- φ **ANYWAY SPANS FROM $\sim$ 1 IN PRIMARY ZONE, TO ABOUT $\sim$ 0,2 – 0,3 AT EXIT**

→ **SEARCH FOR A COMPROMISE SOLUTION, ENABLING TO GLOBALLY MINIMIZE EMISSIONS**

4.8.10 LPP COMBUSTORS

- **LEAN PREMIX–PREVAPORIZER WITH $\varphi = 0{,}5 - 0{,}7$**

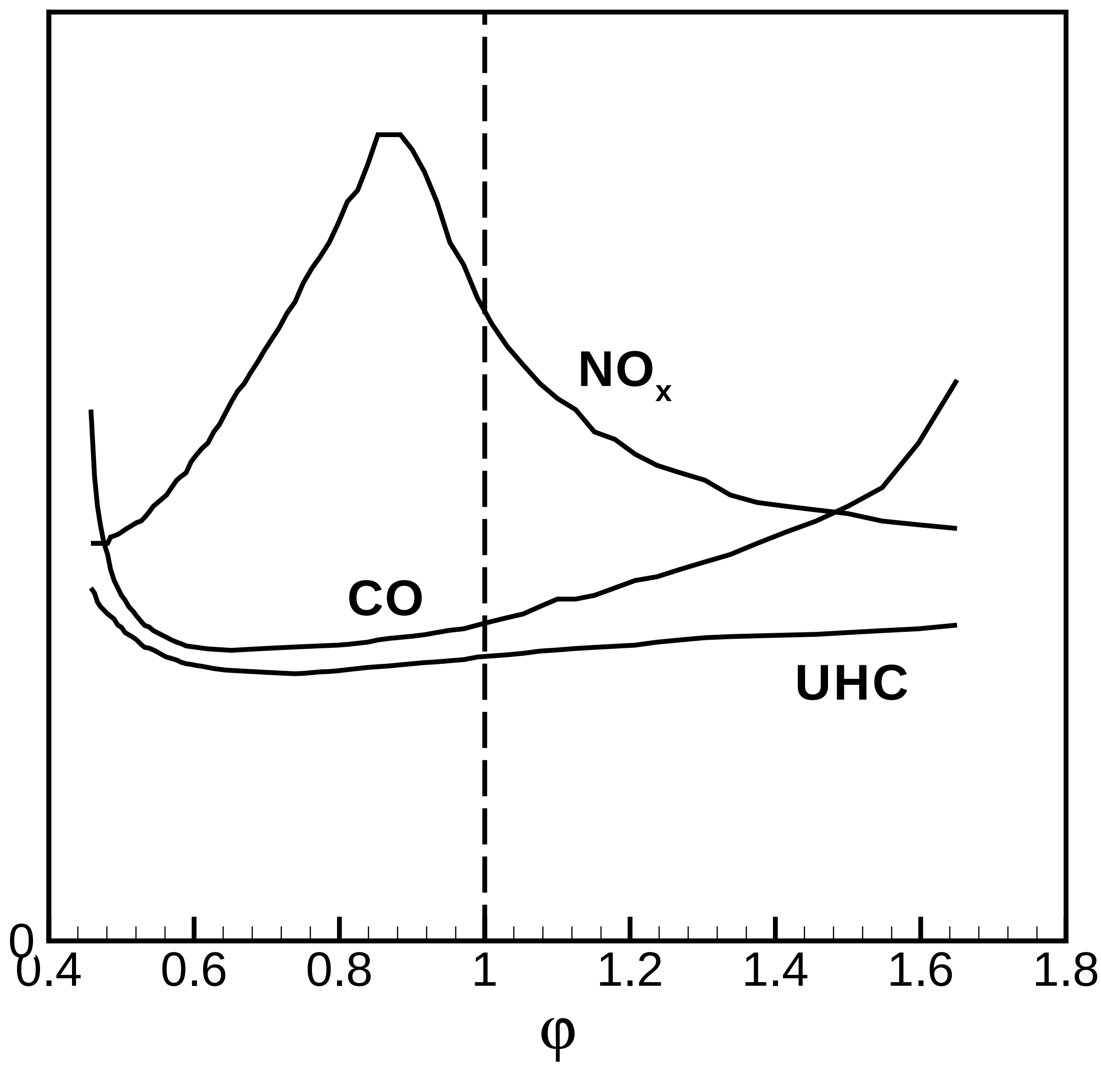


Figure 106: Emission levels of different pollutants from a turbogas combustor as a function of equivalence ratio.

4.8.11 RQL COMBUSTORS

- **RICH BURN, QUICK QUENCH, LEAN BURN**

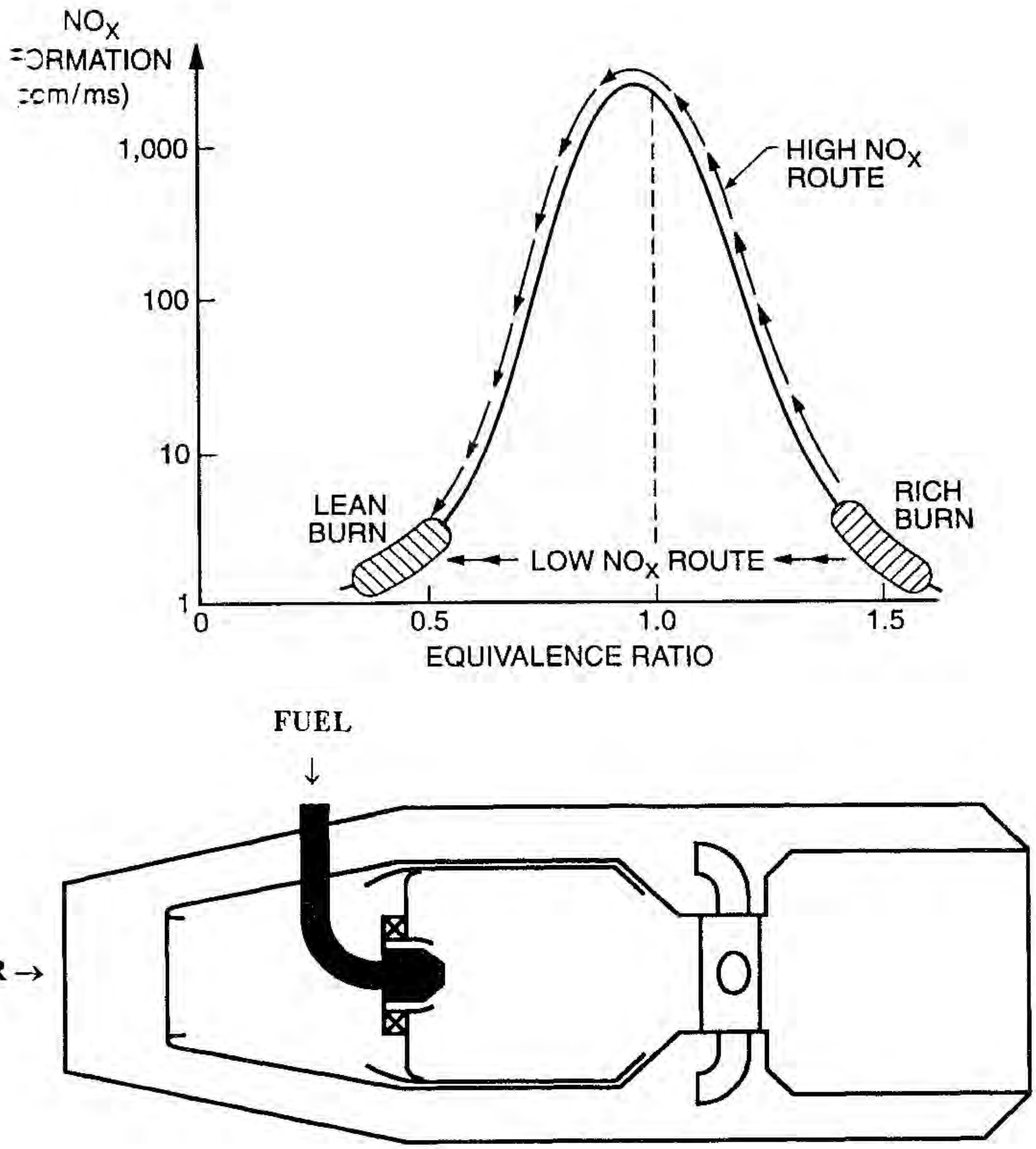


Figure 107: NO_x formation rate as a function of φ (top); RQL combustor (bottom).

5.1 ELEMENTS OF ACOUSTICS

- **SOUND: PERTURBATION CAUSING VARIATION OF p**
- $p = \overline{p} + p'$ **PRESSURE (MEAN + FLUCTUATION) [Pa]**
- $\sqrt{\overline{p'^2}}$ **ROOT MEAN SQUARE**
- W **EMITTED POWER [W]**
- $I = dW/dA$ **ACOUSTIC INTENSITY [W/m^2]**
- **VALUES OF $\sqrt{\overline{p'^2}}$, I, W CAN SPAN SEVERAL ORDERS OF MAGNITUDE**
  → LOGARITHMIC SCALE

5.2.1 PROPAGATION SPEED

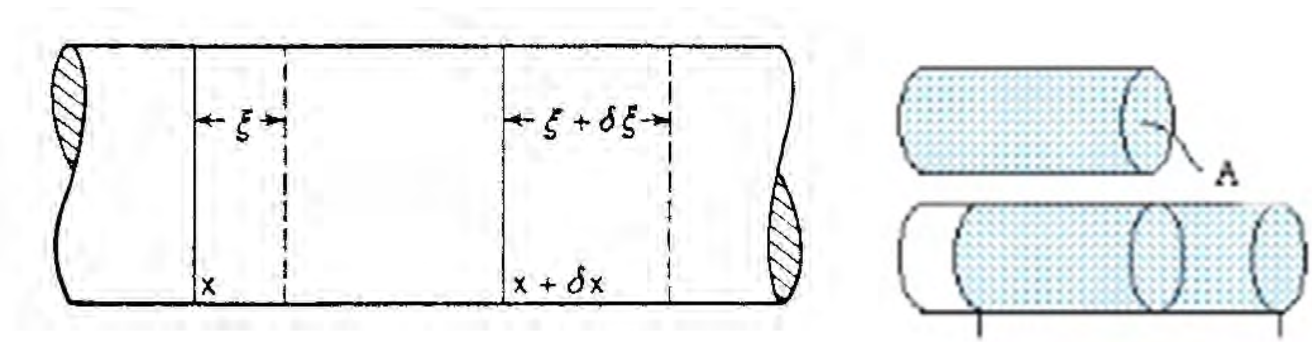


Figure 108: Displacements caused by a wave travelling in a duct (of unit area).

- **x ABSCISSA UNDISTURBED PARTICLE, ξ DISPLACEMENT DUE TO WAVE PASSAGE**

- **MASS CONSERVATION** $\rho_0\,\delta x = \rho\left(1 + \frac{\partial \xi}{\partial x}\right)\delta x$

- **CONDENSATION** $s = \frac{\rho - \rho_0}{\rho_0} \rightarrow \rho = \rho_0\,(1 + s)$

$$\rightarrow \rho_0\,\delta x = \rho_0\,(1 + s)\left(1 + \frac{\partial \xi}{\partial x}\right)\delta x$$

$$\rightarrow 1 = 1 + s + \frac{\partial \xi}{\partial x} + s\,\frac{\partial \xi}{\partial x}$$

5.2.2 AT FIRST ORDER [1]

[1] $$0 \simeq s + \frac{\partial \xi}{\partial x} \rightarrow s \simeq -\frac{\partial \xi}{\partial x}$$

- **ISENTROPIC:** $$p = p_0 \left(\frac{\rho}{\rho_0}\right)^\gamma = \frac{p_0}{\rho_0^\gamma} \left[\rho_0 (1+s)\right]^\gamma =$$

$$= p_0 (1+s)^\gamma = p_0 \left[1 + \gamma s + \frac{\gamma(\gamma-1)}{2} s^2 + \cdots\right]$$

$$\Longrightarrow p - p_0 = \gamma p_0 s \left[1 + \frac{\gamma - 1}{2} s + \cdots\right]$$

[1] $$p - p_0 = \gamma p_0 s \Longrightarrow \frac{p - p_0}{\gamma p_0} = s = -\frac{\partial \xi}{\partial x}$$

- **MOMENTUM EQ.:** $$-\frac{\partial p}{\partial x} \delta x = \rho_0 \delta x \frac{\partial^2 \xi}{\partial t^2}$$

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} = -\frac{\partial (p - p_0)}{\partial x} = -\frac{\partial}{\partial x} \left(-\gamma p_0 \frac{\partial \xi}{\partial x}\right) = \gamma p_0 \frac{\partial^2 \xi}{\partial x^2}$$

- $$\frac{\partial^2 \xi}{\partial t^2} = a_0^2 \frac{\partial^2 \xi}{\partial x^2}$$
- **SOLUTION** $\xi = \xi^+(x - a_0 t) + \xi^-(x + a_0 t)$

5.2.3 FIRST ORDER SOLUTION

- $\xi = \xi^{+}(x - a_0 t) + \xi^{-}(x + a_0 t)$
- **WAVE TRAVELLING AT SPEED** a_0
- **CAN BE EXPRESSED IN FOURIER'S SERIES:**

$$\xi = \sum_k \left\{ \xi^{+}_{max,k} \sin\left[k\,(x - a_0\,t)\right] + \xi^{-}_{max,k} \sin\left[k\,(x + a_0\,t)\right] \right\}$$

(PLUS SIMILAR TERMS IN cosine)

- **SAME FOR OTHER QUANTITIES, e.g.,**

$$p' = \sum_k \left\{ {p'}^{+}_{max,k} \sin\left[k\,(x - a_0\,t)\right] + {p'}^{-}_{max,k} \sin\left[k\,(x + a_0\,t)\right] \right\}$$

5.2.4 RELATIONSHIP BETWEEN I AND $\overline{p'^2}$

- v VELOCITY FLUID PARTICLE, ξ ITS DISPLACEMENT DUE TO PRESSURE WAVE
- WORK $dE = p'\, dA\, d\xi$

$$I = \frac{dE}{dA\, dt} = p' \frac{d\xi}{dt} = p'\, v$$

- FORCE ON AN INFINITESIMAL VOLUME DUE TO $\partial p'/\partial x$

$$\left.\begin{aligned} dF &= -\frac{\partial p'}{\partial x} dx\, dy\, dz = -\frac{\partial p'}{\partial x} dV \\ dF &= dm \frac{\partial v}{\partial t} = \rho\, dV \frac{\partial v}{\partial t} \end{aligned}\right\} \rightarrow -\frac{\partial p'}{\partial x} = \rho \frac{\partial v}{\partial t}$$

- p' FROM SOLUTION WAVE EQ.: SINGLE MODE $p' = p'_{max} \sin(x - a_0 t)$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p'}{\partial x} = -\frac{p'_{max}}{\rho} \cos(x - a_0 t)$$

$$v = \int \frac{\partial v}{\partial t} dt = -\frac{p'_{max}}{\rho} \int \cos(x - a_0 t)\, dt = \frac{p'_{max}}{\rho a_0} \sin(x - a_0 t)$$

$$\rightarrow I = \frac{p'^2_{max}}{\rho\, a_0} \cdot \overline{\sin^2(x - a_0 t)} = \frac{p'^2_{max}}{2\, \rho\, a_0} = \frac{p'^2_{rms}}{\rho\, a_0} = \frac{\overline{p'^2}}{\rho\, a_0}$$

5.2.5 SOUND LEVELS

- $L_W = 10 \log_{10}(W/W_{ref})$
- $L_I = 10 \log_{10}(I/I_{ref})$
- $L_p = 10 \log_{10}(\overline{p'^2}/p_{ref}^2) = 20 \log_{10}(\sqrt{\overline{p'^2}}/p_{ref})$
- MEASURED IN DECIBEL (dB)
- $W_{ref} = 10^{-12}$ W; $I_{ref} = 10^{-12}$ W/m^2; $p_{ref} = 20$ μPa
- VALUES I_{ref}, p_{ref} CORRESPOND TO WEAKEAST AUDIBLE SOUND LEVEL
- $I = \overline{p'^2}/(\rho\, a_0)$
- FOR $\rho = 1{,}225$ kg/m^3, $a_0 = 340$ m/s $\rightarrow I = \dfrac{\overline{p'^2}}{416}$

$$\overline{p'^2} = 416\, I$$

$$p_{ref} = \sqrt{416\, I_{ref}} \simeq 20\sqrt{10^{-12}} = 20\,\mu\text{Pa}$$

- THEN $L_I \simeq L_p$

5.2.6 SUPERIMPOSING SOUNDS

- $L_I = 10 \log_{10}(I/I_{ref})$
- $I = I_{ref} \cdot 10^{L_I/10}$
- $I = I_{ref} \cdot \sum_{j=1}^{J} 10^{L_{Ij}/10}$
- $L_I = 10 \cdot \log_{10} \sum_{j=1}^{J} 10^{L_{Ij}/10}$
- **DOUBLING THE INTENSITY...**
- $L_{2I} = 10 \log_{10} \left(2 \frac{I}{I_{ref}} \right) = 10 \log_{10} \left(\frac{I}{I_{ref}} \right) + 10 \log_{10}(2) =$

  $L_I + 10 \cdot 0,301 = L_I + 3,01 \text{ dB}$

→ **LOG SCALE: + 3 dB LEVEL**

- **LEVEL RESULTING FROM 2 NOISE SOURCES OF 50 dB EACH → 53 dB**

5.2.7 AUDIBLE FREQUENCIES

- **FROM ABOUT 20 TO 20000 Hz**

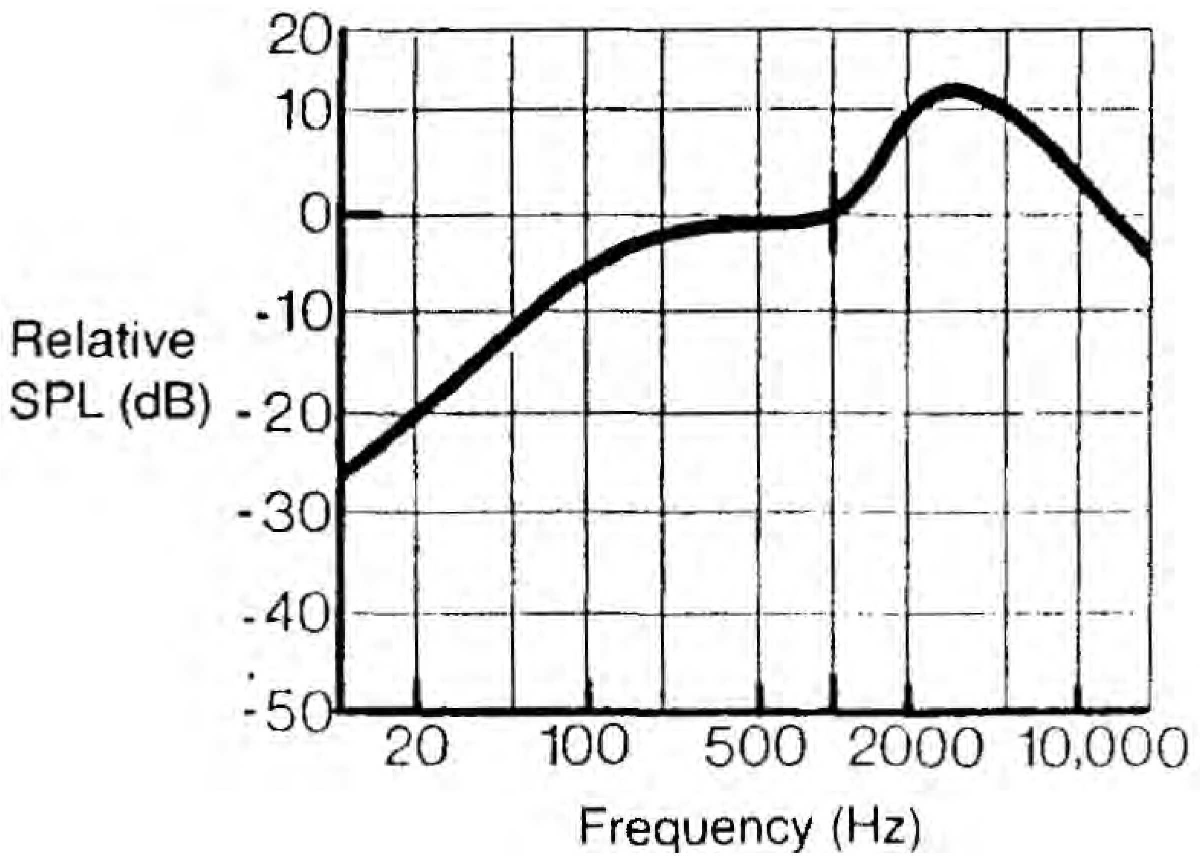


Figure 109: Frequency response of human ear (reference at 1 kHz).

5.2.8 OCTAVES

- **OCTAVE: RATIO** $f_{sup}/f_{inf} = 2$
- **1/3 OCTAVE: RATIO** $f_{sup}/f_{inf} = (2)^{1/3} = 1,26$

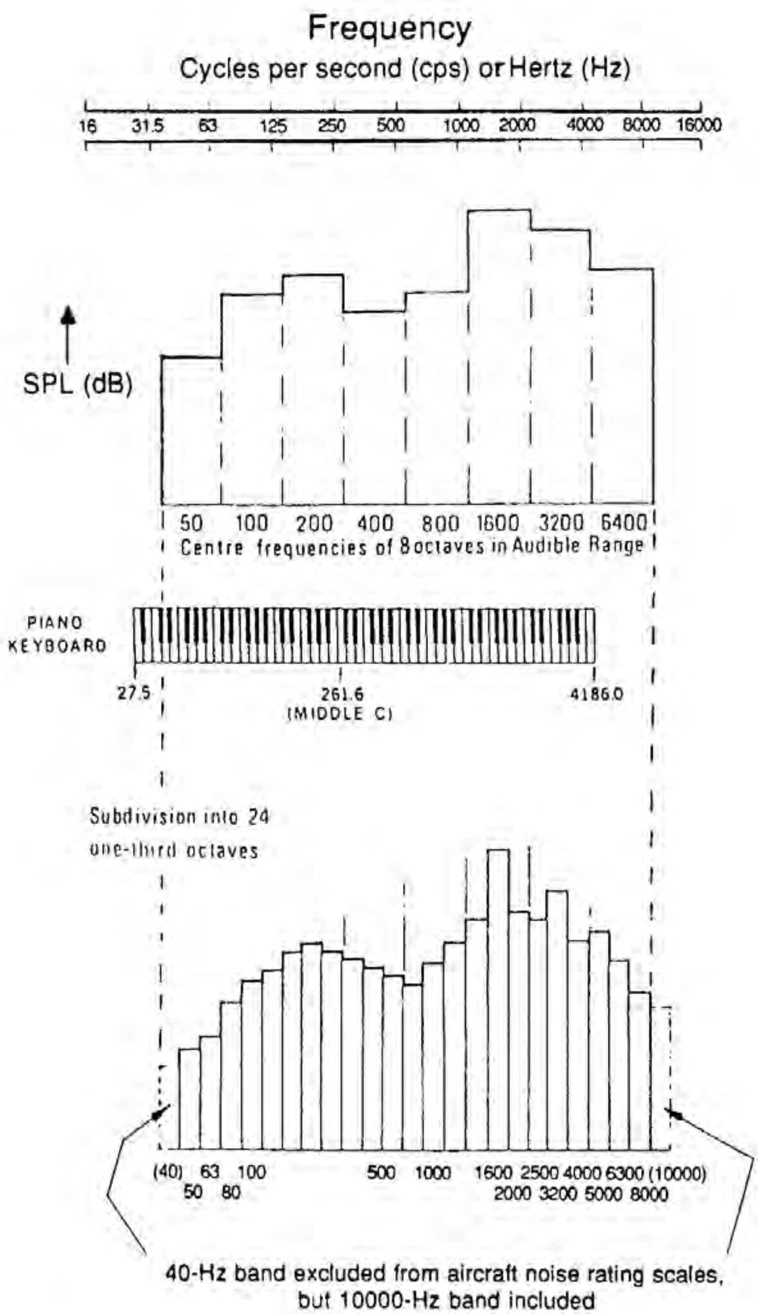


Figure 110: Range of audible frequencies split into octaves.

5.2.9 dB(A) SCALE

- **SOUND LEVELS CORRECTED FOR EFFECT FREQUENCY, AT A *SINGLE* TYPICAL VALUE (WEAK) OF SOUND LEVEL**
- **SCALE NOT PERFECT, BUT EASY TO MEASURE**

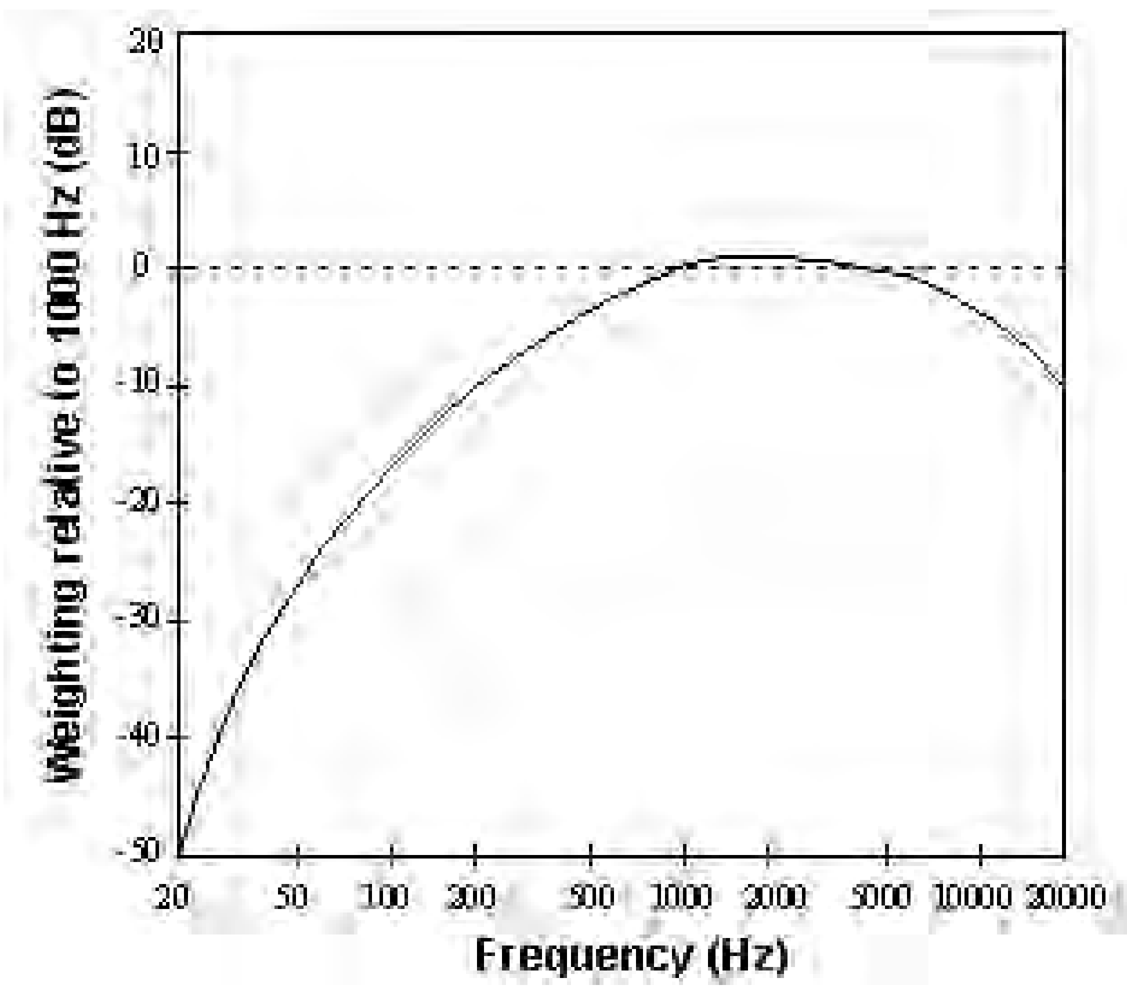
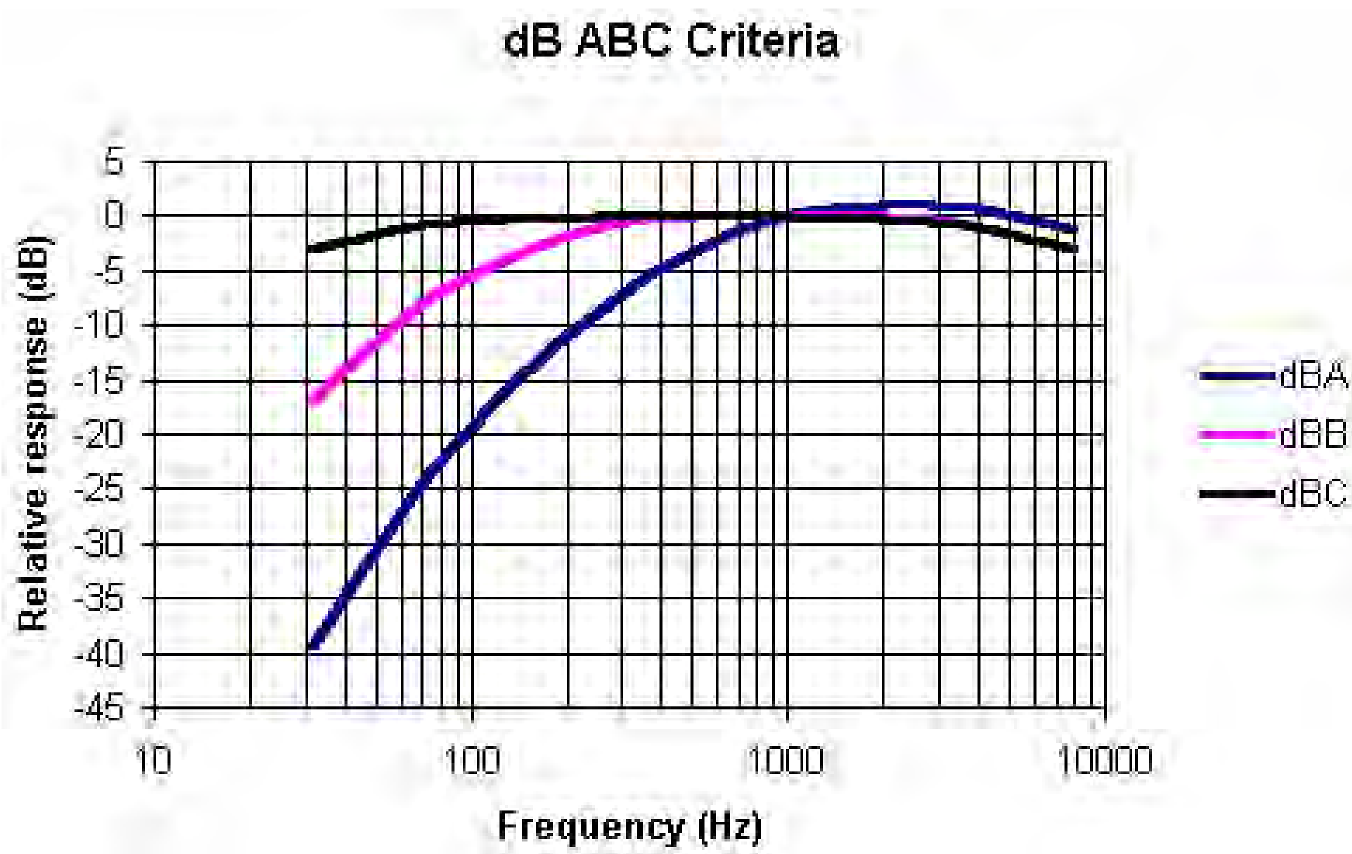


Figure 111: Curve of correction factors of scale dB(A).

5.2.10 dB(A), dB(B), dB(C) SCALES

- **SENSITIVITY OF HUMAN EAR IS A FUNCTION OF f AND SOUND LEVEL**
- **WEIGHTING FACTOR FOR TYPICAL NOISE LEVELS:**
  - **dB(A)↔ WEAK**
  - **dB(B)↔ INTERMEDIATE**
  - **dB(C)↔ INTENSE**



5.2.11 CURVES OF EQUAL NOISINESS

- **SENSITIVITY OF HUMAN EAR IS A FUNCTION OF f AND SOUND LEVEL INTENSITY**

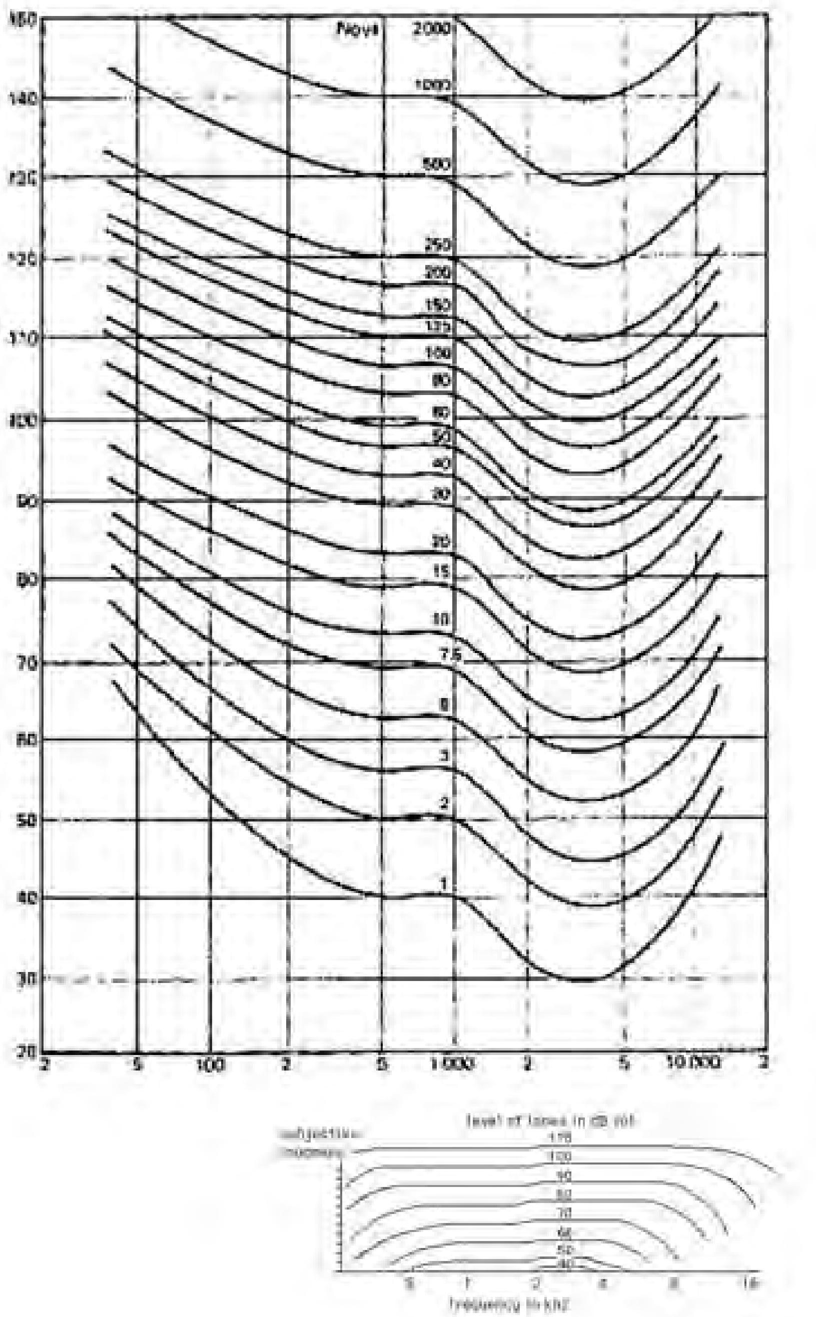


Figure 112: Isonoise curves, and relative response (bottom).

5.2.12 EPN SCALE EFFECTIVE PERCEIVED NOISE

- **SOUND LEVEL CORRECTED FOR EFFECT FREQUENCY AND INTENSITY**
- **ALSO ACCOUNTS FOR PROTRUSION BEYOND BACKGROUND NOISE, DURATION, TIME EVOLUTION...**
- **QUANTIFIES ACTUAL NOISE *DISTURBANCE*, RATHER THAN INTENSITY**
- **EPNdB SCALE ADOPTED FOR EVALUATING AIRCRAFT NOISE**
- **COMPLEX EVALUTATION: SOMETIMES dB(A) SCALE USED TO HAVE MORE IMMEDIATE INDICATIONS**

5.2.13 TYPICAL NOISE LEVELS

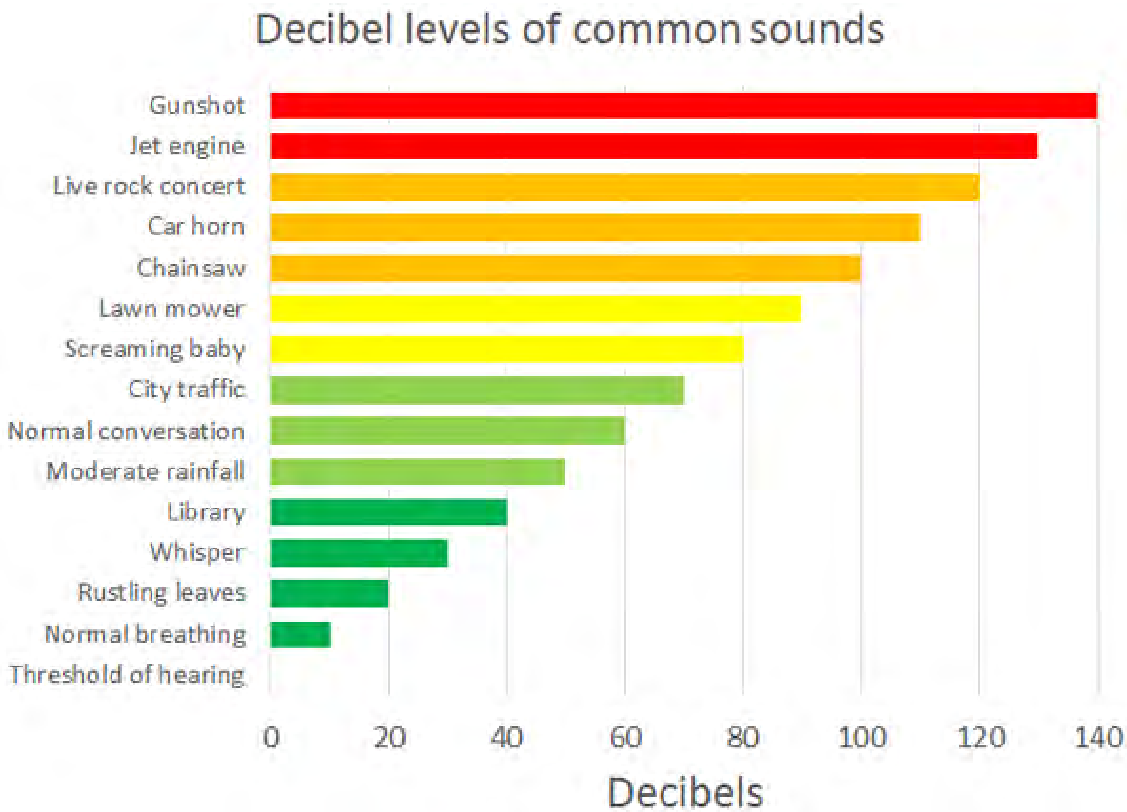


Figure 113: Typical levels of some noise situations.

- **PAIN THRESHOLD AT 140 dB**
- **HEARING LOSS STARTING AT DAY–NIGHT–LEVEL > 75 dB**
- **HOUSE DEPRECIATION UP TO 10% FOR NOISE LEVELS 5 – 15 dB > BACKGROUND**

5.3.1 NOISE ATTENUATION

- **GEOMETRICAL ATTENUATION:**
  - **OMNIDIRECTIONAL SOURCE OF POWER W:**

$$L_p = L_I = 10 \log_{10}\left[\frac{W/(4\pi r^2)}{10^{-12}}\right] =$$

$$= 10 \log_{10}\left(\frac{W}{10^{-12}}\right) - 10 \log_{10}(r^2) - 10 \log_{10}(4\pi) =$$

$$= L_W - 20 \log_{10}(r) - 11$$

- **ATMOSPHERIC ATTENUATION:**

$$L_p = L_W - 20 \log_{10}(r) - 11 - \boxed{A_{atm}}$$

$$A_{atm} = \alpha\, r$$

  - **α ATMOSPHERIC ACOUSTIC ABSORPTION COEFFICIENT, [dB/m], [dB/km]**
  - **STRONGLY DEPENDANT UPON FREQUENCY f, T, ATMOSPHERIC HUMIDITY**

5.3.2 ATMOSPHERIC ACOUSTIC ABSORPTION COEFFICIENT, [dB/km]

- **HIGH *f* NOISE STRONGLY ATTENUATED:**

T (°C)	relative humidity %	central f octave (Hz) 63	125	250	500	1000	2000	4000	8000
10	70	0,12	0,41	1,04	1,93	3,66	9,66	32,80	117,00
20	70	0,09	0,34	1,13	2,80	4,98	9,02	22,90	76,60
30	70	0,07	0,26	0,96	3,14	7,41	12,70	23,10	59,30

- **EFFECT OF ATMOSPHERIC HUMIDITY:**

T (°C)	relative humidity %	central f octave (Hz) 63	125	250	500	1000	2000	4000	8000
15	20	0,27	0,65	1,22	2,70	8,17	28,20	88,80	202,00
15	50	0,14	0,48	1,22	2,24	4,16	10,80	36,20	129,00
15	80	0,09	0,34	1,07	2,40	4,15	8,31	23,70	82,80

6.1 NOISE EMISSIONS

- **SOURCES:**
  - **ENGINES, PROPELLERS**
  - **AIRFRAME**

6.2.1 ACTIONS AGAINST NOISE

- **STEEP CLIMB/DESCENT ANGLES REDUCE GROUND AREA SUBJECTED TO NOISE**
- **IN CASE OF (SINGLE) ENGINE FAILURE, AIRCRAFT (IF CANNOT STOP WITHIN STRIP) MUST BE ABLE TO TAKE–OFF ALL THE SAME**
  - **2–ENGINE A/Cs: 100% THRUST RESERVE → VERY STEEP CLIMB**
  - **3–ENGINE A/Cs: 50% THRUST RESERVE → STEEP CLIMB**
  - **4–ENGINE A/Cs: 33% THRUST RESERVE → LESS STEEP CLIMB**

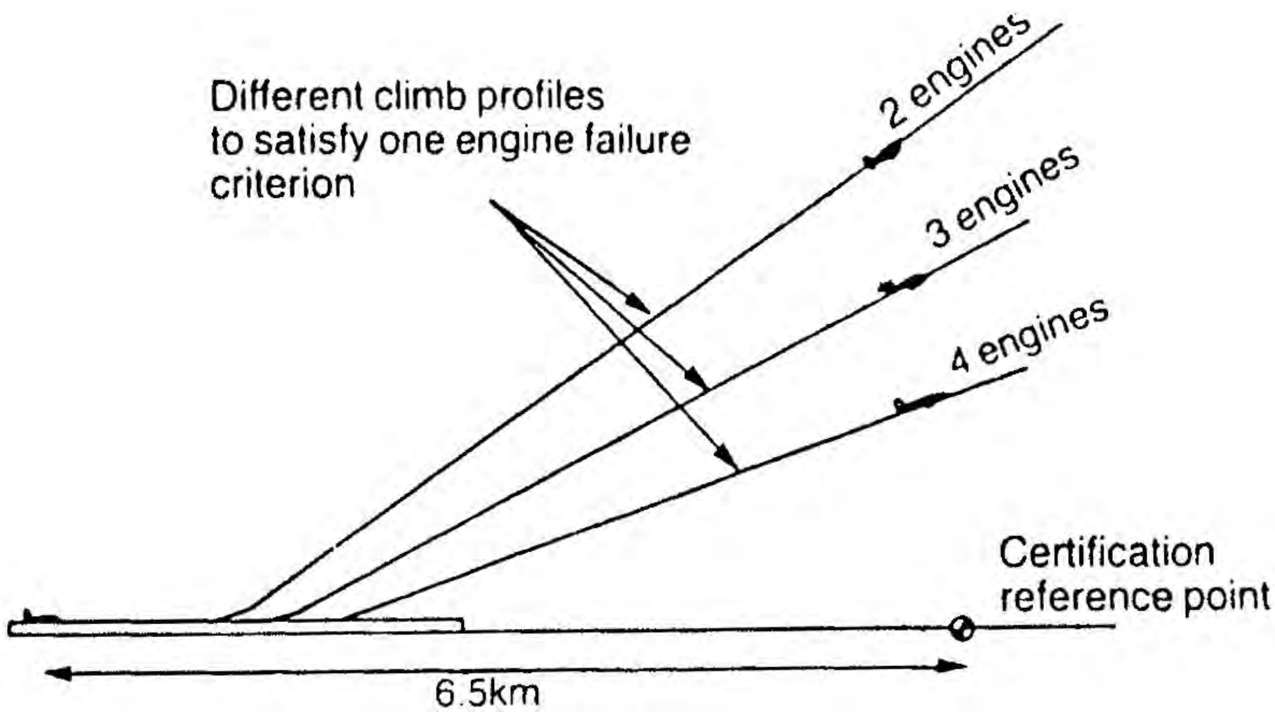


Figure 114: Climb trajectories of twin–, three–, four–engine aircrafts.

6.2.2 THRUST CUTBACK IN CLIMB

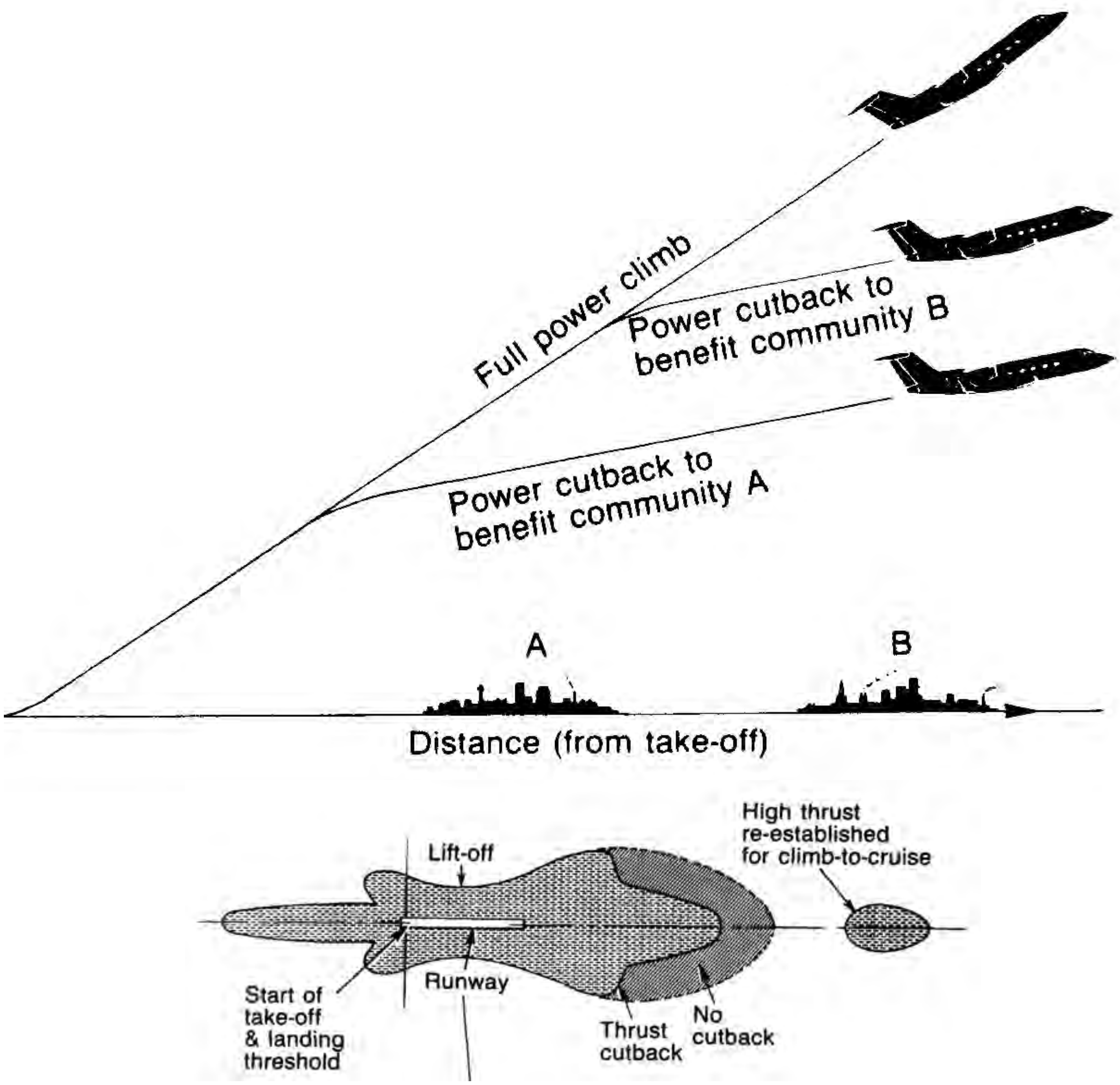


Figure 115: Noise relief due to thrust cutback, and reduction of ground area exposed to intense noise (bottom).

- **NOISE FROM OLD A/Cs CAN BE LIMITED BY ENFORCING REDUCED TAKE–OFF MASS (SUBSEQUENT REFUELLING IN LESS ‘NOISE–CRITICAL’ AIRPORT)**

6.2.3 INCREASED DESCENT ANGLE

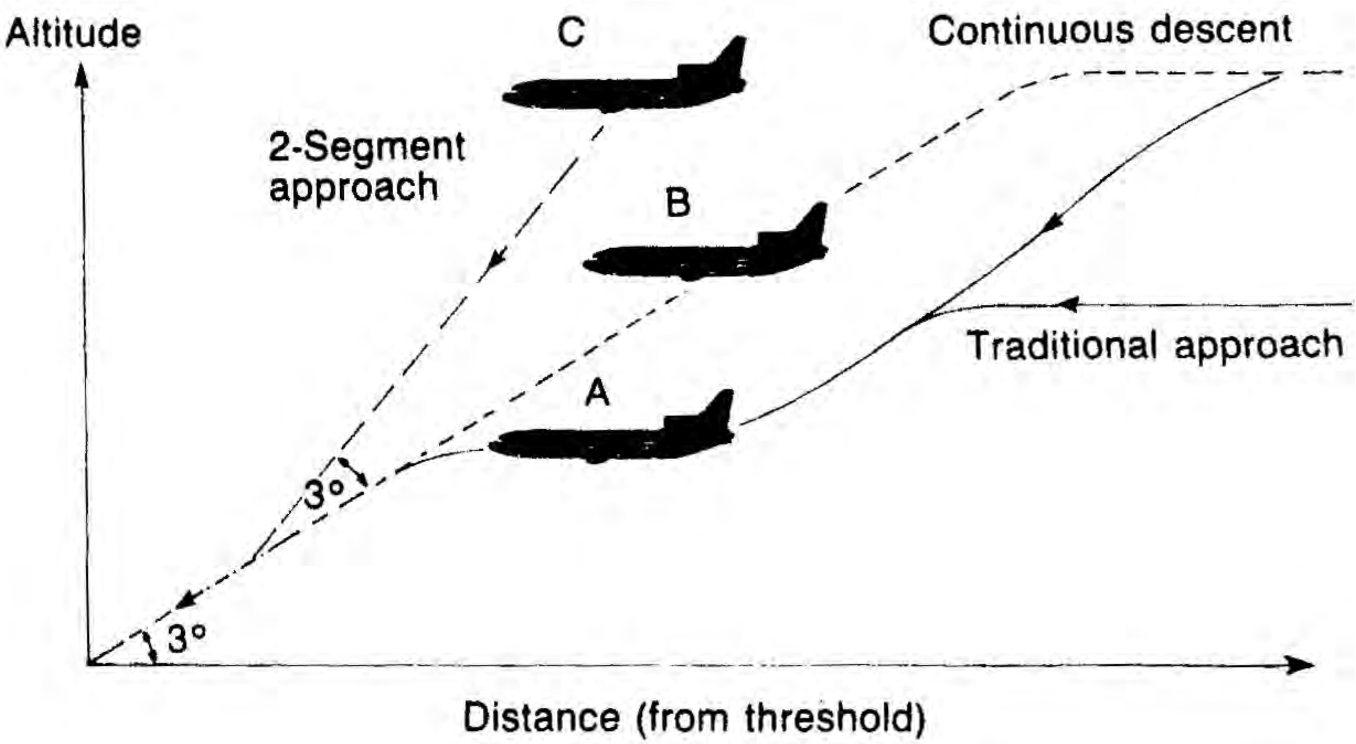


Figure 116: Descent trajectories following different stategies.

6.2.4 APPROACH PATH

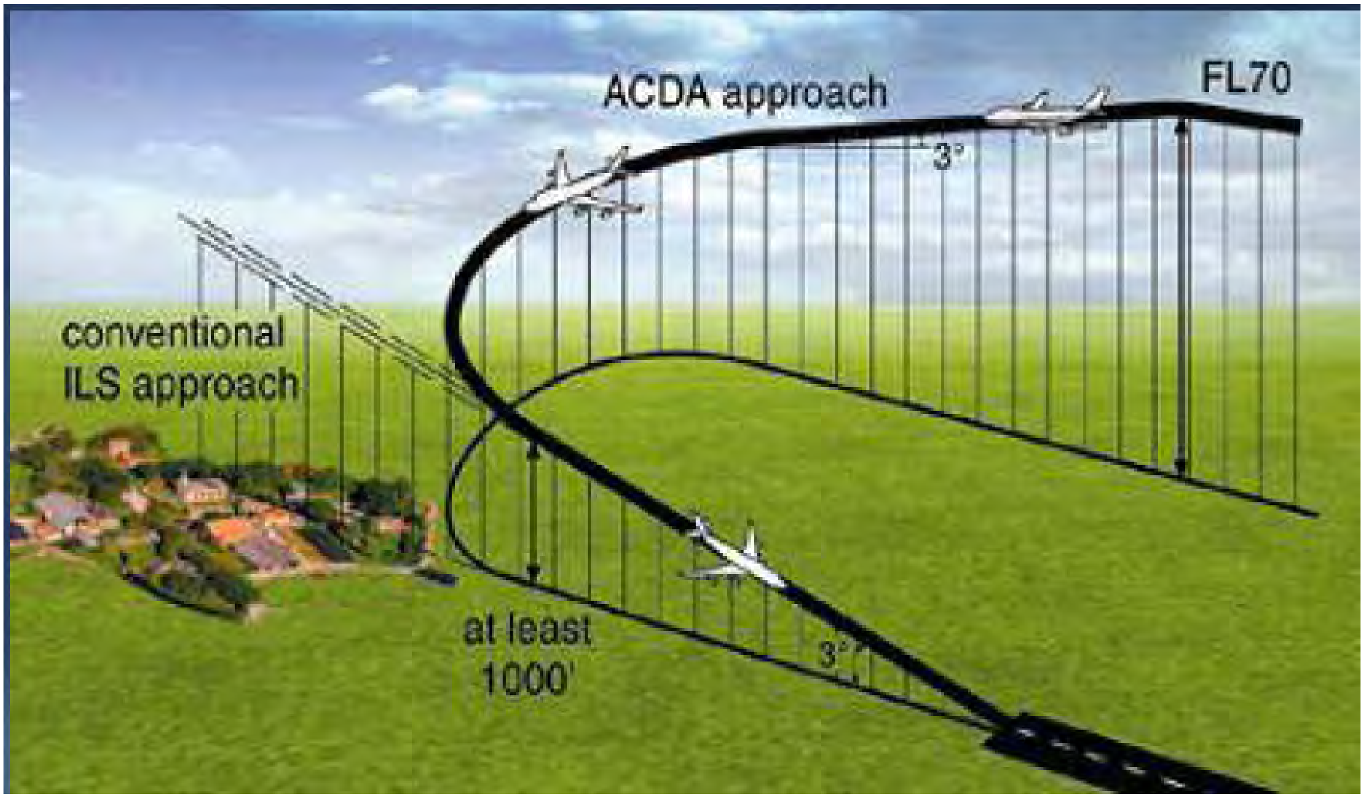


Figure 117: Approach path with/without flight over urban areas.

6.2.5 AIRPORT LOCATION

- **AIRPORTS FAR FROM CITIES REDUCE NOISE IMPACT**
- **HOWEVER, LONGER TRANSFER TIMES AND HIGHER COSTS**

→ URBANIZATION OF AREA NEAR AIRPORTS

Figure 118: Landing at Hong Kong airport.

6.3 NOISE COMPONENTS

- **NOISE FROM ENGINES AND AIRFRAME**
- **TAKE–OFF: ENGINES DOMINATING**
- **LANDING: AIRFRAME ∼ ENGINES**

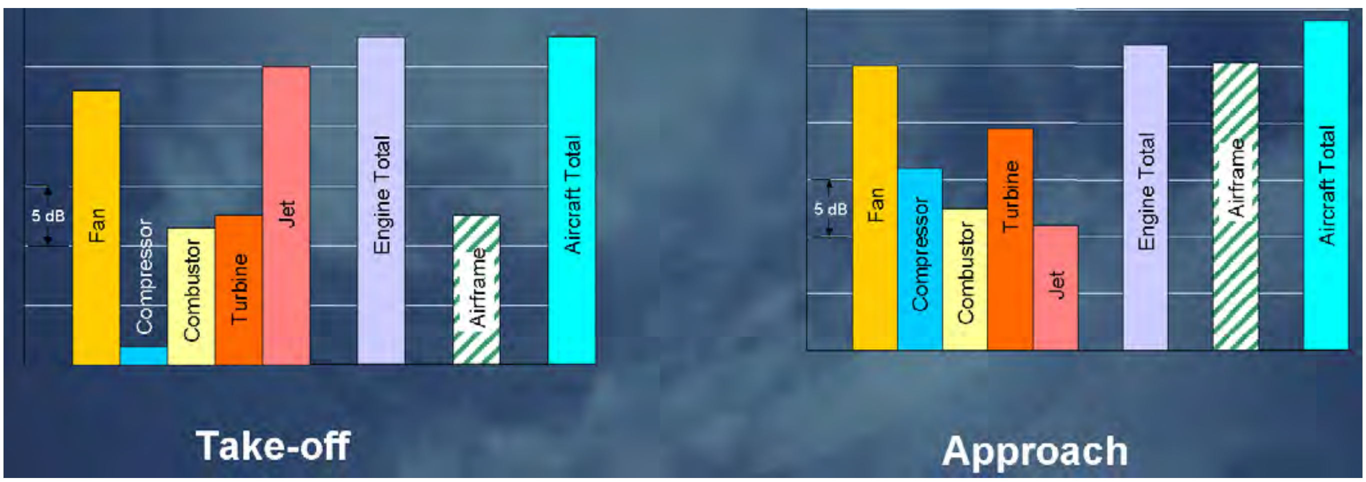


Figure 119: Components of noise perceived at take–off and landing.

6.4 ENGINE NOISE

- GREATLY REDUCED BY TURBOFAN (HIGH *BPR* IN PARTICULAR)

→ REDUCED JET NOISE, BUT INCREASED TURBOMACHINERY NOISE

- NOISE DIRECTIVITY ALSO AFFECTED

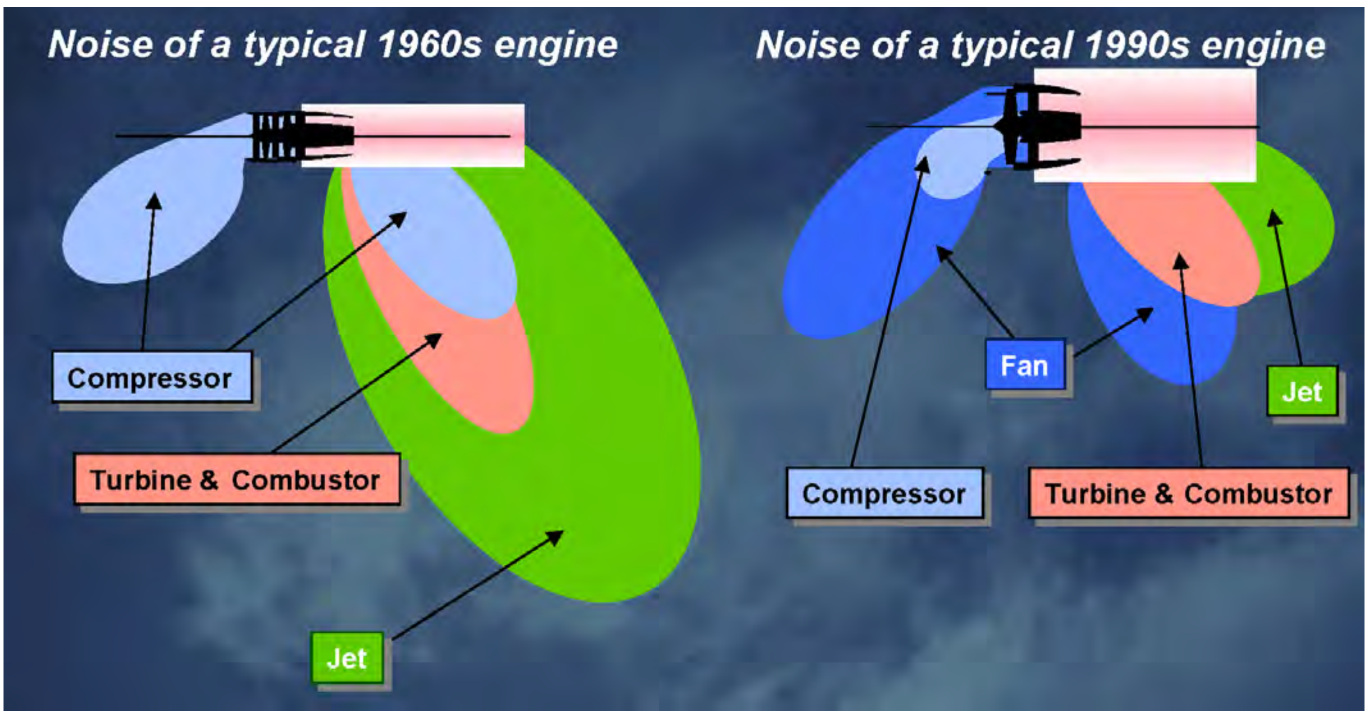


Figure 120: Noise sources of typical engines of the years '60s (left) and '90s (right).

6.5.1 NOISE FROM FAN AND COMPRESSOR (1)

- **NOISE: 'DISCRETE TONES' AND 'WIDEBAND'**
- **WIDEBAND NOISE:**
  - **GENERATED BY INTERACTION BLADES/TURBULENT FLOW**
  - **TURBULENCE GENERATED IN BOUNDARY LAYER, AT DISCONTINUITIES, AND AT EACH STAGE**
  - **e.g., MOTION FAN BLADE TIP IN TURBULENT BOUNDARY LAYER**
  - **ACOUSTIC POWER $\propto$ (FLOW SPEED)^5**

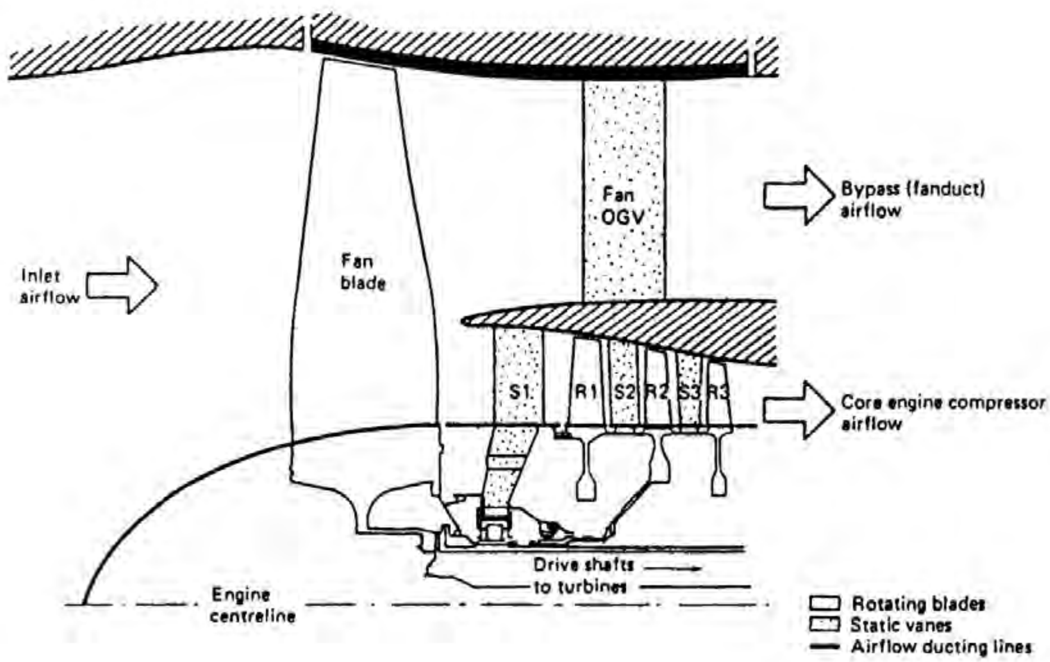


Figure 121: Typical fan and compressor configuration.

6.5.2 NOISE FROM FAN AND COMPRESSOR (2)

- **DISCRETE TONES:**
  - **GENERATED AT PASSAGE BLADES OVER VANES**
  - ***B* NUMBER ROTOR BLADES, *V* NUMBER STATOR VANES**

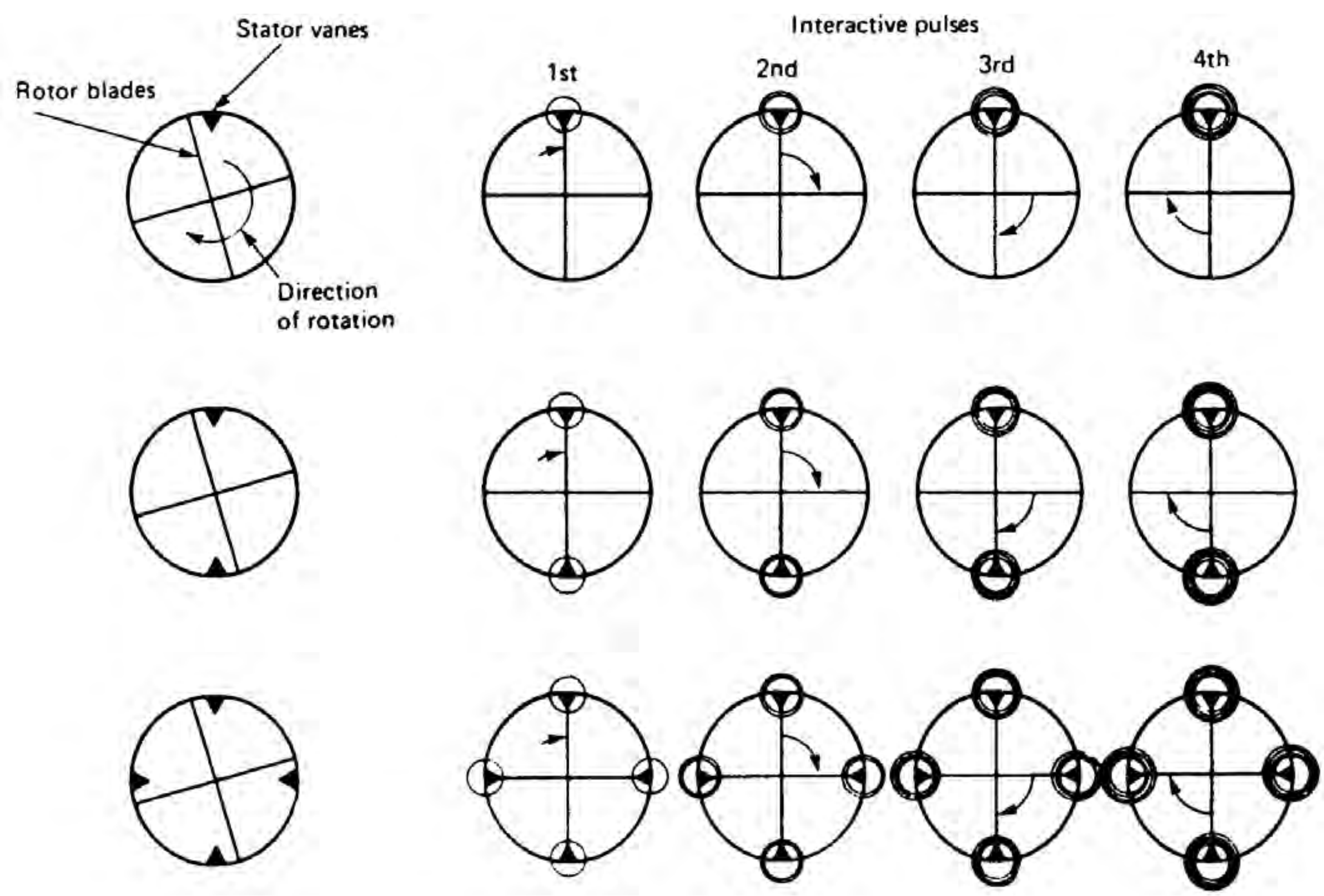


Figure 122: Discrete tone geneneration for B exact multiple of V.

6.5.3 NOISE FROM FAN AND COMPRESSOR (3)

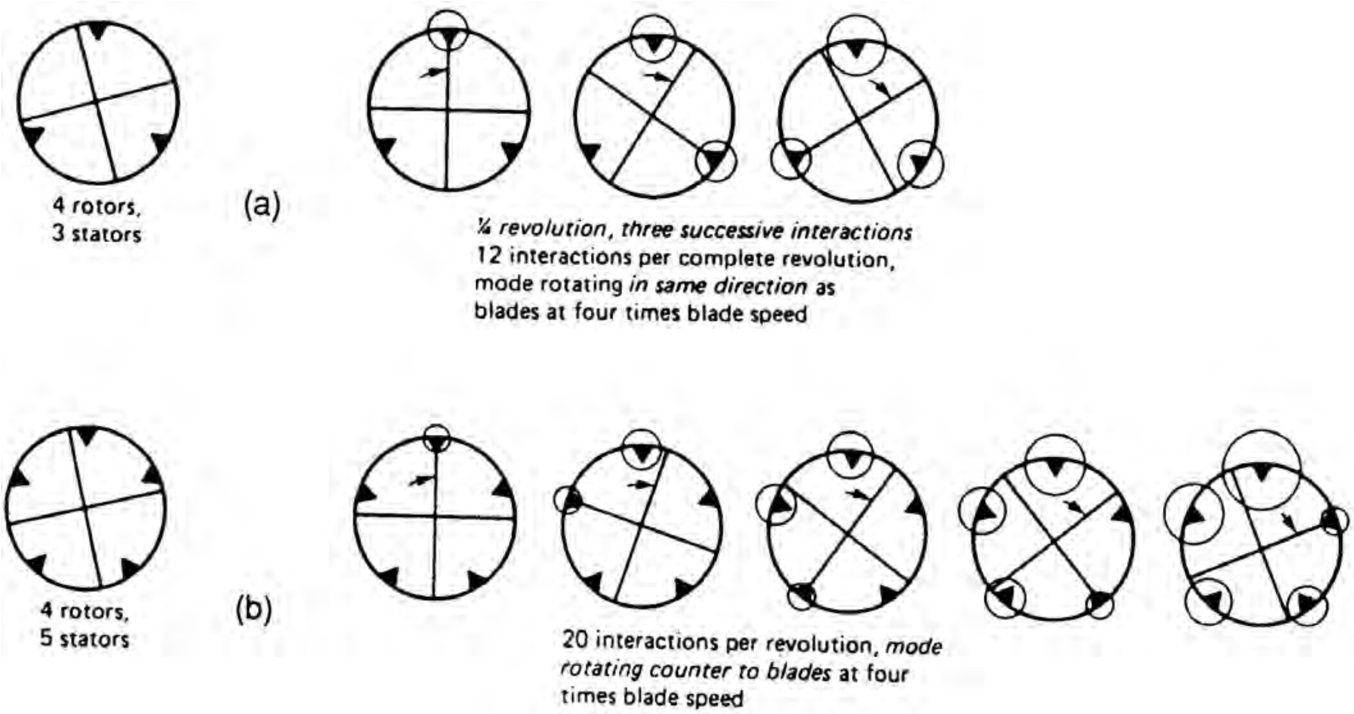


Figure 123: Discrete tone geneneration for B not a multiple of V: (top) case $B > V$, (bottom) case $B < V$.

- **FUNDAMENTAL FREQUENCY + HARMONICS**

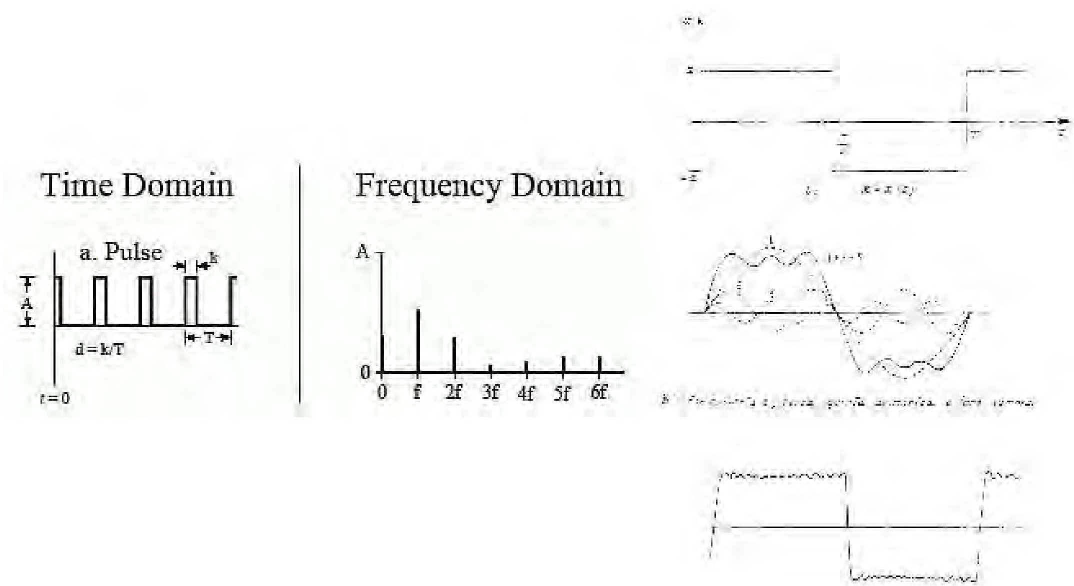
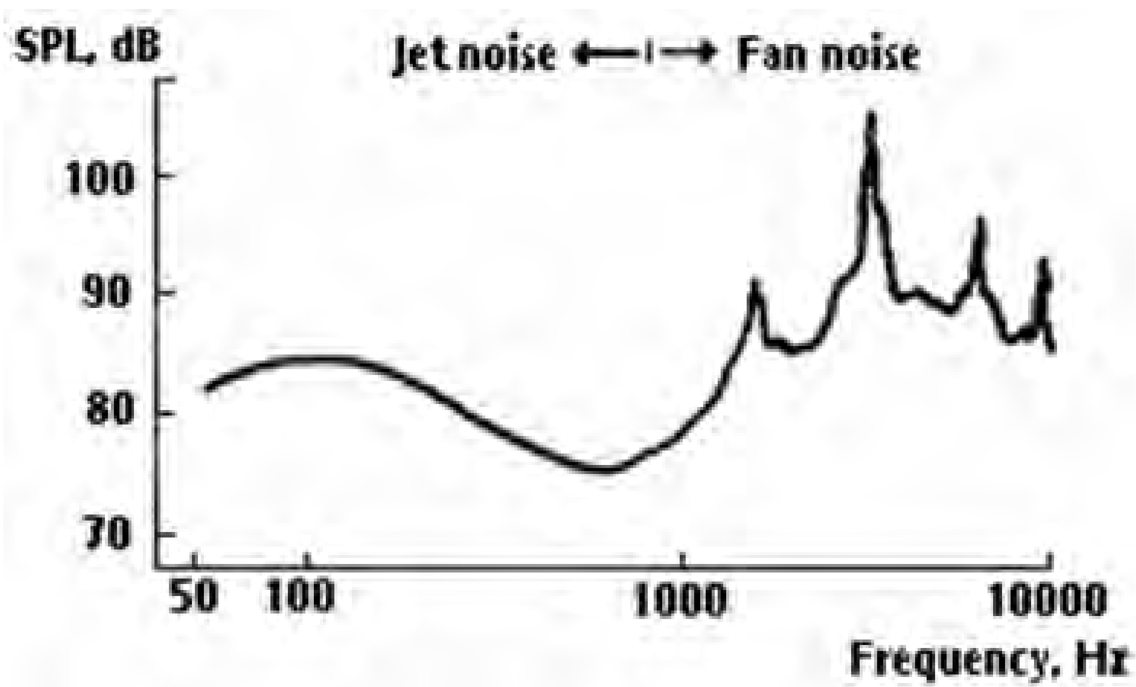


Figure 124: Fourier decomposition of a pulse train.

6.5.4 NOISE FROM FAN AND COMPRESSOR (4)

- **MODERN FAN CAN OPERATE WITH BLADE TIPS SUPERSONIC → SHOCK WAVES NOISE**
- **BLADES ALL NOMINALLY EQUAL, BUT ACTUALLY NOT → NOISE SPECTRUM WIDENED**



6.5.5 NOISE FROM FAN AND COMPRESSOR (5)

- **DIRECTIVITY DUE TO INTAKE GEOMETRY**

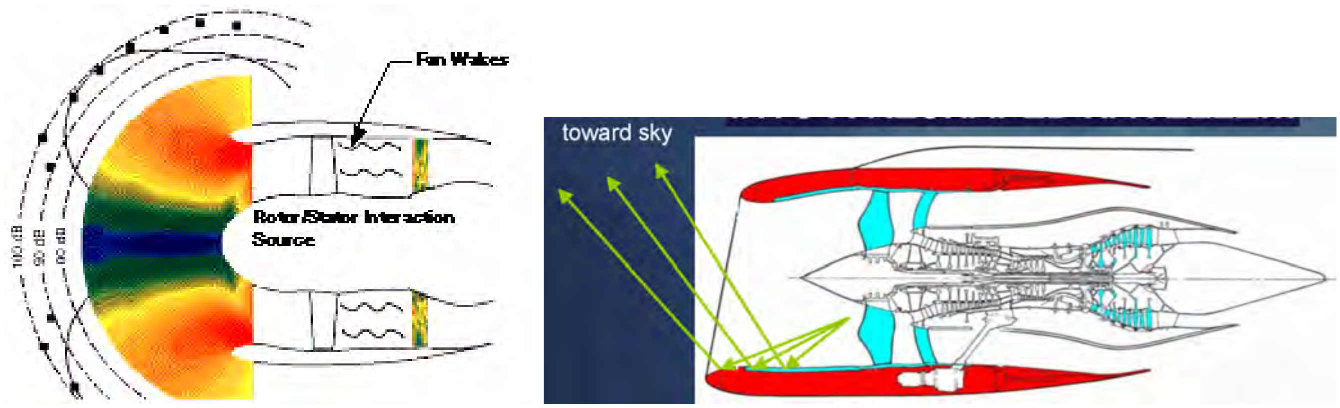


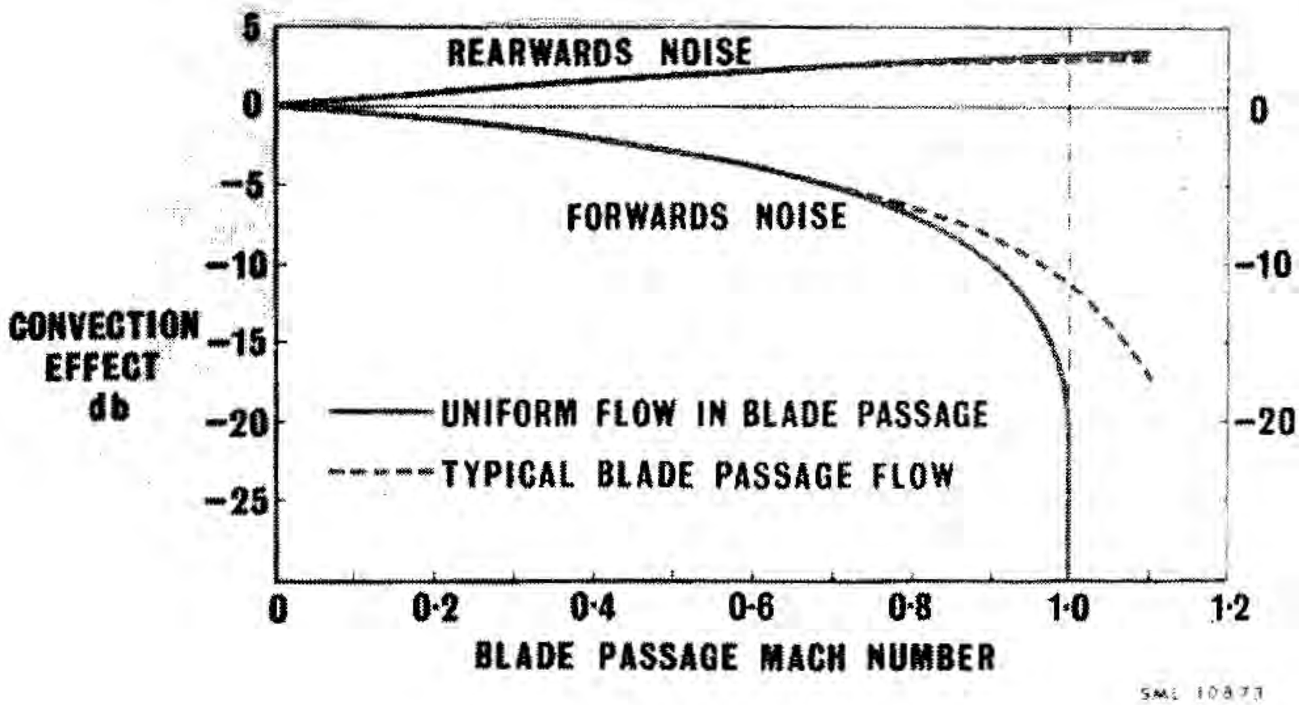
Figure 125: Effect of air intake on directivity of noise from fan and compressor.

- **MEASURES TO CONTROL NOISE:**

  1. **ROTOR/STATOR SPACING (BUT INCREASED WEIGHT)**
  2. **no. B AND V; IF $V > 1,1\,(1+M)\,k\,B$ MODES OF ORDER k SUPPRESSED (VERY HIGH V)**
  3. **B AND V <u>COPRIME</u> TO SHIFT NOISE TO HIGH f**
  4. **SHIELDING FROM UPSTREAM STAGES**
  5. **AIR INTAKE AERODINAMICALLY 'CLEAN' (NO SLATS, NO BOTTOMING)**

6.5.6 CUTOFF

- **CUTOFF OF FORWARD NOISE IF $M \geq 1$**
- **BUT ACTUALLY M NOT UNIFORM ACROSS BLADES (LOWER AT HUB) → CUTOFF NOT COMPLETE**



6.5.7 AIR INTAKE:

SLATS

HAMSTERIZED (BOTTOMING)

Figure 126: *Slats* (left) on the engines of a Boeing 707; (right) ‘hamsterized’ air intake of a Boeing 737 with CFM56 engines.

6.5.8 FAN NOISE CONTROL

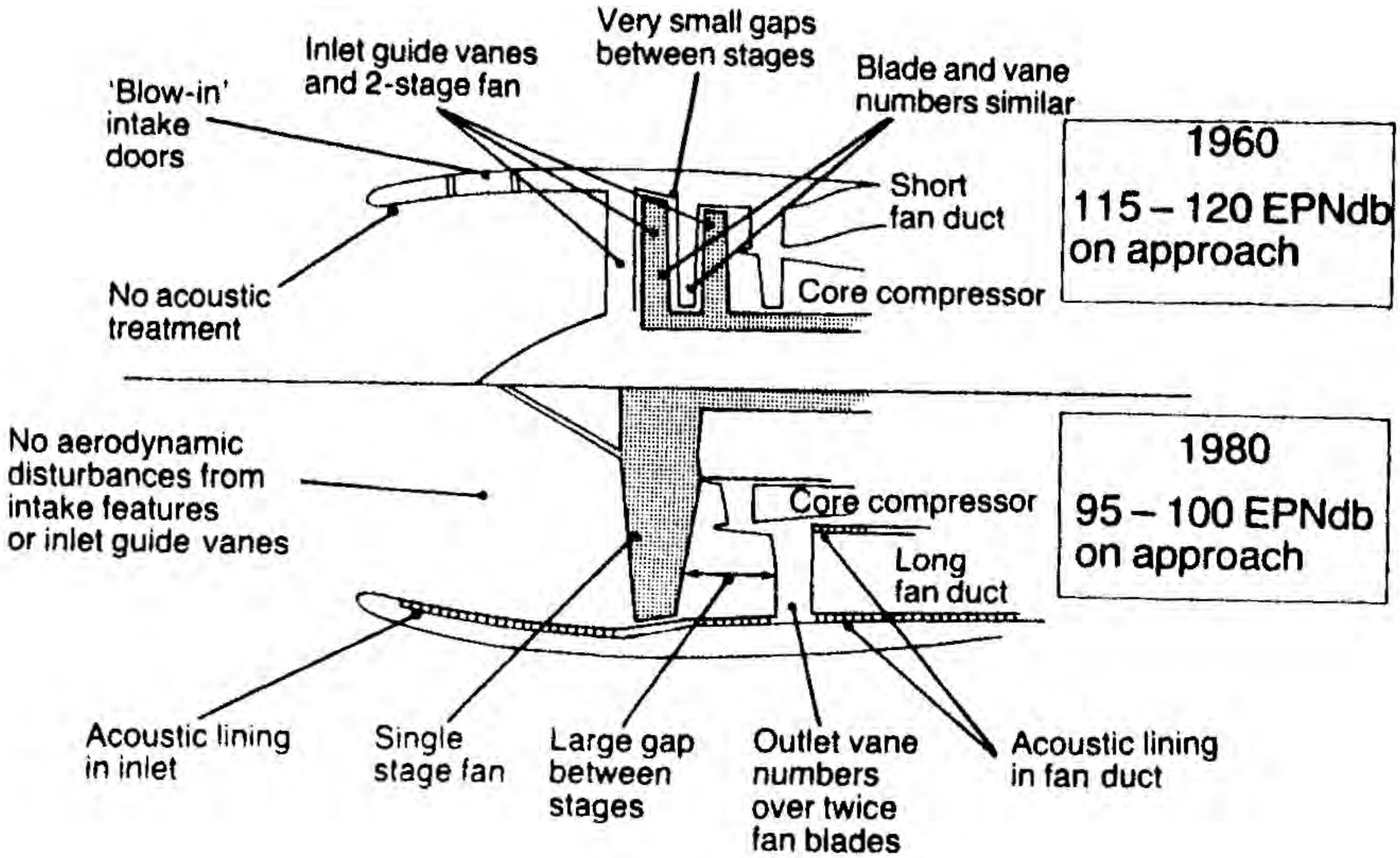


Figure 127: Evolution of fan noise control.

6.6.1 TURBINE NOISE

- **NOZZLE GUIDE VANES SONIC → NOISE PROPAGATED REARWARDS ONLY**
- **GENERATED BY INTERACTION BLADES/TURBULENT FLOW**
- **NOISE REFRACTED BY MIXING LAYER ACROSS HOT/COLD FLOW AND ATMOSPHERE**
- **FOR SAME GAS SPEED, LOWER M (HIGHER T) → $V > 1,1(1+M)kB$ EASIER TO SATISFY**
- **ACT ALSO ON STATOR/ROTOR SPACING**

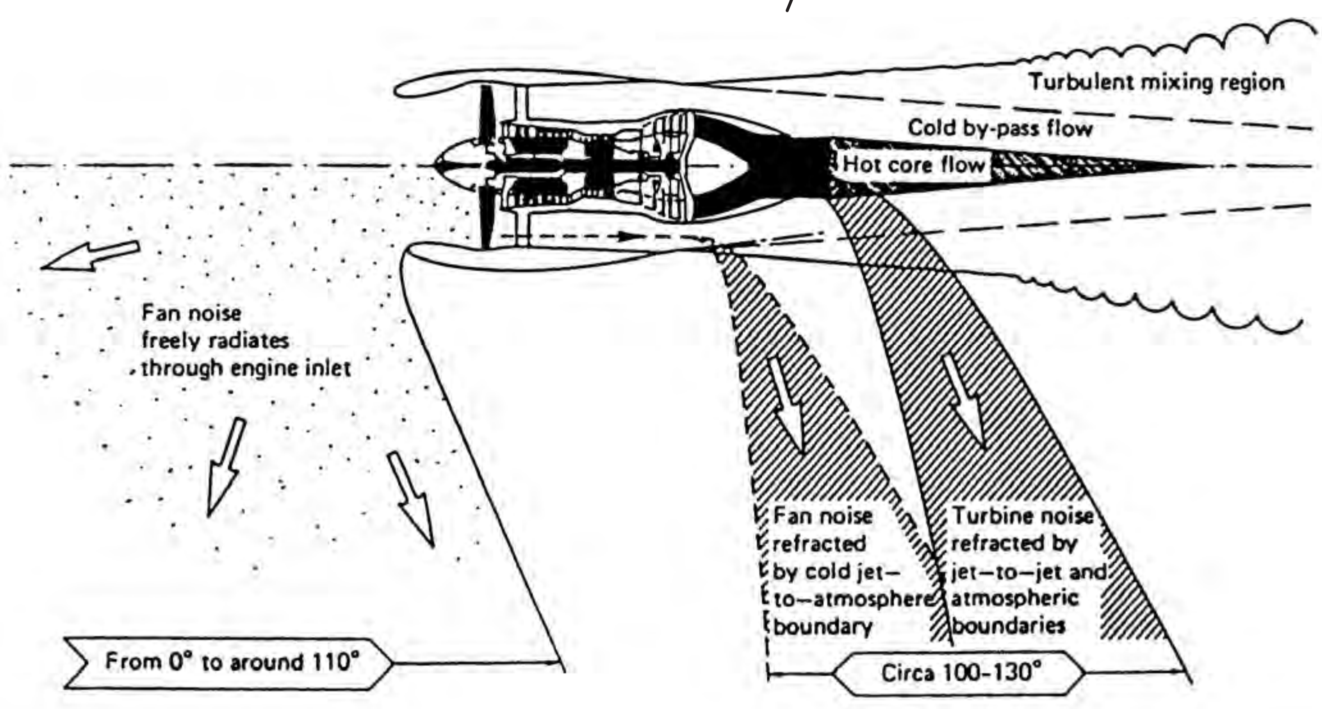


Figure 128: Refraction of noise from nozzles.

6.6.2 NOISE REFRACTION

- **SOUND SPEED** $a = \sqrt{\gamma R T} \propto \sqrt{T}$
- **SNELL'S LAW:**

$$\frac{\sin\theta_2}{a_2} = \frac{\sin\theta_1}{a_1}$$

$$\sin\theta_2 = \sin\theta_1 \frac{a_2}{a_1} = \sin\theta_1 \sqrt{\frac{T_2}{T_1}}$$

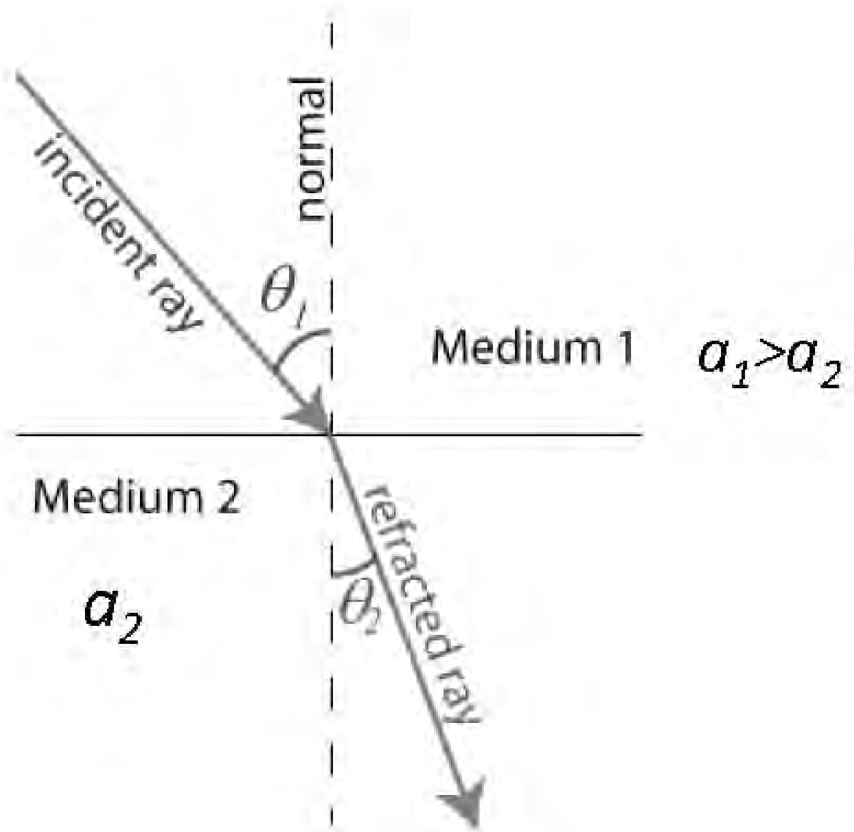
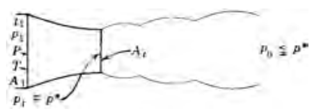


Figure 129: Passage of a wave across two media with different sound propagation speed.

6.7.1 JET NOISE

- **DUE TO:**
  MIXING (BTWN FLOWS AT DIFFRNT SPEED)
  SHOCKS (IF OVER/UNDEREXPANDED)
- **ALSO REFRACTED**

Figure 130: Shocks at exit of underexpanded nozzle.



- **MIXING:**
  - **NOISE INTENSITY IN THEORY** $\propto \boldsymbol{u_e^8}$
  - **DEPARTURES AT LOW/HIGH SPEED** ($\propto \boldsymbol{u_e^3}$)

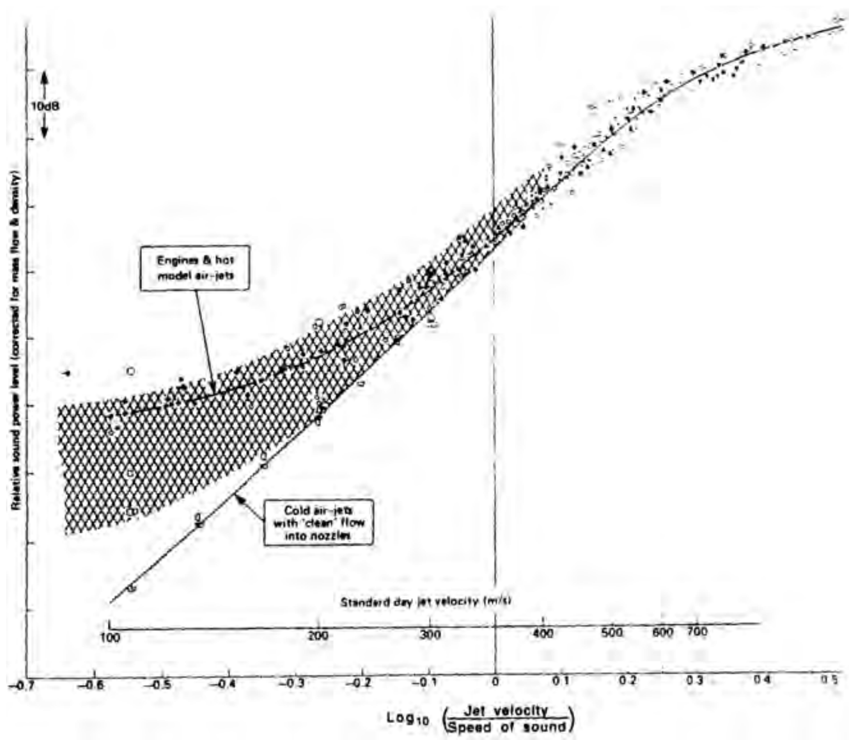


Figure 131: Intensity level of mixing noise *vs.* jet speed.

6.7.2 JET NOISE IN TURBOFANS

- IN SEPARATED FLOW TFs, PRIMARY JET HAS:
  - SPEED $\sim$ 1,5 · SECONDARY JET
  - TEMPERATURE $\sim$ 2 – 3 · SECONDARY JET
  - TWO MIXING LAYERS (PRIMARY/SECONDARY JET, JET/ATMOSPHERE)
- ASSOCIATED FLOW TFs MUCH QUIETER
- HIGH *BPR* TFs EMIT AT LOWER FREQUENCIES (LARGER SIZE), CAN CAUSE VIBRATIONS OF STRUCTURES AND WINDOWS
- *CHEVRON* NOZZLES

6.7.3 NOISE SUPPRESSION IN EARLY TURBOJETS

- **JET SPLIT INTO SMALLER JETS**
- **LOWER SIZE SHIFTS NOISE SPECTRUM TOWARDS HIGHER $f \rightarrow$ GREATER ATMOSPHERIC ATTENUATION**
- **LOSSES DUE TO GREATER INNER AND OUTER DRAG**
- **WEIGHT INCREASE**
- **JET NOISE ABSOLUTELY DOMINATING IN EARLY TJs**

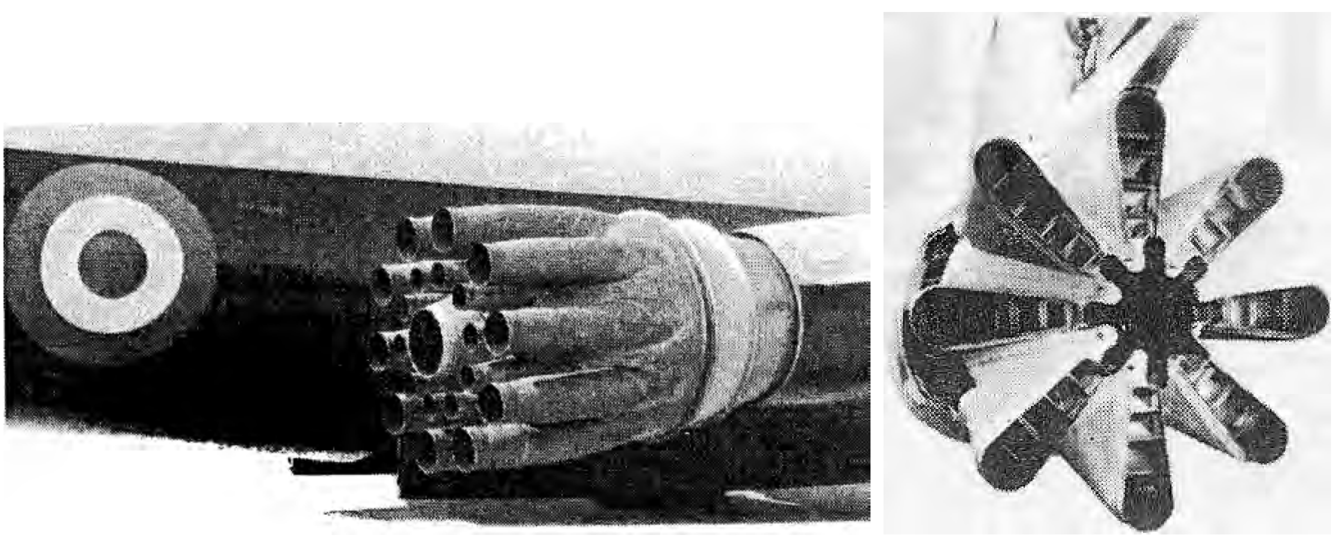


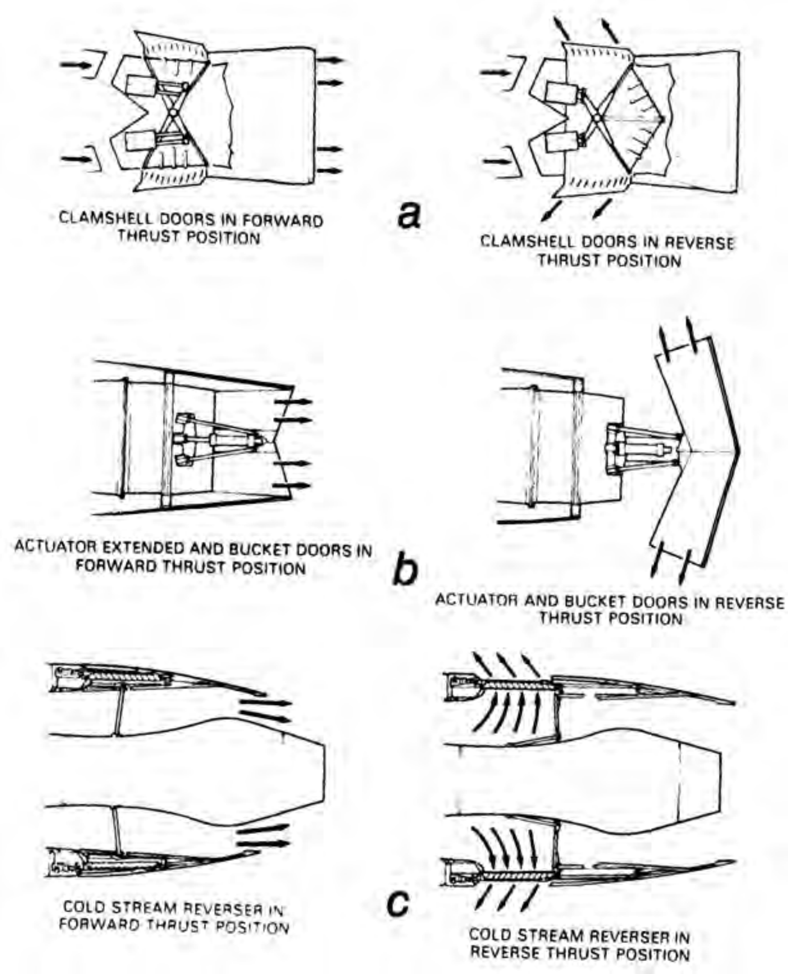
Figure 132: 21–tube nozzle for Boeing 707 engines (left); 8–lobe corrugated nozzle (right).

6.8 NOISE FROM COMBUSTION CHAMBER

- **TURBULENCE IN CHAMBER GENERATES WIDEBAND NOISE**
- **USUALLY NOT SO IMPORTANT TO REQUIRE CHANGES IN CHAMBER DESIGN**

6.9 NOISE FROM THRUST REVERSERS

- **USED AT LANDING**
- **NEARLY AS MUCH NOISE AS AT TAKE–OFF (BUT SHORTER DURATION)**
- **SOME REVERSE COLD JET ONLY (HIGH BPR IN PARTICULAR; LESS NOISE BECAUSE OF LOWER p)**
- **IN SOME AIRPORTS ALLOWED ONLY IN AN EMERGENCY, OR SLIPPERY STRIP**



6.10.1 ACOUSTIC LINERS

- **ACOUSTIC ABSORPTION MECHANISMS:**
  - **DAMPING ('RESISTIVE')**
  - **CANCELLATION BY REFLECTED WAVE ('REACTIVE'), DEPENDING UPON $d \leftrightarrow f$**
- **CHANCES THAT WATER/FUEL/OIL TRAPPED IN HONEYCOMB**
- **ATTENUATION $\sim$ 5 dB IN AIR INTAKE, $>$ 10 dB IN EXHAUST DUCTS**
- **MUST BE ABLE TO OPERATE AT -50 $< T <$ 500 ^{o}C, LIGHTWEIGHT**
- **CAN CONTRIBUTE TO NACELLE STRUCTURAL STIFFNESS**

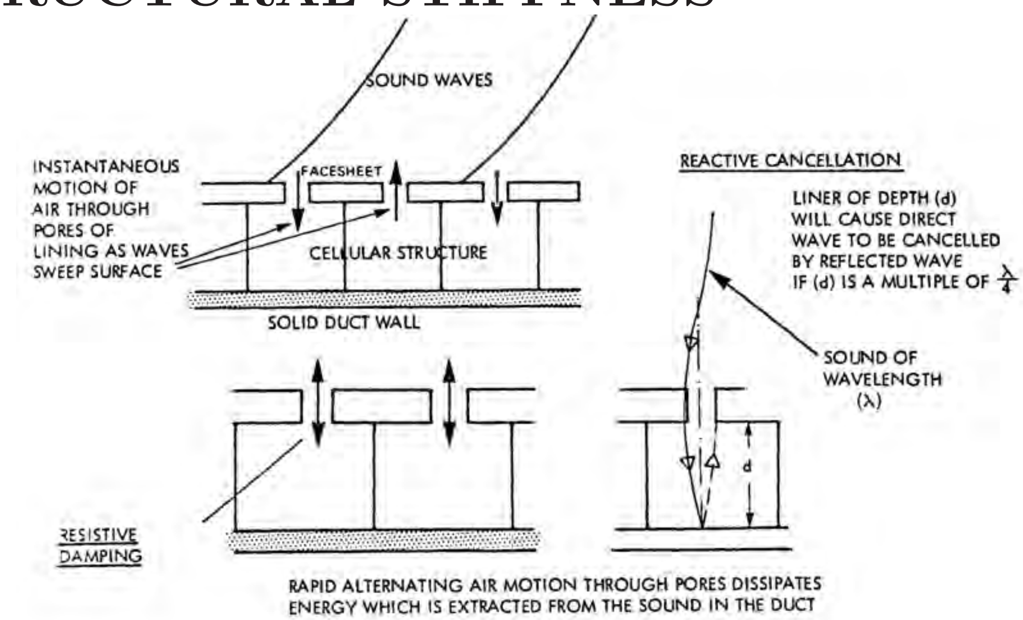


Figure 133: Noise absorption mechanisms by an acoustic liner.

6.10.2 USE OF ACOUSTIC LINERS

• DUCTS POSSIBLY FEATURING A HIGH L/D

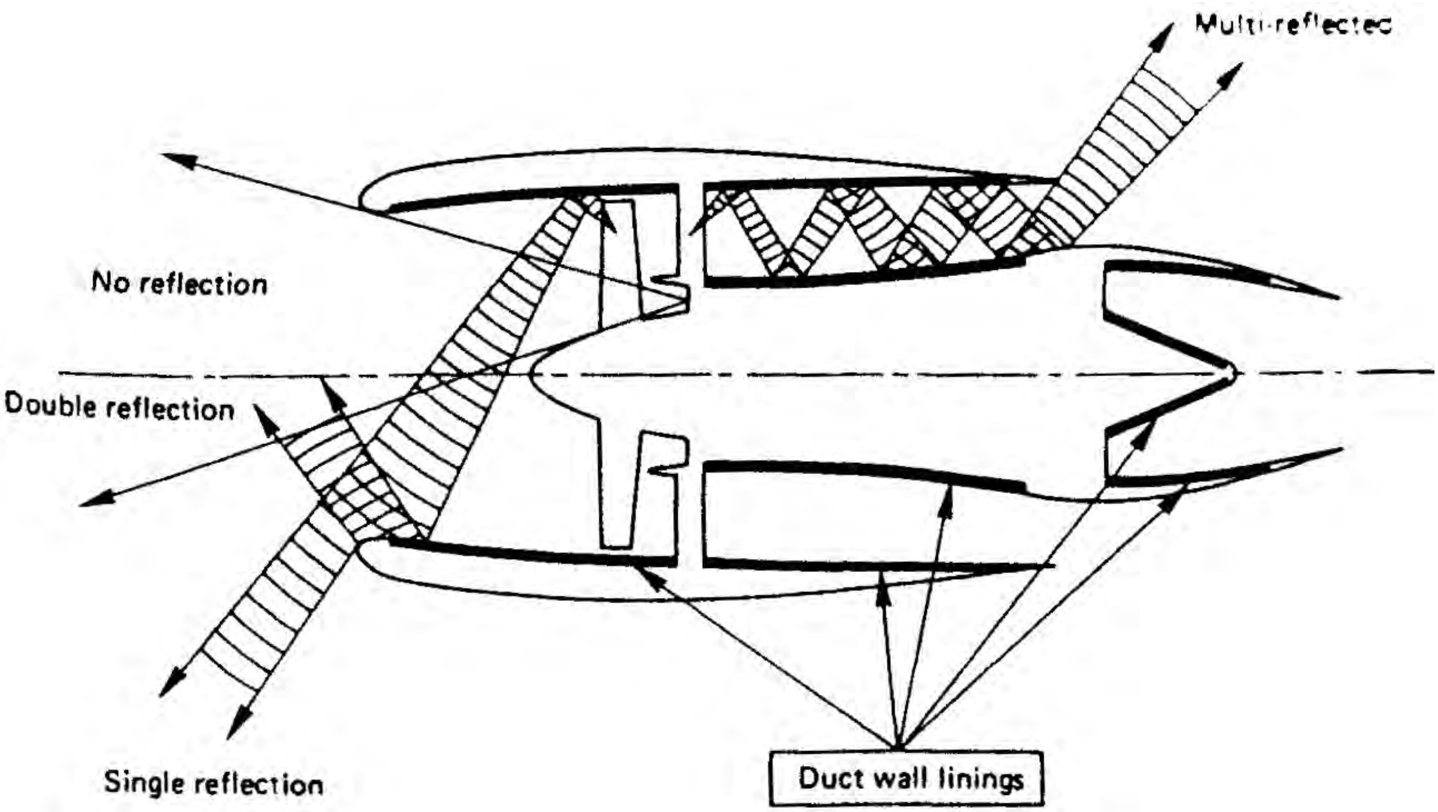


Figure 134: Noise reduction opportunities by acoustic liners.

6.10.3 TYPES OF ACOUSTIC LINERS

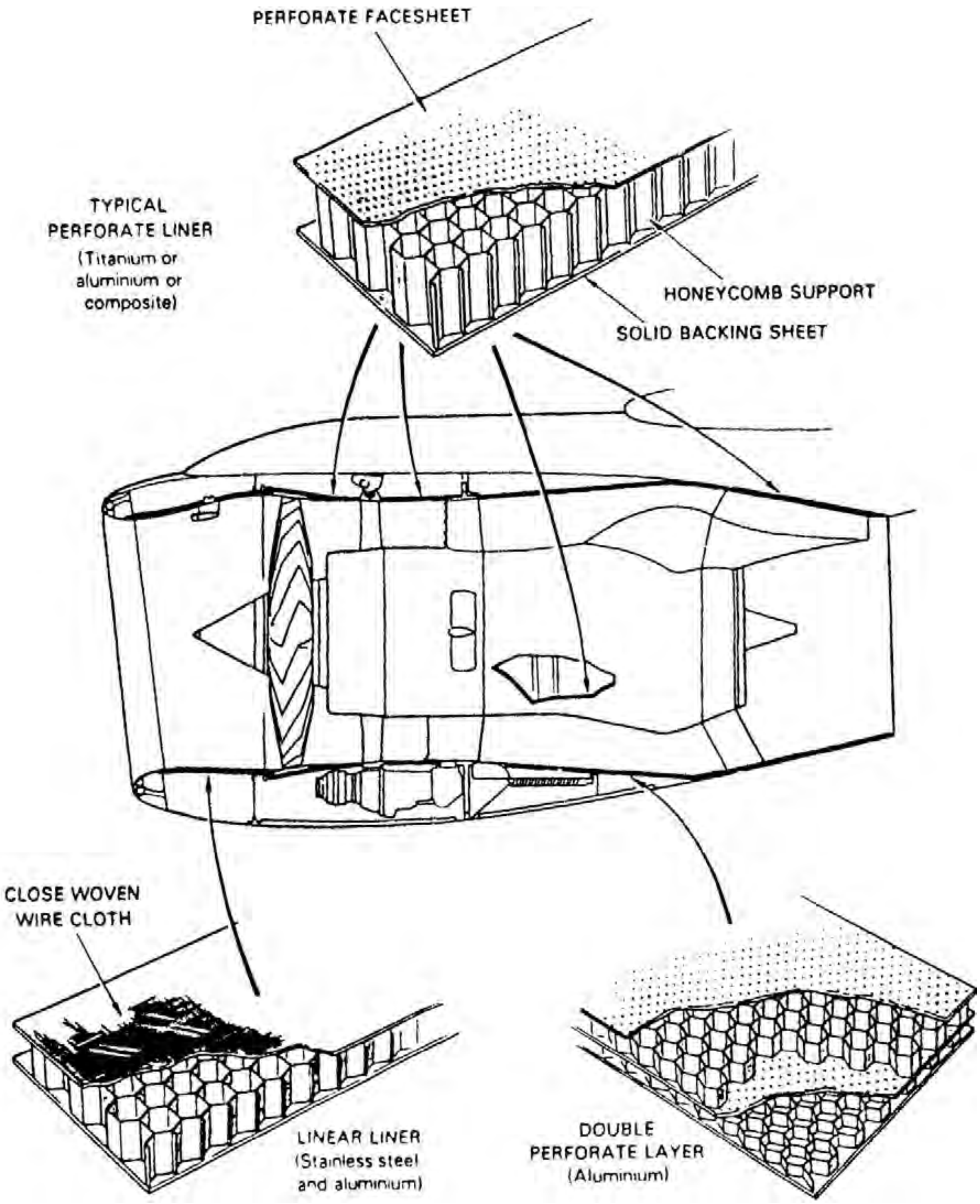


Figure 135: Types of acoustic liners.

6.11 TURBOFAN NOISE CONTROL

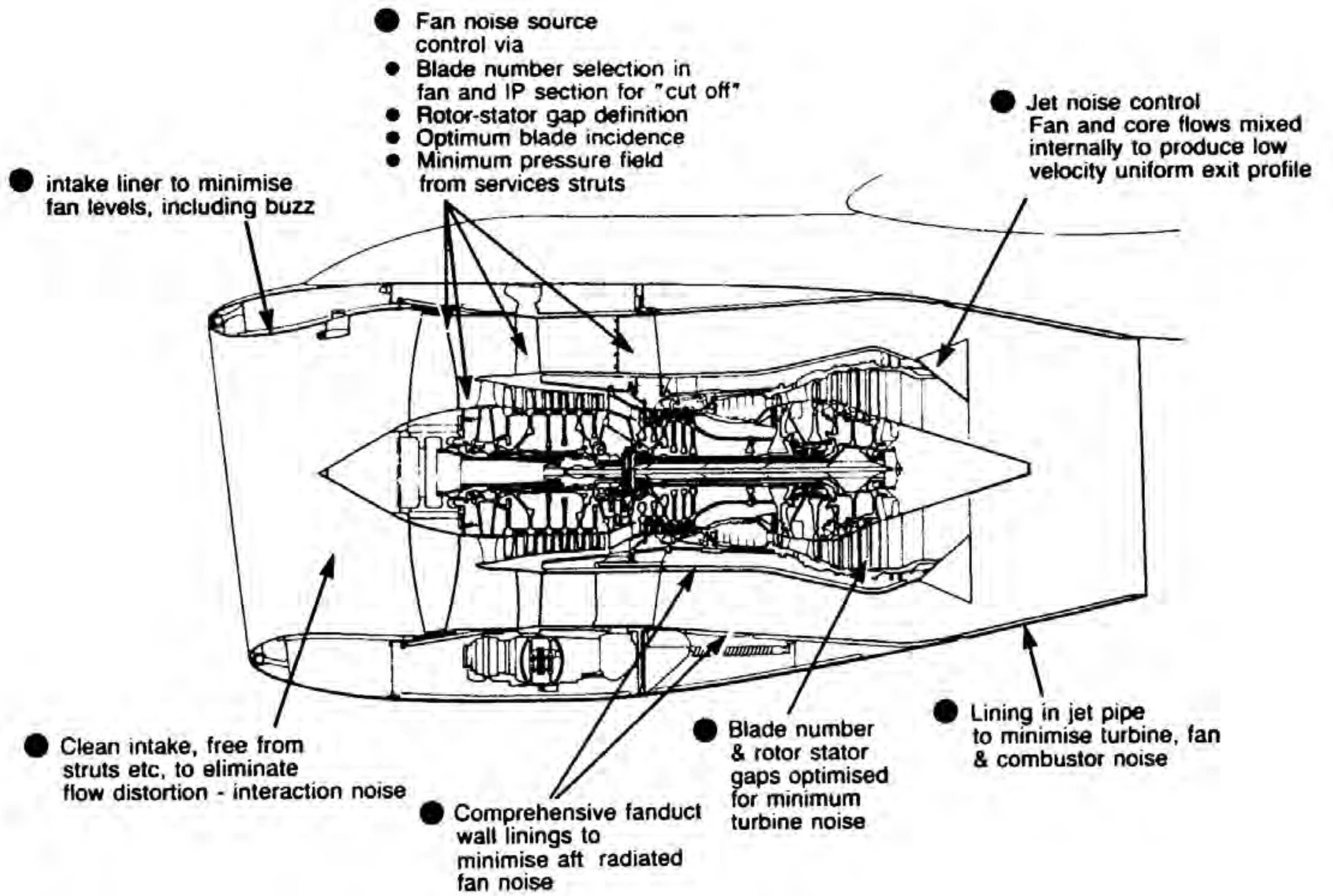


Figure 136: Devices for turbofan noise control.

6.12.1 PROPELLER NOISE

- **MAINLY DISCRETE TONES (GENERATED BY BLADE PASSAGE)**
- **WIDEBAND COMPONENT DUE TO TURBULENCE**
- **INTENSE WHEN M_{tip} CLOSE TO 1 ↔ CRUISE**

$$M_{tip} = \left[M_0^2 + \left(\frac{\omega \, D_{propeller}}{2 \, a_0} \right)^2 \right]^{1/2}$$

- **INTENSE CABIN NOISE IN CRUISE → TFs PREFERRED FOR LONG LEGS**
- **IN ORDER TO REDUCE NOISE:**
  - **REDUCE M_{tip}**
  - **INCREASE BLADE NUMBER N (HIGHER f, LOWER EAR SENSITIVITY, GREATER ATMOSPHERIC ATTENUATION)**
  - **FOR CONTRAROTATING PROPELLERS:**
    - **INCREASE SPACING BETWEEN THE TWO PROPELLER DISKS**
    - **USE COPRIME NUMBER OF BLADES**

6.12.2 PROPFAN (OPEN ROTOR) NOISE

- **HIGH M_0 → NOISE**
- **TAIL–MOUNTED, PUSHING PROPELLERS**

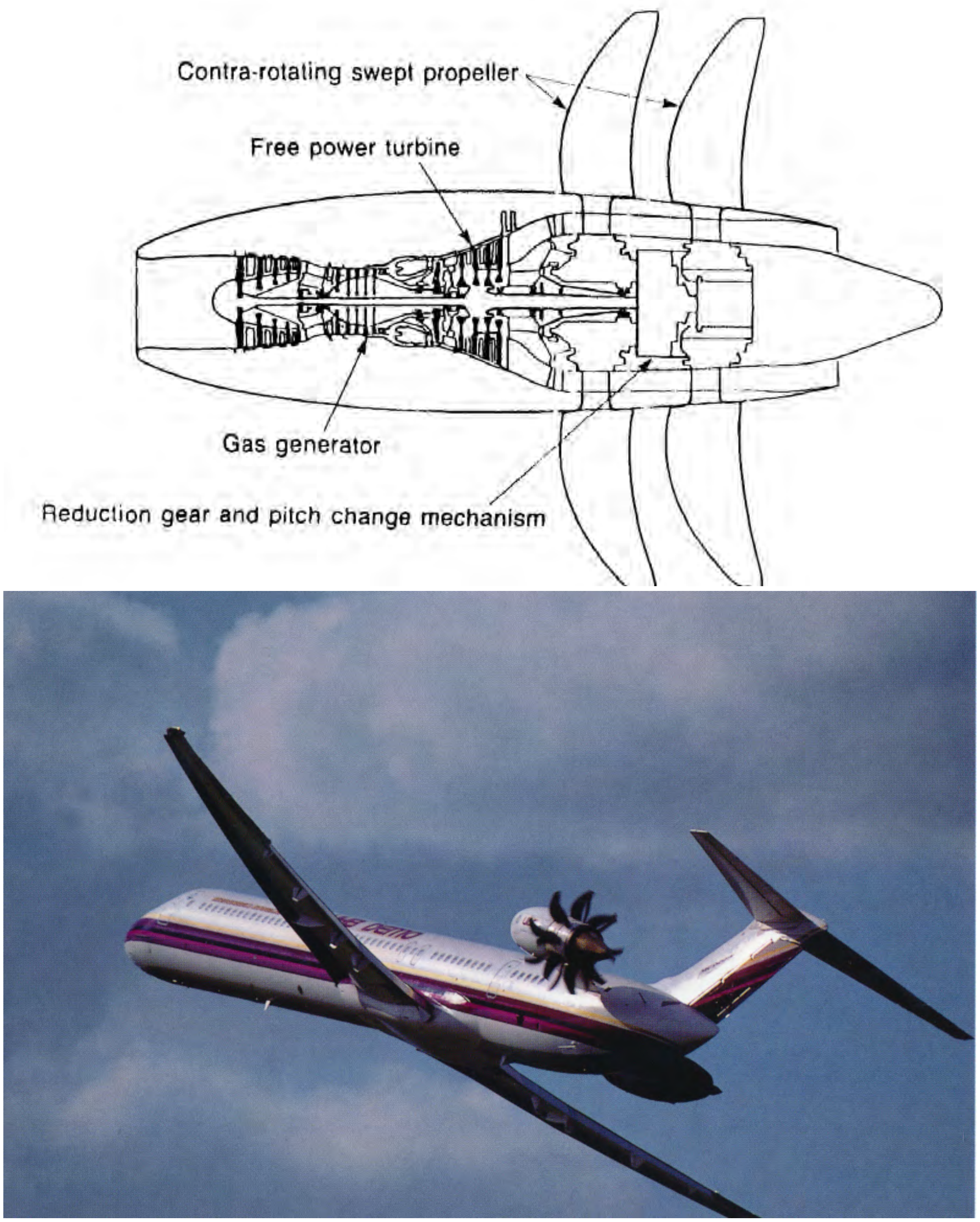


Figure 137: Propfan with contrarotating, pushing propellers.

6.12.3 PROPFAN PROPELLER

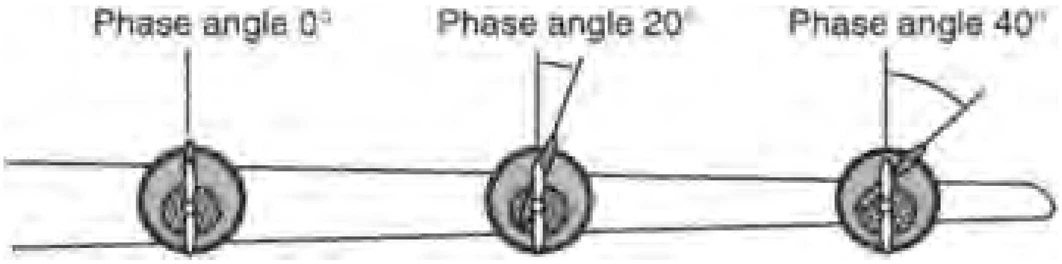
- **BLADE SHAPE SIMILAR TO SWEPT WING**

6.12.4 PUSHER vs. TRACTOR PROPELLERS

- **PUSHER PROS: LOWER INTERACTION PROPELLER WAKE/WING**
- **PUSHER CONS: GROUND CLEARANCE AT TAKE–OFF, MORE NOISY, ENGINE T**

6.12.5 MULTI–ENGINE AIRPLANES

- **ALL PROPELLERS MUST ROTATE AT SAME SPEED TO AVOID BEATS**
- **SYNCROPHASING (SAME PHASE)**



6.13 AIFRAME NOISE

- **TURBULENT BOUNDARY LAYER**
- **HIGH–LIFT DEVICES**
- **UNDERCARRIAGE**
- **VORTICES AT TRAILING EDGES OF WINGS, EMPENNAGES, FUSELAGE**

- **BOUNDARY LAYER LAMINARIZATION TECHNIQUES (ALSO REDUCE DRAG)**
- **UNDERCARRIAGE FAIRING (WEIGHT)**

6.14 CABIN NOISE

- **TURBULENT BOUNDARY LAYER:**
  - **INTENSITY $\propto V_0^{5-6}$, $\propto p_a^2$**
  - **MAX AT TAKE–OFF, LOWER IN CRUISE**
- **NOISE FROM AIR CONDITIONING/ PRESSURIZATION PLANTS**
- **ENGINE NOISE**
- **NOISE INCREASES FROM NOSE TO TAIL (BOUNDARY LAYER): 1st CLASS FORE**
- **SOUND–PROOFING**
- **ENGINE NOISE PARTIALLY SHIELDED BY WINGS (WHICH HOWEVER INCREASE NOISE RADIATED TOWARDS GROUND)**

7.1 SUPERSONIC AIRCRAFT EMISSIONS

- **ENVIRONMENTAL IMPACT OF SST (*Super-Sonic Transport*) PARTICULARLY HIGH DUE TO:**

  1. **HIGH FUEL CONSUMPTION PER PAX–km → CONTAMINANTS AND POLLUTANTS (PLUS COSTS)**
  2. **HIGH FLIGHT ALTITUDE (HIGH CONCENTRATION OZONE)**
  3. **INTENSE NOISE:**
     - **JET**
     - **BANG**

7.2.1 FUEL CONSUMPTION

- **RANGE**

$$\boldsymbol{s = \frac{Q_f}{g} \eta_o \frac{L}{D} \log \frac{m_{TO}}{m_L}}$$

- **FUEL FRACTION:**

$$\boldsymbol{\frac{m_f}{m_{TO}} = \frac{m_{TO} - m_L}{m_{TO}} = 1 - \exp\left(-\frac{s\,g}{\eta_o \frac{L}{D} Q_f}\right)}$$

DECREASING WITH $\boldsymbol{\eta_o \frac{L}{D}}$

7.2.2 EFFICIENCIES *vs.* M_0

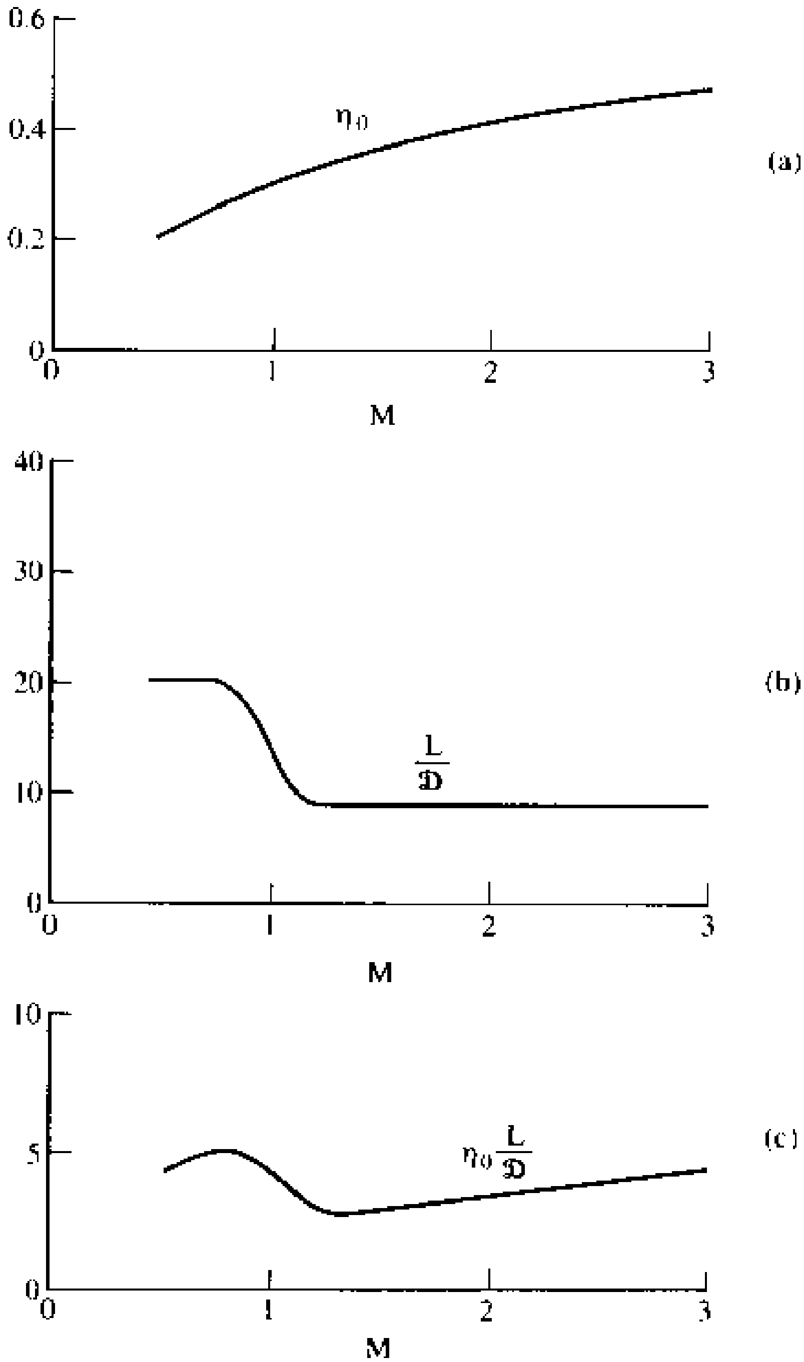


Figure 138: Typical trend of engine overall efficiency, aerodinamic efficiency, and their product as a function of flight Mach number.

7.2.3 EFFECT OF $\eta_o\, L/D$

- **FOR $M_0 < 3$**

$\rightarrow \eta_o\, L/D$ LOWER THAN SUBSONIC A/Cs:

- **m_f LARGER, m_{pl} SMALLER $\rightarrow$ HIGHER FUEL CONSUMPTION PER PAX–km**
- **HIGHER EMISSIONS OF GHGs**
- **HIGHER EMISSIONS OF POLLUTANTS ($EINO_x$, EICO, EIUHC)**

- **FOR $M_0 > 3$**

$\rightarrow \eta_o\, L/D$ HIGHER THAN SUBSONIC A/Cs:

- **HOWEVER, ALUMINUM CANNOT BE USED FOR $M_0 > 2,4$**
- **STEEL OR TITANIUM, HEAVIER ($\rightarrow$REDUCTION m_{pl}) AND MORE COSTLY**

7.3 EFFECT ON OZONE LAYER

- **SUPERSONIC A/Cs ATTAIN OPTIMAL L/D AT ALTITUDE HIGHER THAN SUBSONIC**
- **HIGHER FLIGHT ALTITUDE $z \longrightarrow$ HIGHER OZONE CONCENTRATION $\longrightarrow$ HIGHER DEPLETION**

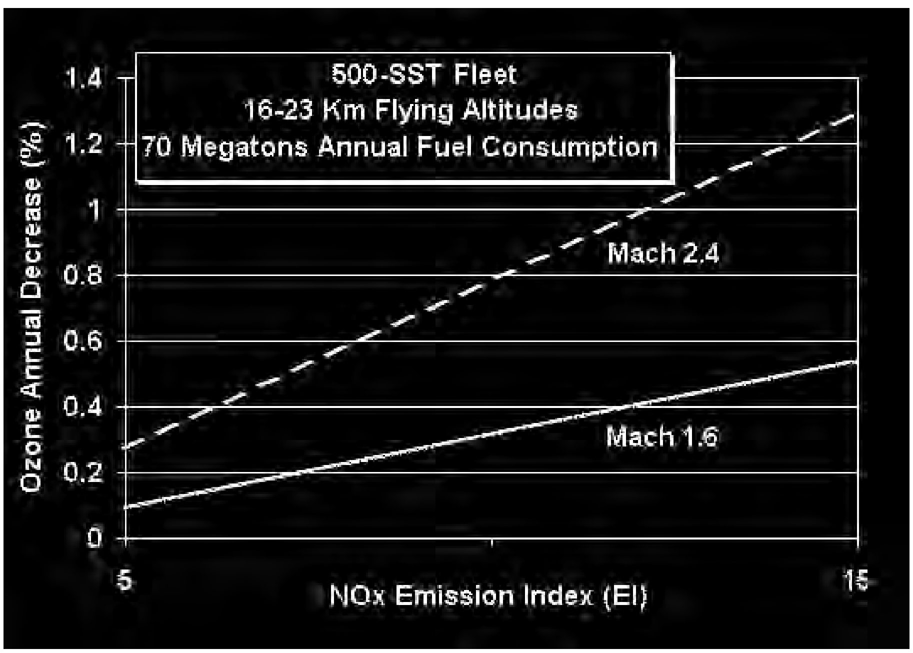


Figure 139: Effect of a SST fleet on stratospheric ozone depletion.

7.4.1 NOISE FROM SUPERSONIC AIRCRAFTS

1. **u_e VERY HIGH $\longrightarrow$ JET NOISE VERY INTENSE (VARIABLE–CYCLE ENGINES REQUIRED – IN PRINCIPLE)**
2. **SONIC BANG (ON GROUND VERY SMALL Δp e.g., CONCORDE $\simeq$ 100 Pa, BUT dp/dt HIGH)**
   - **SHOCK INTENSITY $\Delta p \propto (M_0^2 - 1)$ (BUT FUEL CONSUMPTION PER PAX–km HIGH AT MODERATE M_0, DUE TO η_o L/D)**

7.4.2 WAVE EQUATION AT SECOND ORDER [2]

[2] $$p - p_0 = \gamma\, p_0\, s \left(1 + \frac{\gamma - 1}{2} s\right) = \rho_0\, a_0^2\, s \left(1 + \frac{\gamma - 1}{2} s\right)$$

- MASS CONS. (EXACT): $s = -(1+s)\,\dfrac{\partial \xi}{\partial x}$

$$p - p_0 = -\rho_0\, a_0^2\, \frac{\partial \xi}{\partial x}(1 + s)\left(1 + \frac{\gamma - 1}{2} s\right) =$$

$$= -\rho_0\, a_0^2 \frac{\partial \xi}{\partial x}\left(1 + s + \frac{\gamma - 1}{2} s + \frac{\gamma - 1}{2} s^2\right)$$

[2] $$p - p_0 = -\rho_0\, a_0^2\, \frac{\partial \xi}{\partial x}\left(1 + \frac{\gamma + 1}{2} s\right)$$

- MOMENTUM EQ.:

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} = -\frac{\partial (p - p_0)}{\partial x} = \rho_0\, a_0^2 \frac{\partial^2 \xi}{\partial x^2}\left(1 + \frac{\gamma + 1}{2} s\right) +$$

$$+ \rho_0\, a_0^2\, \frac{\gamma + 1}{2}\, \frac{\partial \xi}{\partial x}\, \frac{\partial s}{\partial x}$$

- $\dfrac{\partial \xi}{\partial x}\dfrac{\partial s}{\partial x} = s\, \dfrac{\partial^2 \xi}{\partial x^2}$

$$\Longrightarrow \frac{\partial^2 \xi}{\partial t^2} = a_0^2\, [1 + (\gamma + 1)\, s]\, \frac{\partial^2 \xi}{\partial x^2}$$

POSITIVE PEAKS TRAVEL FASTER THAN NEGAT. PEAKS

7.4.3 DEFORMATION OF A FINITE–AMPLITUDE WAVE

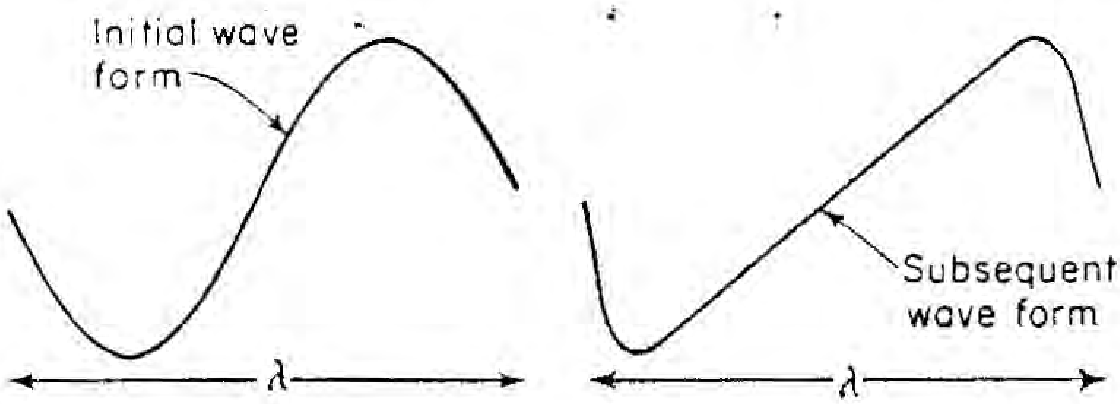


Figure 140: Deformation of wave shape.

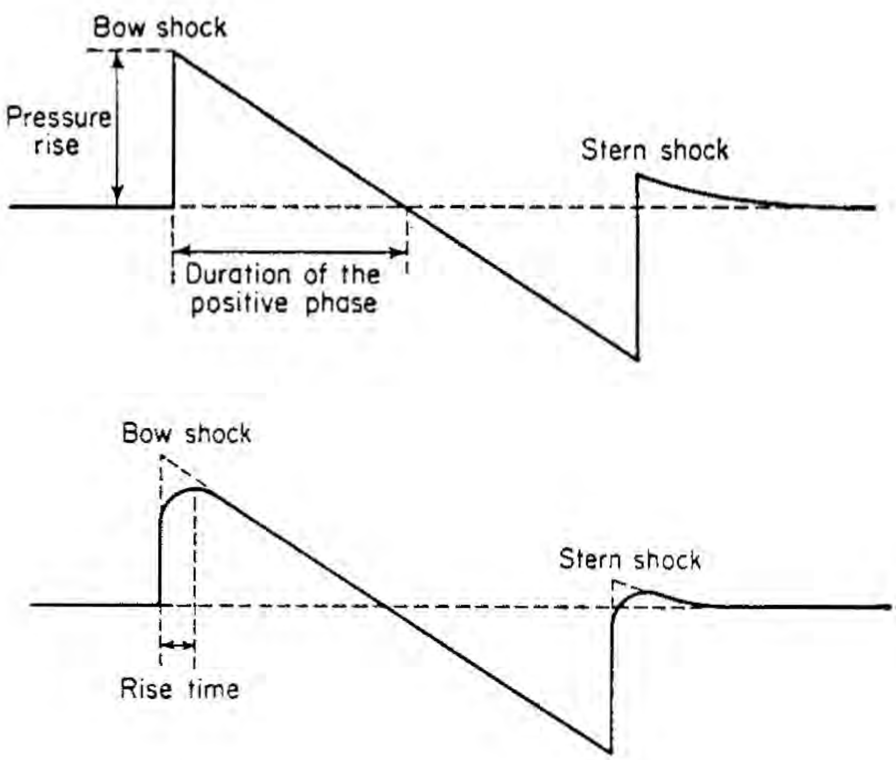


Figure 141: Ideal N–wave (top) and real one (bottom).

7.4.4 SHOCK CONOID

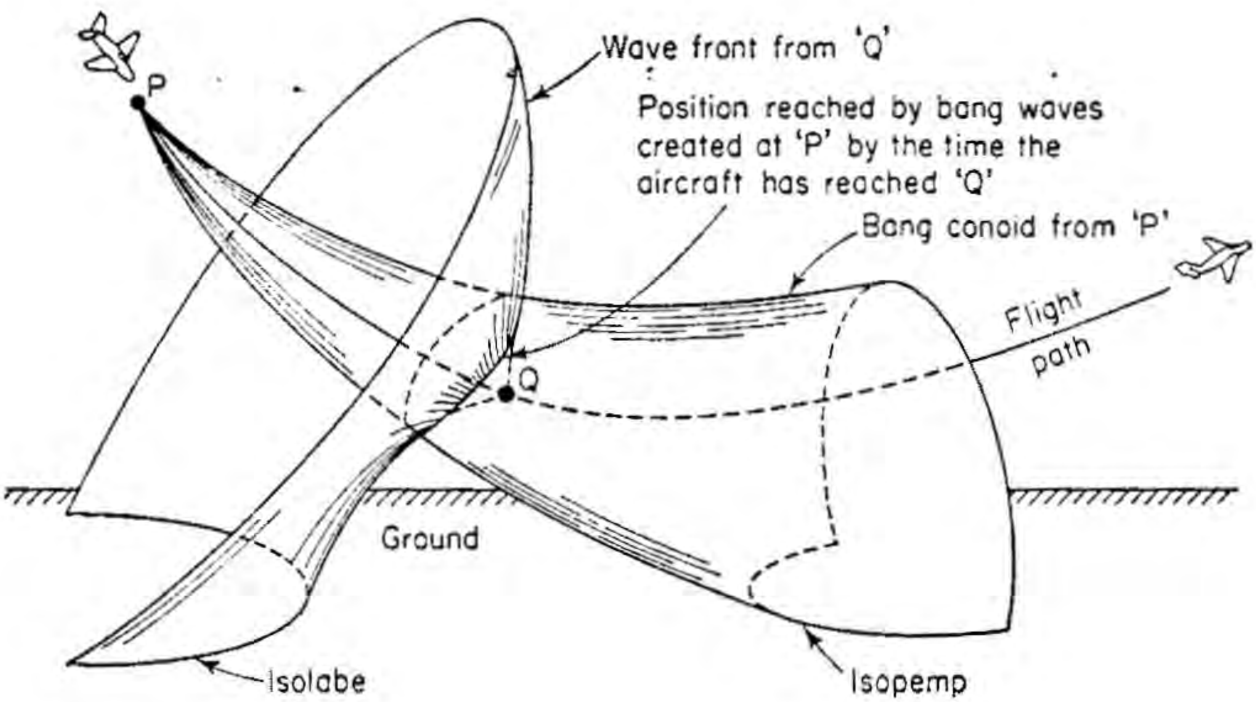


Figure 142: Wave front and shock conoid.

- **ϕ ANGLE BTWN BANG RAY AND HORIZONTAL**
- **SNELL's LAW:** $\dfrac{\sin\theta_1}{a_1} = \dfrac{\sin\theta_2}{a_2}$ → **FOR LEVEL FLIGHT** →

$$\longrightarrow \frac{\cos\phi_1}{a_1} = \frac{\cos\phi_2}{a_2} \quad\Longrightarrow\quad \cos(\phi_2) = \frac{a_2}{a_1}\cos(\phi_1)$$

- $\phi_2 < \phi_1$ **IF** $a_2 > a_1$, $\quad \phi_2 > \phi_1$ **IF** $a_1 > a_2$

7.4.5 GROUND EFFECT

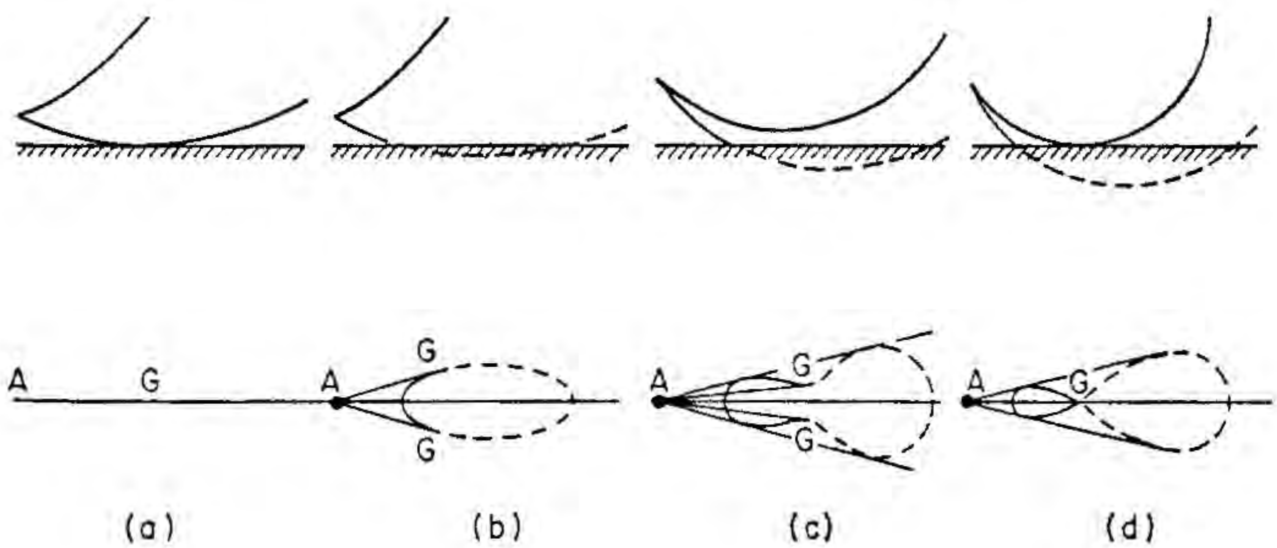


Figure 143: Interaction of conoid with the ground.

7.4.6 MAX DEFLECTION OF BANG RAYS

- **μ MACH CONE ANGLE:**

$$\sin(\mu) = \frac{1}{M}$$

- $\phi = \frac{\pi}{2} - \mu \longrightarrow \cos(\phi) = \sin(\mu) = \frac{1}{M}$

- $\cos(\phi_2) = \frac{a_2}{a_1}\frac{1}{M}$

- **$\phi=0$ CAN BE ATTAINED ONLY IF $M_0 < \frac{a_{S/L}}{a_0}$**

  (=1,15 FOR ALTITUDES $11000 \le z \le 20000$ m)

- **ADDITIONAL EFFECTS OF WIND, LATERAL TEMPERATURE GRADIENTS,...**

7.4.7 EFFECT OF GROUND REFLECTION

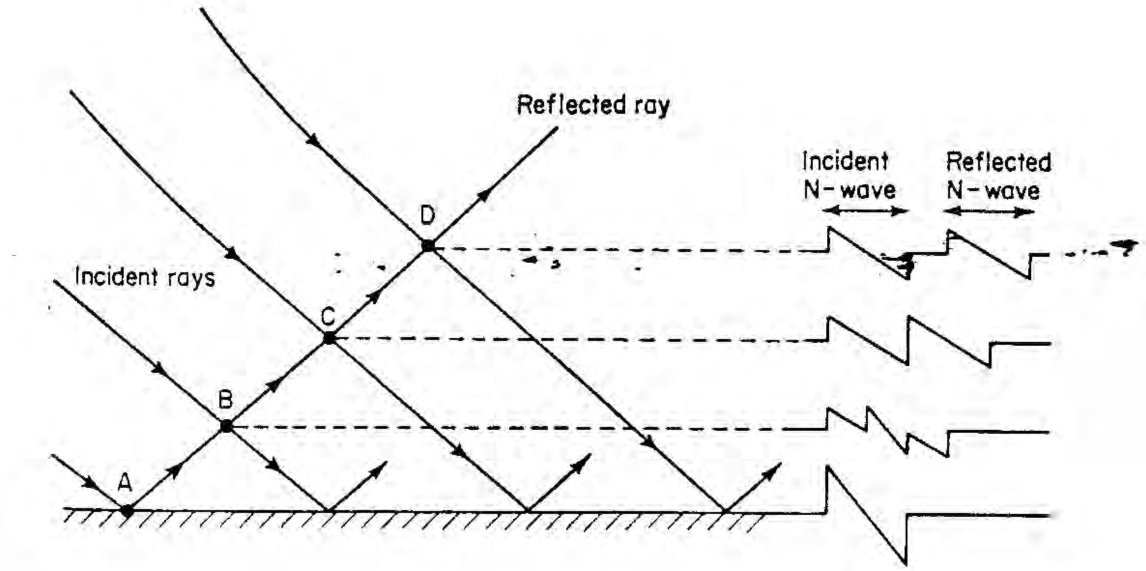


Figure 144: Effect of ground reflections.

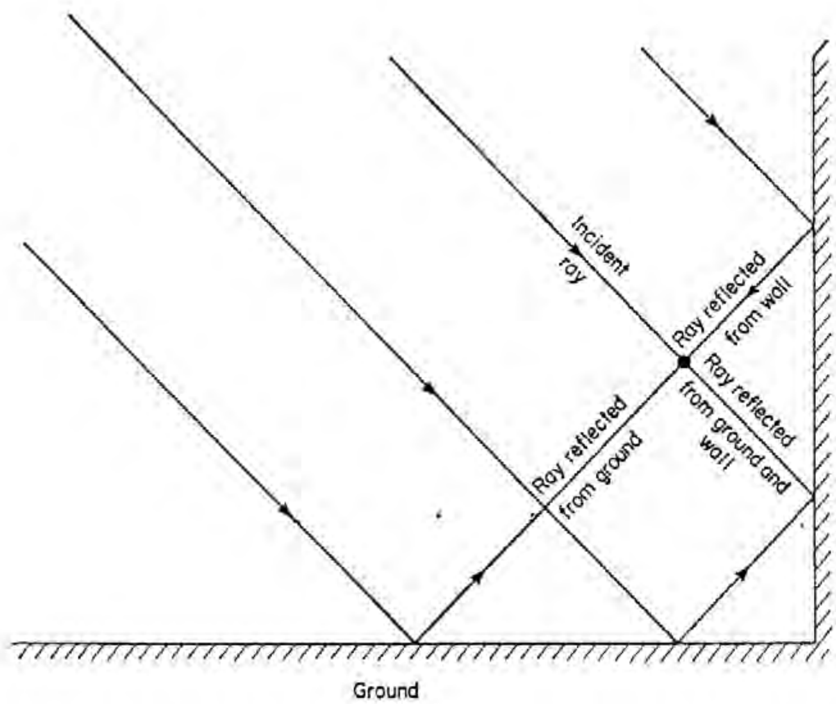


Figure 145: Effect of reflections on the ground and on vertical walls.

7.5.1 FURTHER PROBLEMS OF SSTs

- **LARGE SENSITIVITY TO INCREASE OF $TSFC$ OR m_e**
- **FLIGHT STABILITY WITH VARYING M_0 (VARIABLE GEOMETRY)**
- **PRESSURE CENTRE SHIFTS REARWARD AS M_0 IS INCREASED**

7.5.2 COMPENSATION OF PRESSURE CENTRE SHIFT – XB–70

Figure 146: (top) XB–70 at take–off; (below) wing tips dropping at altitude.

7.5.3 COMPENSATION OF PRESSURE CENTRE SHIFT – CONCORDE

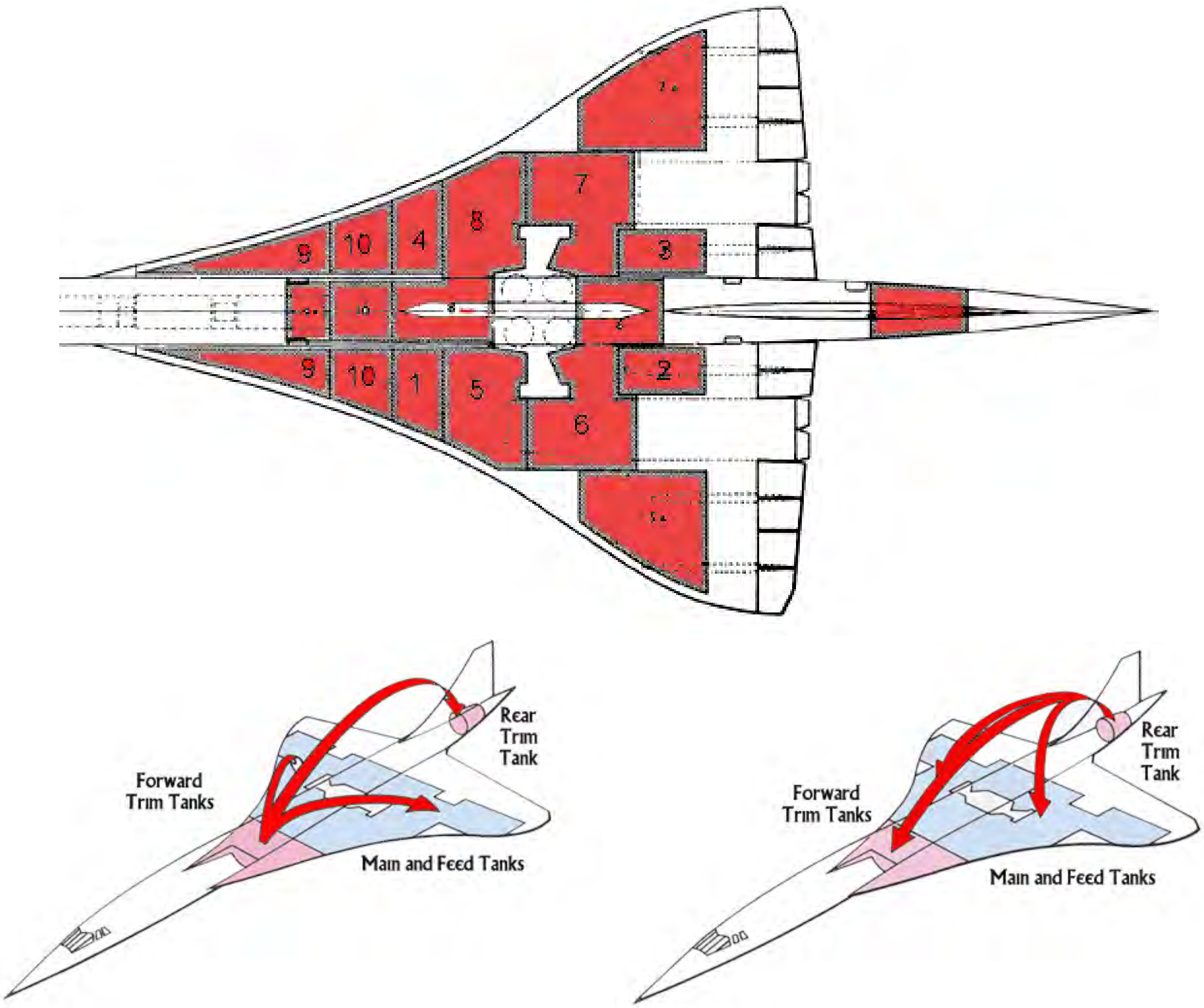


Figure 147: Compensation of pressure centre shift in the Concorde.

7.5.4 ALTERNATIVE CONFIGURATION

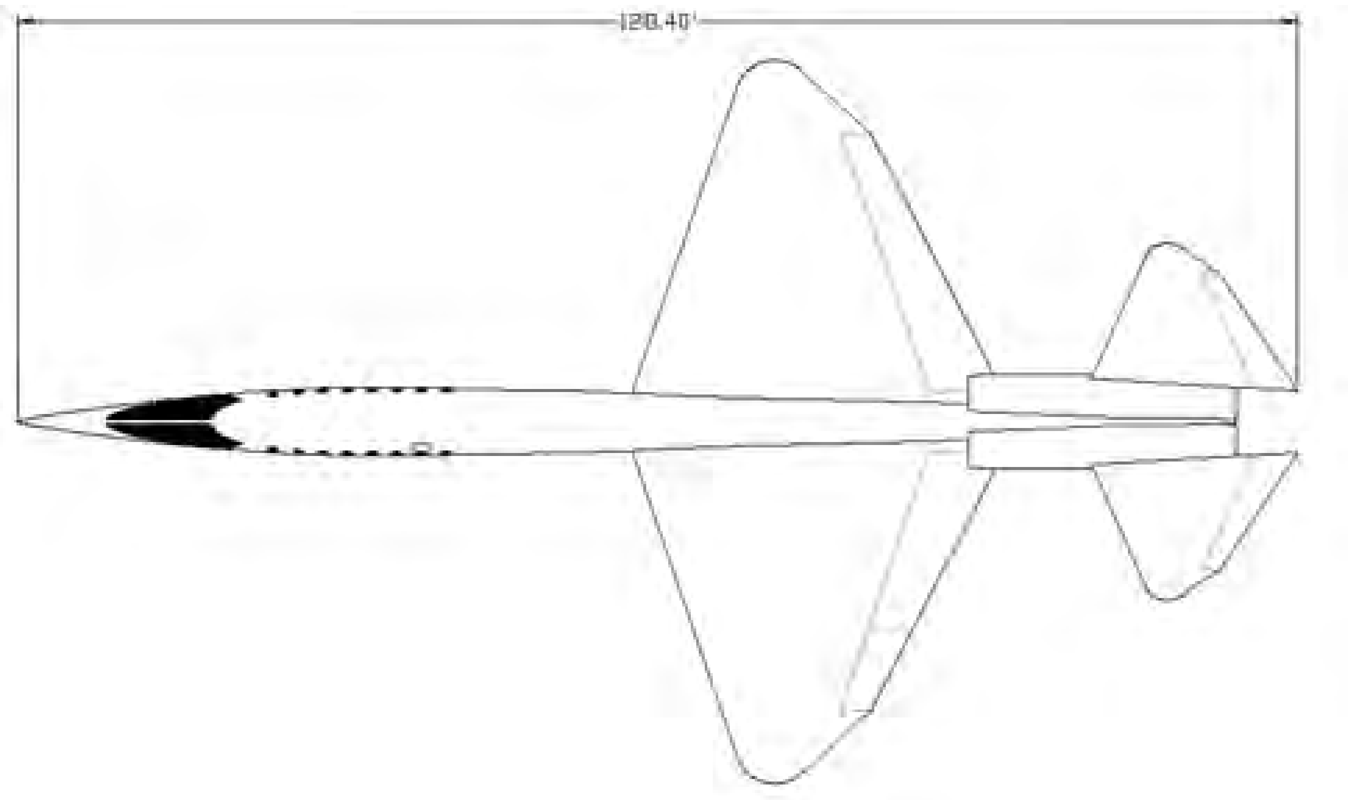


Figure 148: Straight wing configuration of a supersonic business jet.

→ **LARGER STRUCTURAL MASS, LIMITED M_0**

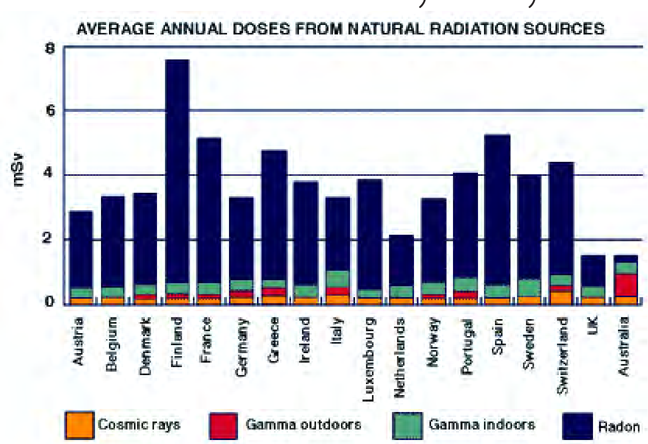
7.5.5 EXPOSURE TO COSMIC RAYS

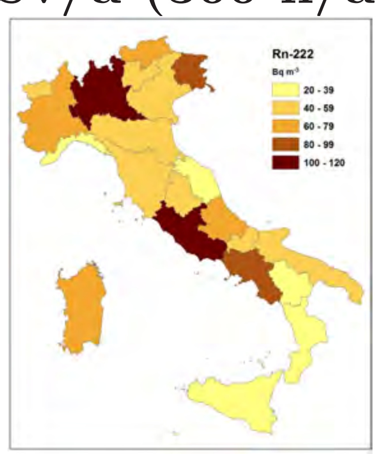
- **MEASURED IN Sievert (Sv): $D \cdot Q$**

D DOSE: ENERGY PER UNIT BODY MASS, J/kg

Q QUALITY FACTOR: 1 FOR PHOTONS/ELECTRONS 10 FOR NEUTRONS, 20 FOR α PARTICLES

- **NATURAL BACKGROUND DOSE $\sim$ 2,4 mSv/a**
- **COSMIC RAY INTENSITY DEPENDS ON ALTITUDE, LATITUDE, SOLAR ACTIVITY**
- **FLIGHT DOSES:**
  - **SHORT RANGE A/Cs: 1 – 3 μSv/h**
  - **LONG RANGE A/Cs: 5 μSv/h**
  - **CONCORDE: 12 – 15 μSv/h**
- **CREW ANNUAL EFFECTIVE DOSE:**
  - **LONG RANGE A/Cs: 2,1–4,6 mSv/a (700 h/a)**
  - **CONCORDE: 2,6–2,8 mSv/a (300 h/a)**





8.1 UNCONVENTIONAL CONFIGURATIONS

- **INTENDED TO:**
  - **INCREASE L/D AND/OR DECREASE WEIGHT**
    → LESS POWERFUL ENGINES
    → LOWER EMISSIONS OF POLLUTANTS AND NOISE
  - **SHIELD NOISE RADIATED TOWARD GROUND**

8.2.1 MULTIFUSELAGE CONFIGURATIONS

- **REDUCE WING LOAD → WEIGHT; EASIER EMERGENCY EVACUATION**
- **GREATER DRAG; LANDING PROBLEMS WITH ONE ENGINE OFF**

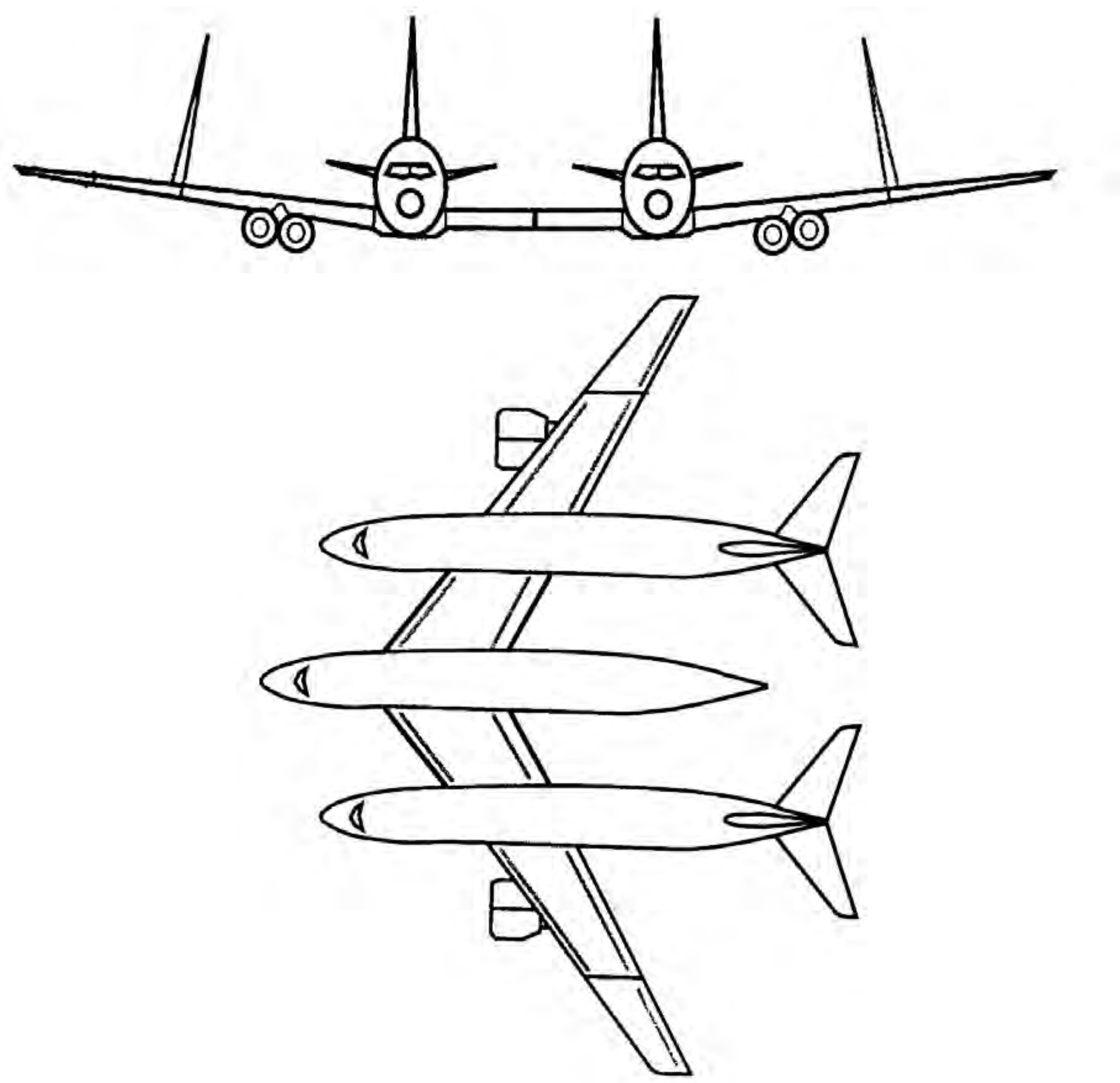


Figure 149: Multifuselage configurations.

8.2.2 COMPARISON OF CONFIGURATIONS WITH 1 AND 2 FUSELAGE(s) (1)

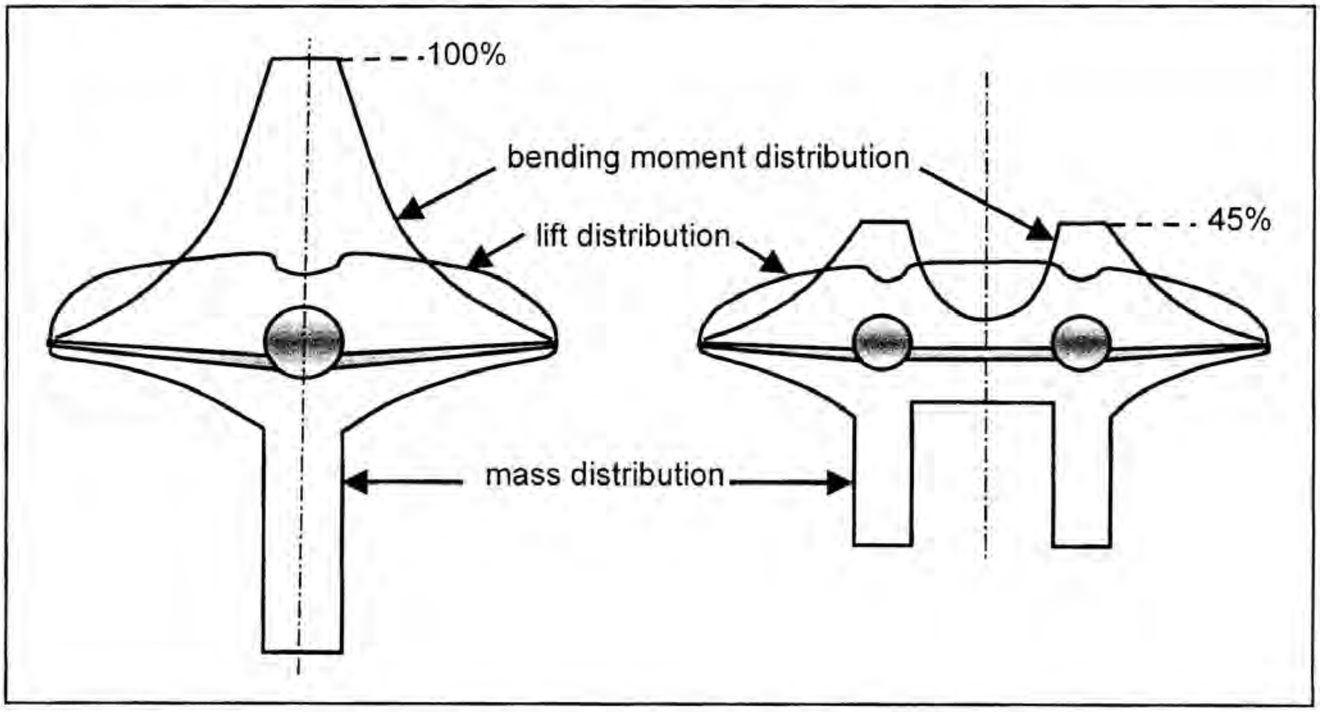


Figure 150: Distribution of lift, mass and bending momentum in configurations with single fuselage (left) and two fuselages (right).

8.2.3 COMPARISON OF CONFIGURATIONS WITH 1 AND 2 FUSELAGE(s) (2)

- **TWO MODIFIED AIRBUS 318 FUSELAGES**

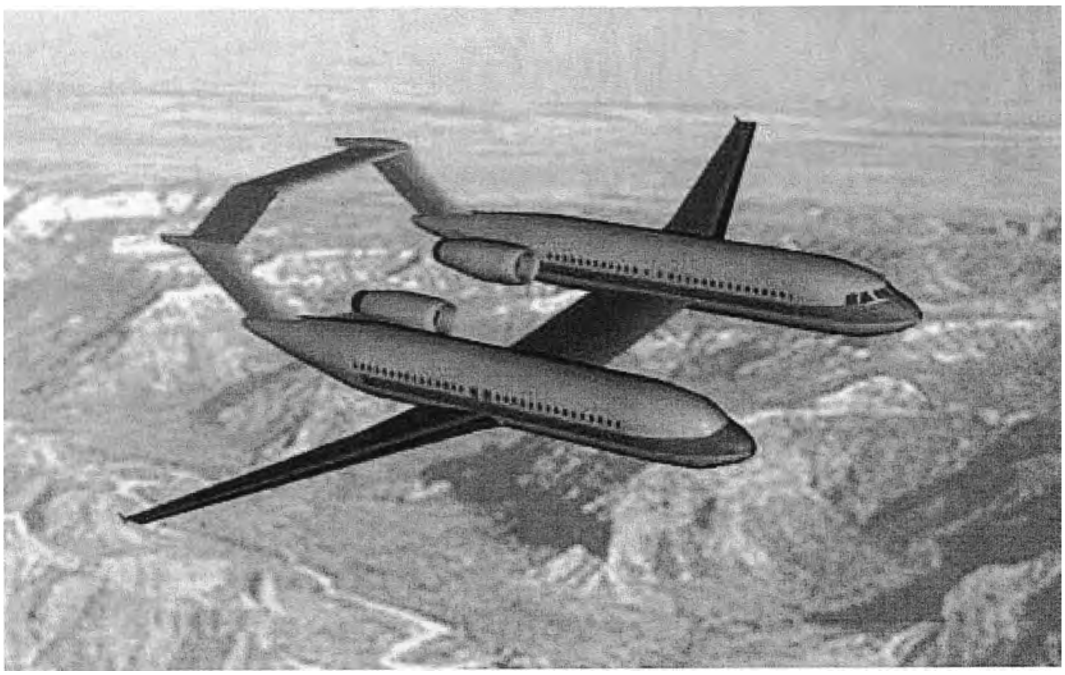


Figure 151: Configuration with engines mounted in between fuselages to reduce ground noise.

design mass, kg	conventional	2-F	Δ %
MTOW	155,000	134,000	-13.5
MLW	128,000	113,000	-11.7
MZFW	120,000	106,000	-11.7
OEW	84,000	70,000	-16.7
payload (struct. limit)	36,000	36,000	0
block fuel (8,000 km)	40,715	34,245	-15.9
installed thrust, kN	2 × 222.5	2 × 178.0	-20.0

Figure 152: Comparison of masses and thrust in configurations with single and two fuselage(s).

8.2.4 SPAN–LOADER CONFIGURATION

- **WING LOAD REDUCED → WEIGHT**
- **'VIRTUAL WINDOWS' FOR REAR SEATS**
- **LIMIT: *FLYING WING***

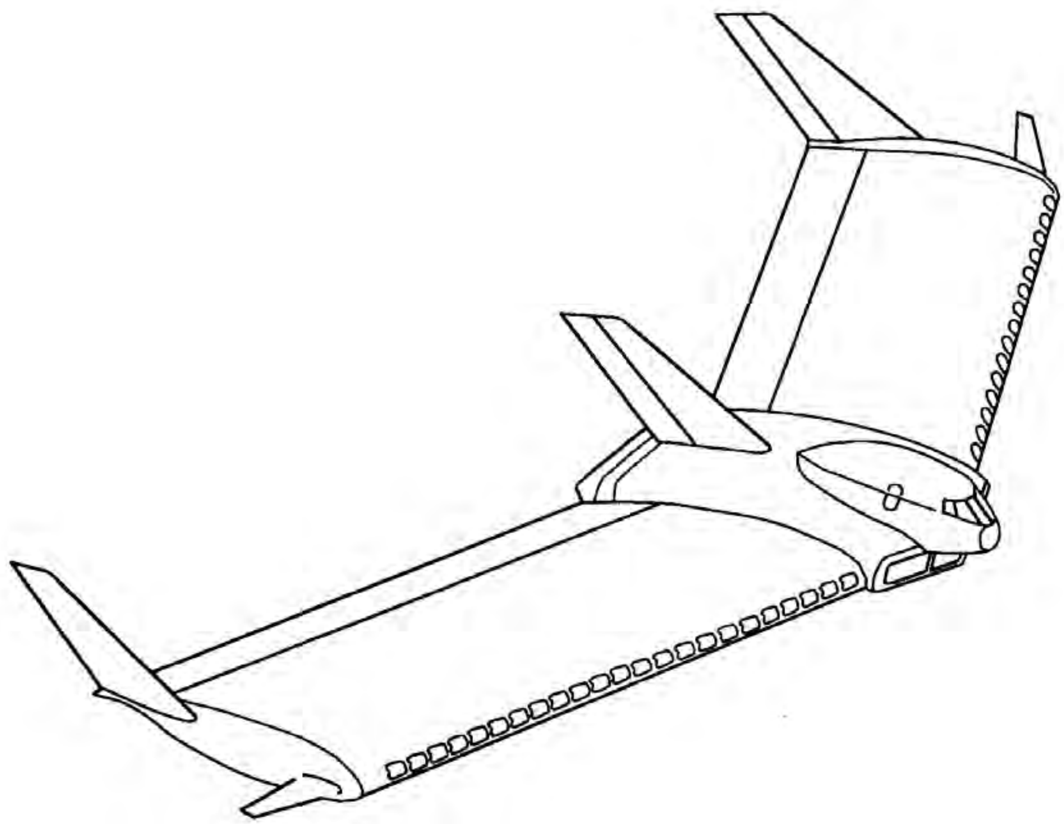


Figure 153: Span–loader configuration.

8.2.5 OPTIMAL SPLITTING OF VOLUME BETWEEN WINGS AND FUSELAGE

- **e.g., BOEING 747: 18% VOLUME IN WINGS, 82% FUSELAGE**
- **LIMIT SPAN–LOADER: *FLYING WING* (100% VOLUME IN WING)**

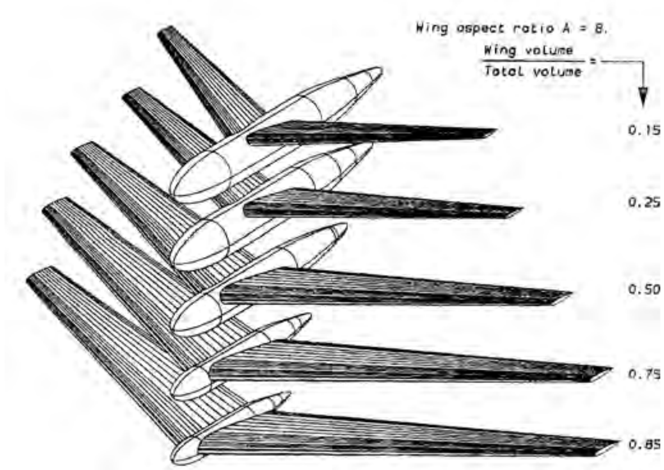


Figure 154: Wing–fuselage combinations with same total volume.

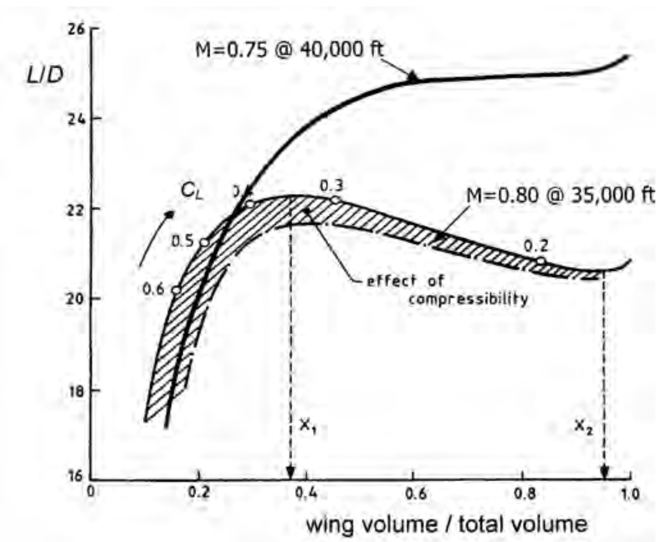


Figure 155: L/D ratio as a function volume fraction allotted to wings.

8.2.6 PRANDTL WING CONFIGURATION

- **MINIMUM INDUCED DRAG**
- **HORIZONTAL TAILPLANE ELIMINATED → REDUCED WEIGHT AND DRAG**
- **REDUCED WINGSPAN**
- **STRESS CONCENTRATION**
- **CABIN NOISE**

Figure 156: Prandtl wing configuration.

8.2.7 OBLIQUE FLYING WING CONFIGURATION

- **ENABLES ADAPTING SWEPT–WING ANGLE TO FLIGHT SPEED**
- **ROTATION ENGINES AND EMPENNAGES**

Figure 157: Oblique flying wing configuration.

8.2.8 FORMATION FLYING

- **REDUCED AERODYNAMIC DRAG THANKS TO HIGHER ASPECT RATIO $AR = S/b^2$**

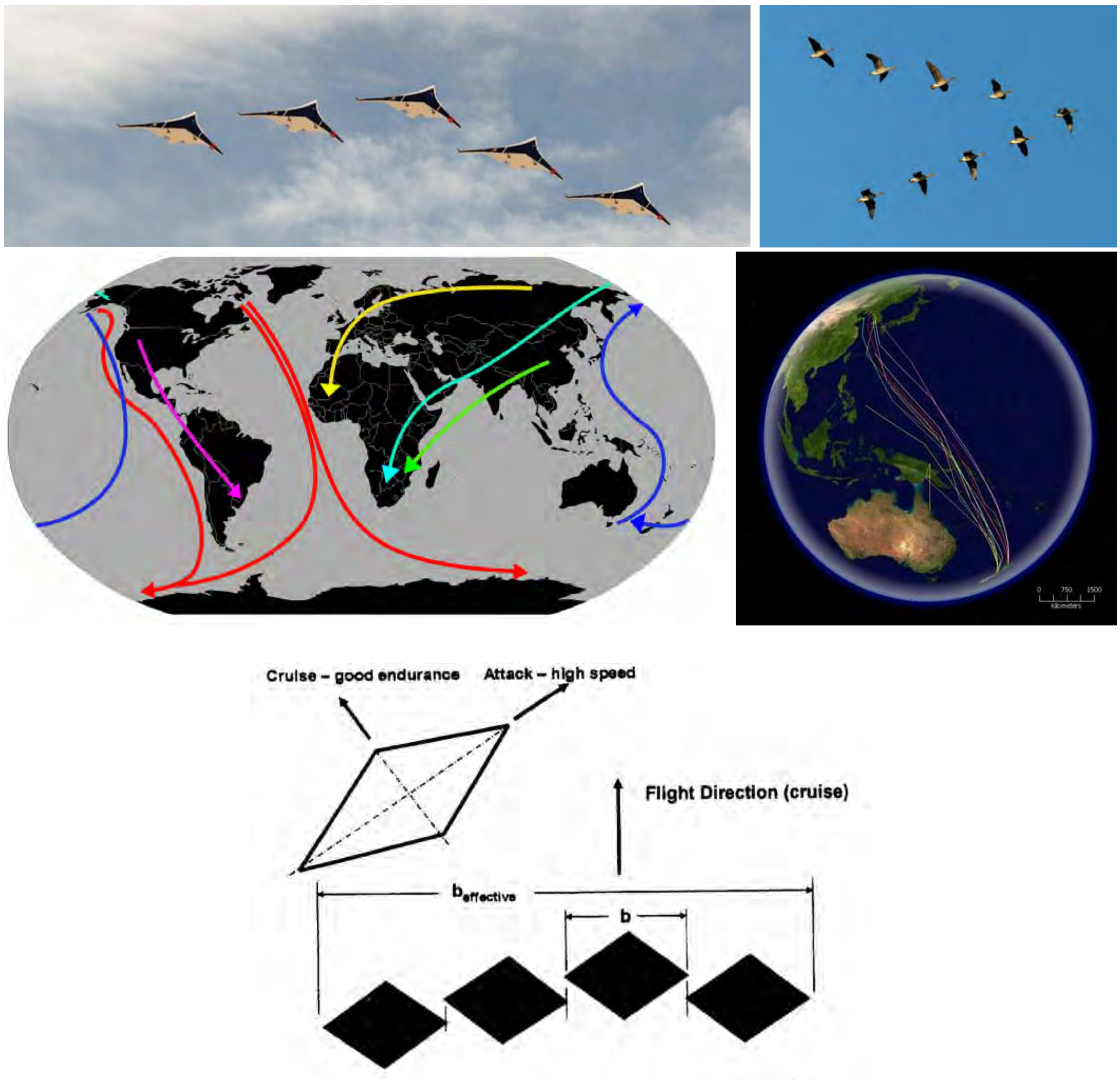
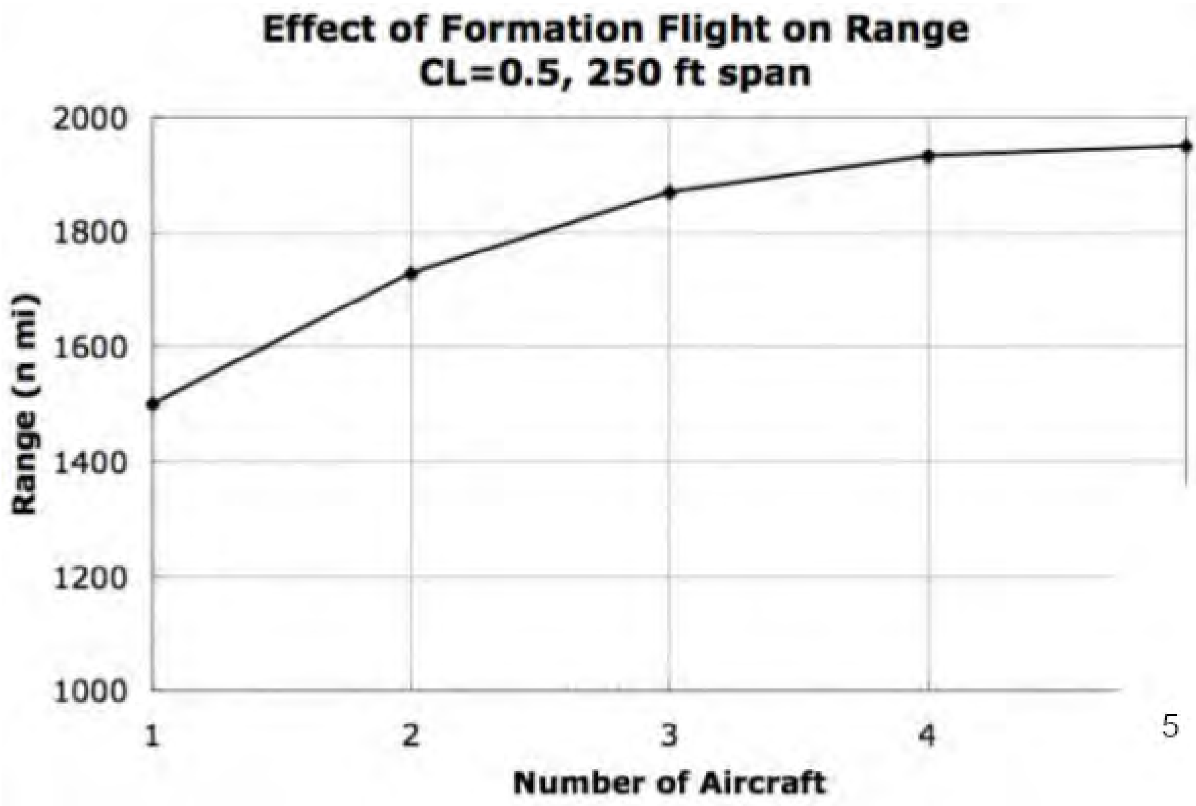


Figure 158: Increase of effective wingspan; possible use in two operating conditions (top).

8.2.9 EFFECT OF NO. AIRCRAFTS IN FORMATION



- **HOWEVER:**
  - **OPERATIONAL COSTS MULTIPLIED**
  - **HIGHER RISK OF COLLISION**
  - **POSSIBLY CONVENIENT FOR FLIGHTS TO CLOSE DESTINATIONS, e.g.:**

ROME →
NEW YORK
BOSTON
WASHINGTON
PHILADELPHIA

8.3.1 OWN AND RFN CONFIGURATIONS

- **NOISE RADIATED TOWARDS GROUND SHIELDED**
- **OWN: MORE INTENSE CABIN NOISE**
- **RFN: LARGER WEIGHT**

Figure 159: Over the Wing Nacelle configuration.

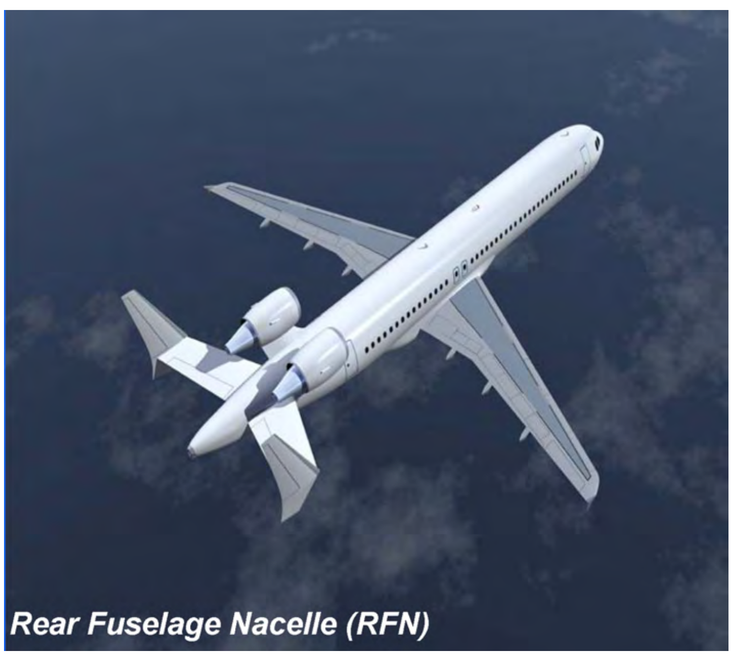


Figure 160: Rear Fuselage Nacelle configuration.

8.3.2 BLENDED WING–BODY CONFIGURATION

- **REDUCES WING LOAD → WEIGHT**
- **DOWNWARD NOISE SHIELDED**
- **MUCH REDUCED WINDOWS**
- ***EMBEDDED* CONFIGURATION QUIETER, BUT FLOW DISTORTED, LOWER ϵ_d, VERY CLOSE INTEGRATION ENGINE/AIRFRAME**

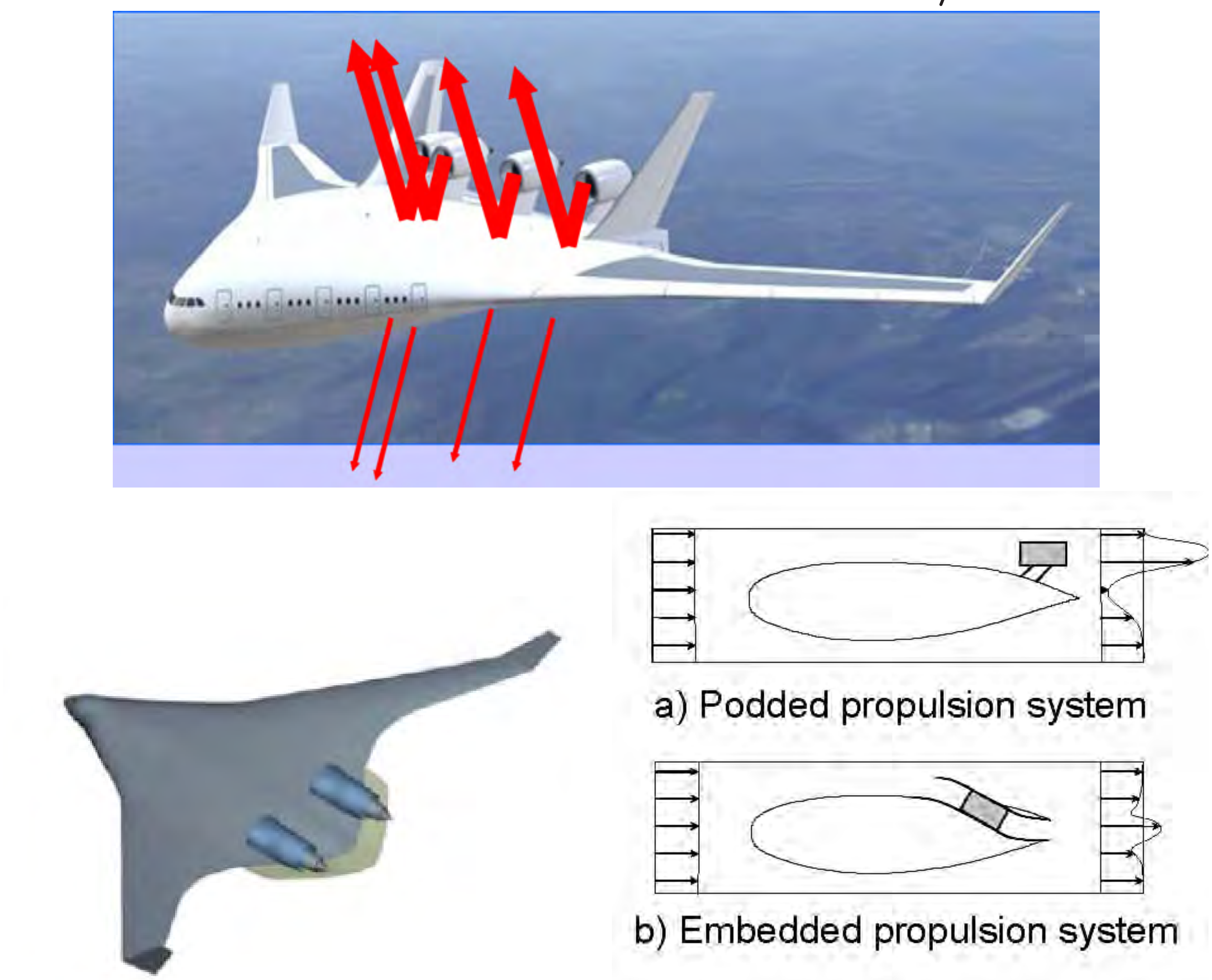


Figure 161: Blended wing–body configuration.

8.3.3 CANARD CONFIGURATION

- **FAN NOISE TOO SHIELDED (w.r.t. RFN)**
- **CONTROL MORE PROBLEMATIC**

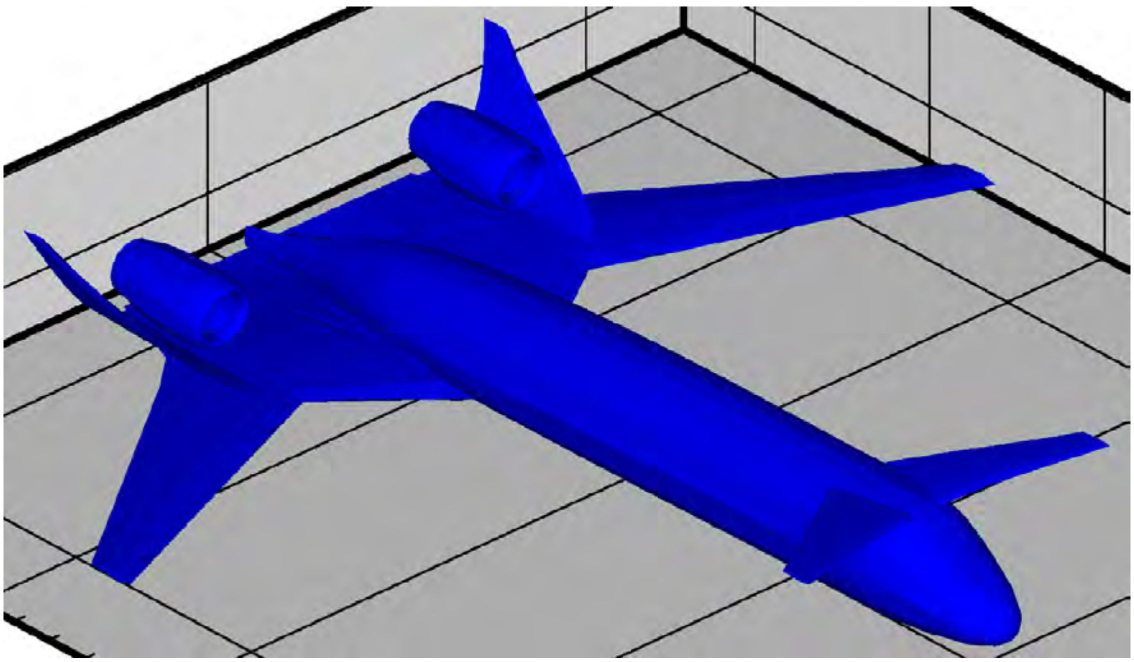


Figure 162: Canard configuration.

8.3.4 ENGINE OVER FUSELAGE CONFIGURATION

- **DOWNWARD NOISE SHIELDED**
- **WORSE PATTERN FACTOR**

Figure 163: EOF configuration.

8.3.5 QUIET SUPERSONIC A/C CONFIGURATION

- **TURBOFAN ENGINES AT TAKE–OFF/LANDING, TURBOJETS IN CRUISE**
- **MECHANICALLY COMPLEX**

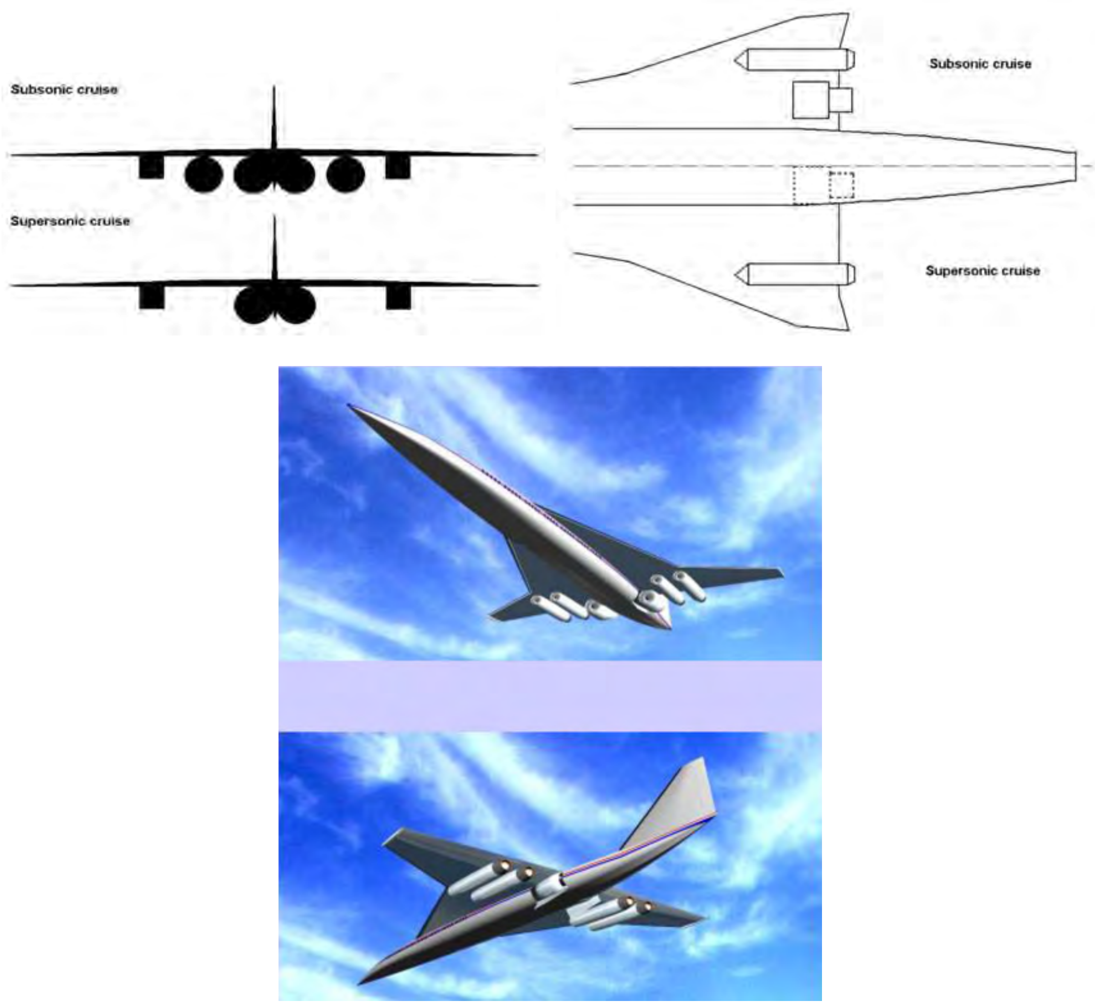


Figure 164: Supersonic aircraft with retractable engines.

8.4 FLATBED CONFIGURATION

- **REDUCED BOARDING/DISEMBARKMENT TIME**
- **SLIGHTLY NEGATIVE EFFECT ON EMISSIONS DUE TO INCREASED WEIGHT**

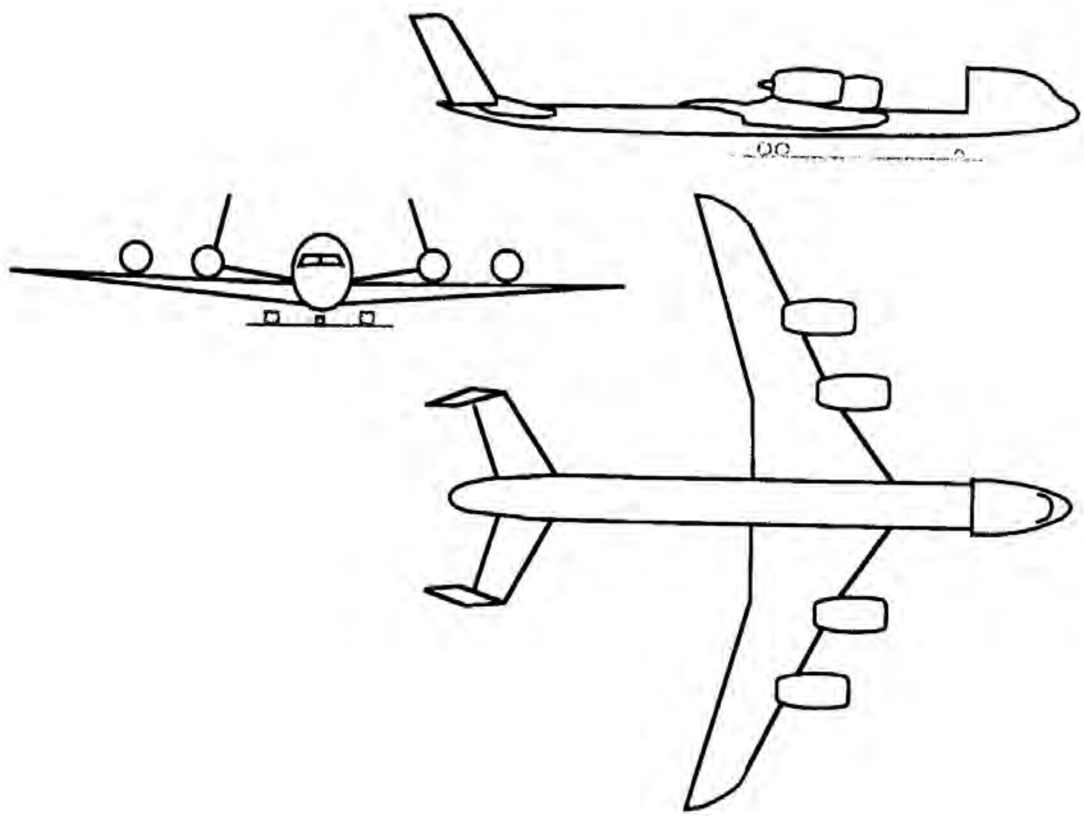
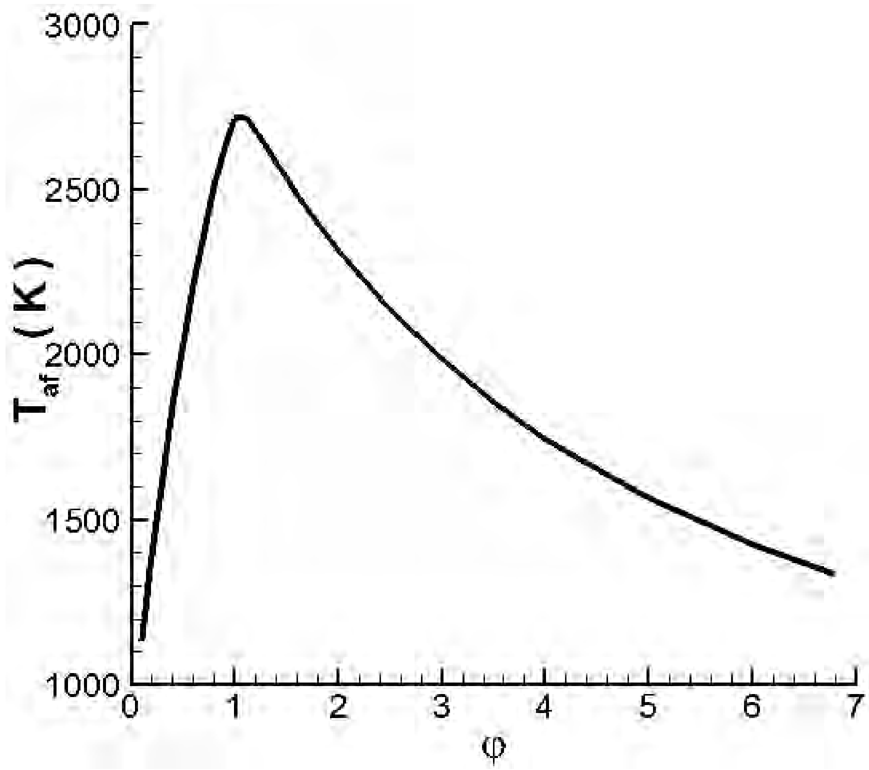


Figure 165: Flatbed configuration.

8.5.1 HYDROGEN–FUELLED A/Cs

- **LOWER EINO$_x$ $\sim$ 4.3 g/kg$_f$ THANKS TO WIDER FLAMMABILITY RANGE**



- **HYDROGEN: $\sim$ 3 TIMES AS MUCH ENERGY AS Jet–A PER UNIT MASS, BUT ONLY 0.26 PER UNIT VOLUME → LARGER, HEAVIER TANKS**
- **ZERO CO_2 AND SOOT → NO CONDENSATION OF ATMOSPHERIC UMIDITY**
- **HOWEVER, HYDROGEN IS MERELY AN ENERGY *CARRIER*, NOT A SOURCE**

8.5.2 HYDROGEN TANK LOCATION

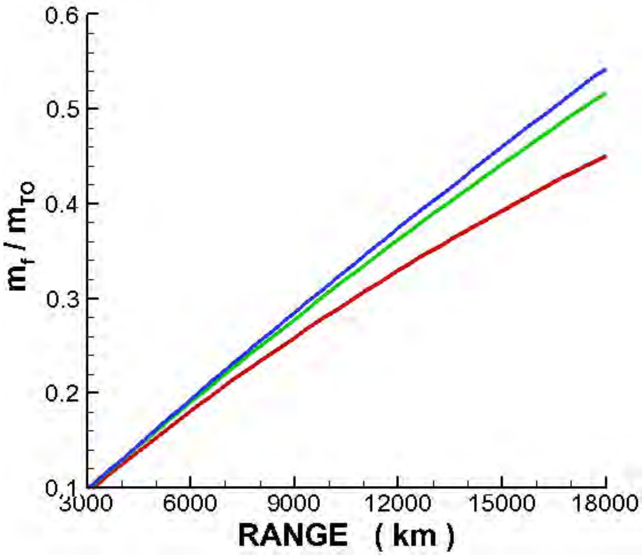
- **TANK ABOVE CABIN TO MINIMIZE CONSEQUENCES OF LEAKS**

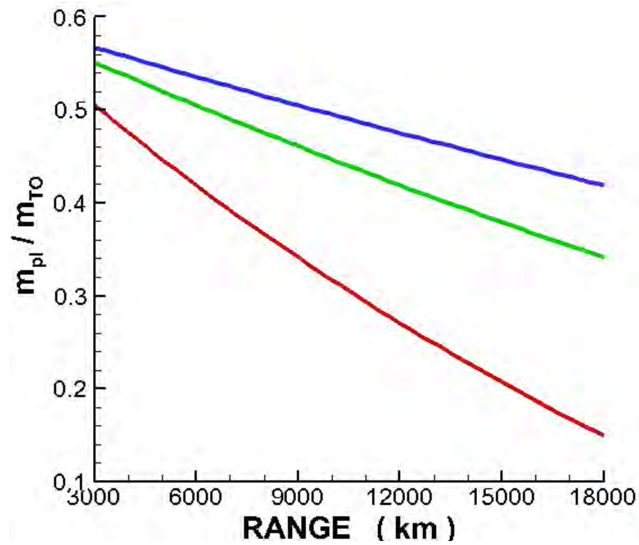
Figure 166: Airbus' Cryoplane.

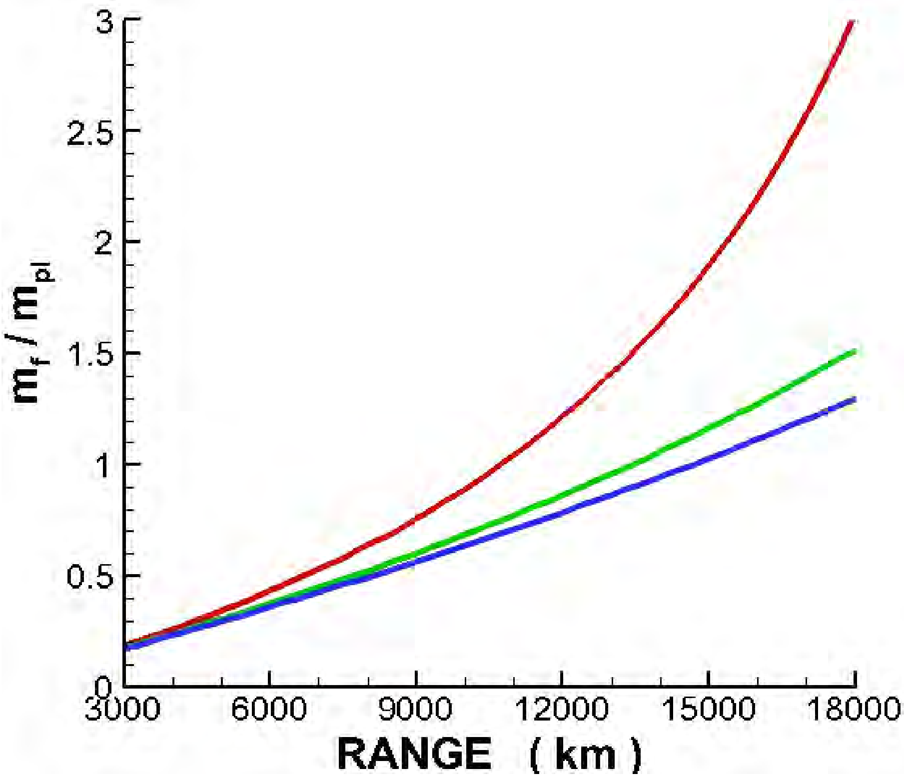
- **CURRENT LH PRODUCTION $\ll$ 1% OF WHAT NEEDED**
- ***LONG* TIME TO BUILD INFRASTRUCTURES**

8.5.3 IN–FLIGHT REFUELLING (1)

- **REFUELs: RED NONE, GREEN 1, BLUE 2**







- **COST–EFFECTIVE FOR LONG–RANGE FLIGHTS**

8.5.4 IN–FLIGHT REFUELLING (2)

- **ACCOUNTING FOR TANKER FUEL CONSUMPTION:**

range nmi / km	3000 / 5556	6000 / 11112	9000 / 16668
airliner fuel consumption for direct flight (kg)	13412	35124	85113
airliner fuel consumption with in–flight refuelling every 3000 nm (kg)	—	26825	40237
tanker(s) fuel consumption (kg)	—	1500	3000
overall fuel consumption (kg)	—	28325	43237
fuel mass saving	—	19,36%	49,20%

OPPORTUNITIES AND CHALLENGES FOR ELECTRIC PROPULSION OF AIRLINERS

- **OUTLINE:**

1. INTRODUCTION
2. DEDICATED AIRFRAME
3. OPTIONS
4. RANGE
5. OTHER LIMITATIONS
6. CONCLUSIONS

Dyson 2017

SAPIENZA
UNIVERSITÀ DI ROMA

1a. INTRODUCTION

- AVIATION CONTRIBUTES ~ 2.5% TO GLOBAL CO_2 EMISSIONS
- CONTRAILS ADD ~ 1.1%
- TOTAL CONTRIBUTION TO RADIATIVE FORCING ~ 4.9%
- STATOSPHERIC OZONE DEPLETION BY NO_x
- AIR TRAFFIC GROWING AT ~ 5%/year

→ URGENT ACTIONS NEEDED TO CURB EMISSIONS

Adventure Aviation

1b. AVENUES TO REDUCE EMISSIONS

- **BIOFUELS: NO NET CO_2 EMISSIONS, BUT SUPPLY 1% OF DEMAND USING 1% OF ARABLE LAND**
- **FURTHER, DEDICATED CULTIVATIONS EMIT N_2O (GHG, ODG)**
- **HYDROGEN-FUELLED AIRCRAFTS**
- **<u>ELECTRIC AVIATION</u>**

2a. NEED FOR DEDICATED AIRFRAMES

- ELECTRIC ENGINES NOT A DROP-IN REPLACEMENT FOR EXISTING ENGINES
- BOUNDARY LAYER INGESTION: REDUCED DRAG, IMPROVED PROPULSION EFFICIENCY
- TIP SWIRLERS
- DISTRIBUTED PROPULSION: SAFER OEI, HIGHER LIFT → LOWER $S_{wing} \rightarrow m_{TO} \rightarrow m_{fuel} \rightarrow$ etc.

TU München

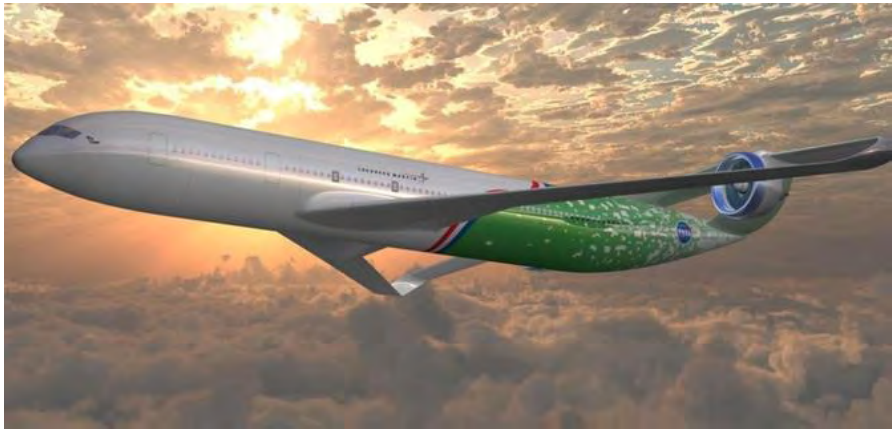
Ampere, ONERA

2b. DISTRIBUTED PROPULSION A *NECESSITY*

- **1 MW ELECTRIC MOTOR DRIVING A FAN WITH PRESSURE RATIO 1.25 GENERATES ONLY ~ 6 kN THRUST AT TAKE-OFF**

- **FURTHER, PRANDTL WING → HIGHER *L/D***

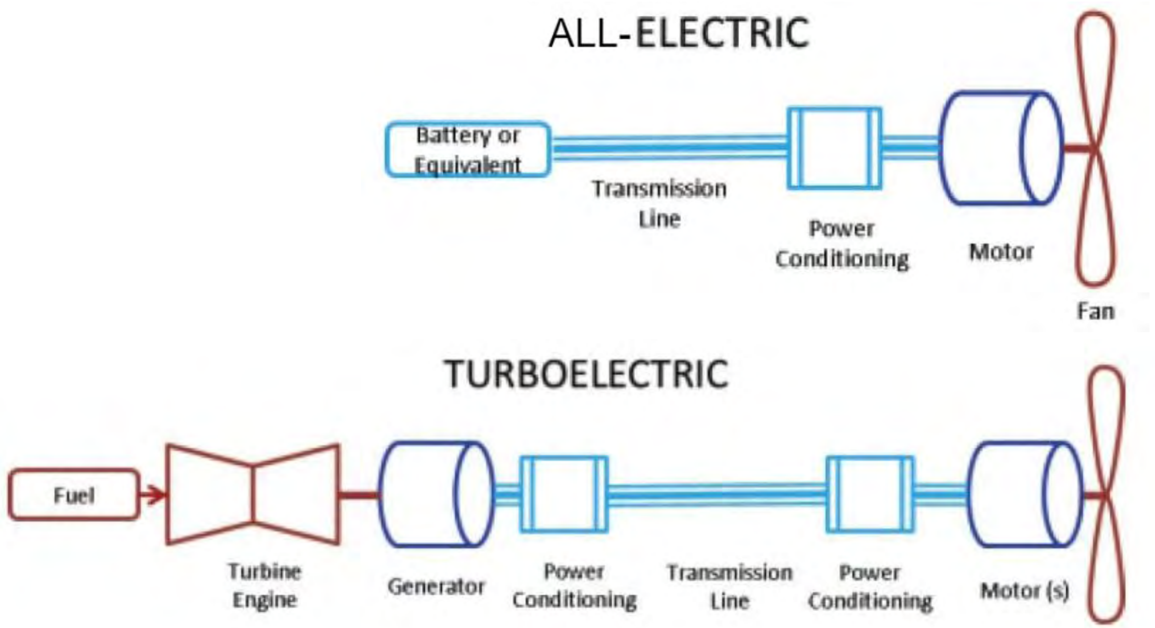
Lockheed, conventional



NASA, electric

3. OPTIONS FOR ELECTRIC AIRCRAFT

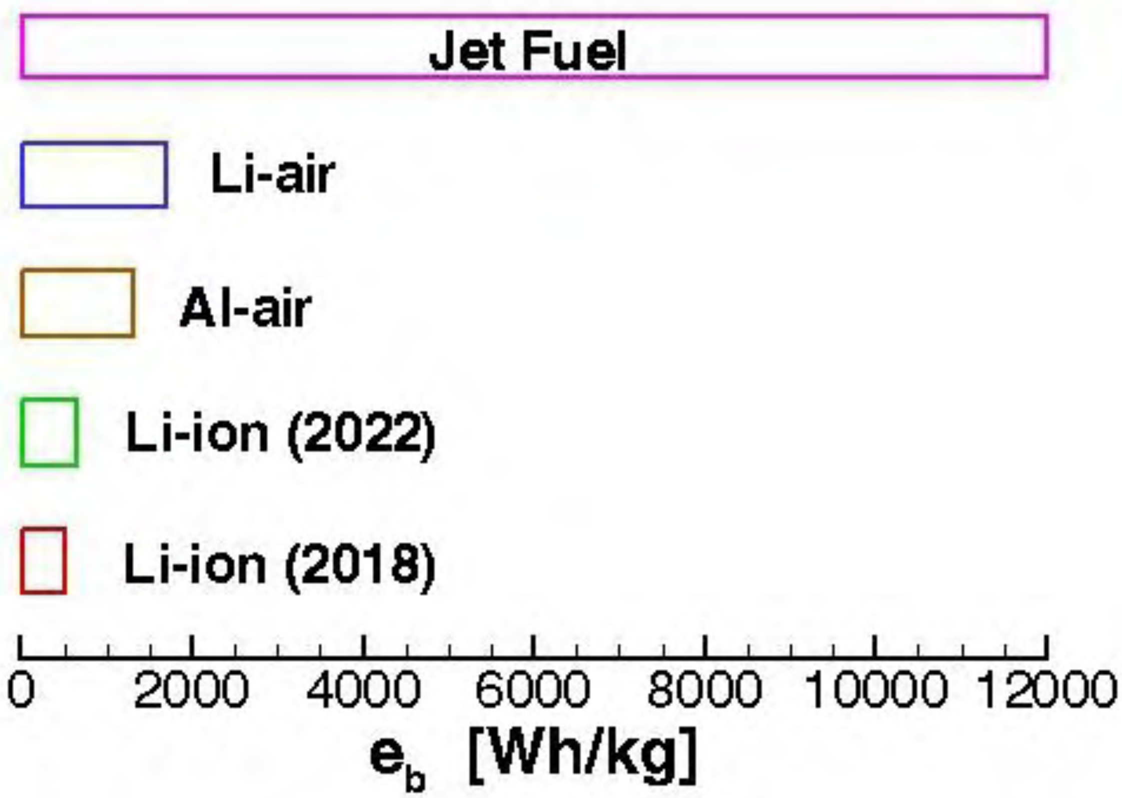
- **ALL-ELECTRIC AIRCRAFT (AEA)**
- **TURBO-ELECTRIC AIRCRAFT (TEA)**
- **HYBRID-ELECTRIC AIRCRAFT (SERIAL/PARALLEL) (HEA)**



Del Rosario 2014

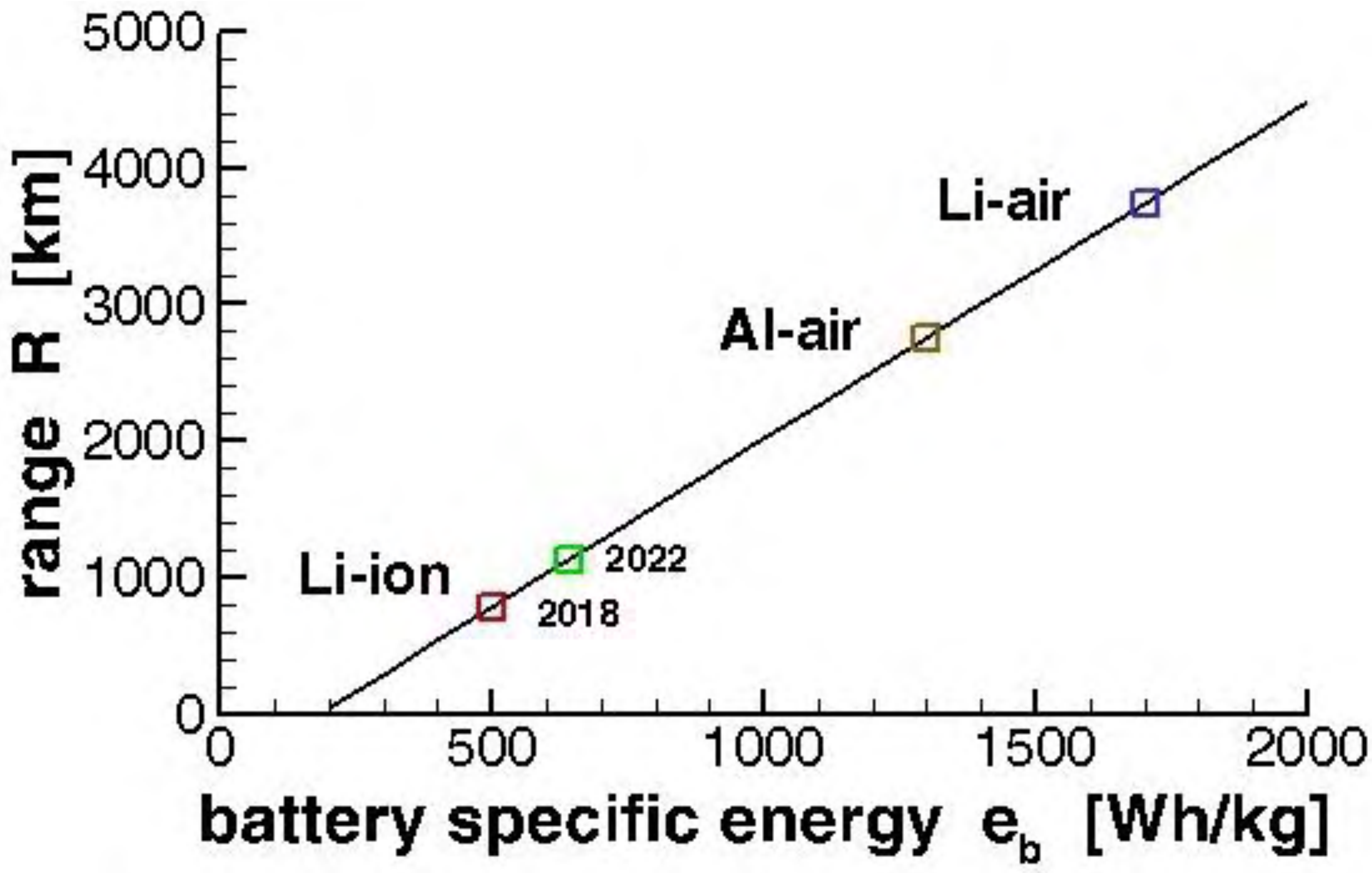
4a. AEA RANGE

- **DIRECTLY RELATED TO BATTERY SPECIFIC ENERGY (Wh/kg)**
- **Al-AIR and Li-AIR STILL FAR FROM EIS**

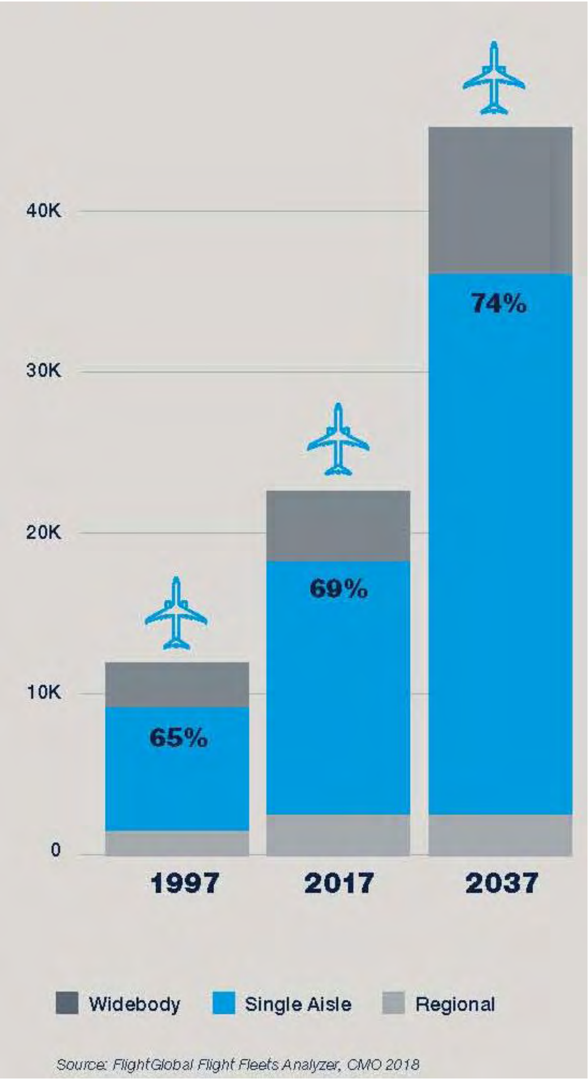


4b. RANGE FOR ALL-ELECTRIC AIRCRAFT (AEA)

- **INCLUDING ½ HOUR RESERVE**
- **WITH PRESENT-DAY TECHNOLOGY, NO MORE THAN ~ 1000 km**



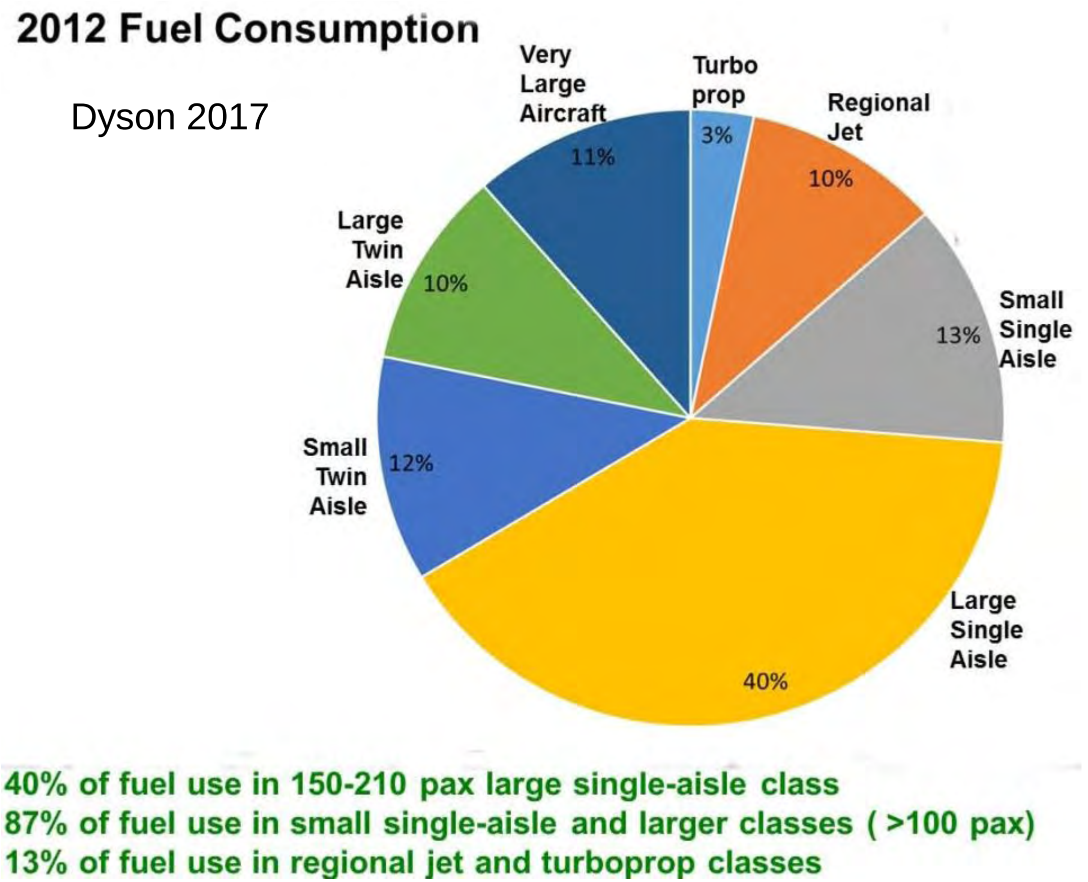
4c. POSSIBLE MARKET/FUEL SHARE OF AEA



Boeing 2018

← **MARKET SHARE OF SHORT-HAUL A/Cs ~ 1.7%**

FUEL CONSUMPTION SHARE ~ 10% ↓



4d. CONS OF AEA FOR SHORT-HAUL FLIGHTS

- **RELATIVELY LONG RECHARGE TIME → ADVERSE ECONOMIC IMPACT**
- **CAN BE SHORTENED, BUT AT THE EXPENSE OF BATTERY LIFE**

4e. TURBO-ELECTRIC AIRCRAFT (TEA)

- **GAS TURBINE → ALTERNATOR → ELECTRIC MOTOR → FAN**
- **REDUCED η_{th}, HIGHER η_p → SLIGHTLY IMPROVED η_o (~7%)**
- **SMALL EFFECT ON CO_2 EMISSIONS, UNLESS…**
- **USING HYDROGEN AS A FUEL**

4f. TEA: HYDROGEN-FUELLED AIRCRAFT

- **GAS TURBINE → ALTERNATOR → ELECTRIC MOTOR → FAN**
- **NO CO_2, GREATLY REDUCED CONTRAILS AND NO_x**
- **HYDROGEN GIVES 2.8·SPECIFIC ENERGY JET FUEL (Wh/kg), BUT ONLY 0.26·ENERGY DENSITY (Wh/m^3)→**
- **LARGE, HEAVY TANKS → DRAG**
- **SUPERCONDUCTIVITY → IMPROVED ELECTRICAL η**
- **DIFFICULT WITH DISTRIBUTED PROPULSION**
- **VERY FAST PROPAGATION POSSIBLE ELECTRIC FAULTS**

AIRBUS CRYOPLANE (conventional)

4g. HYBRID ELECTRIC AIRCRAFT (HEA)

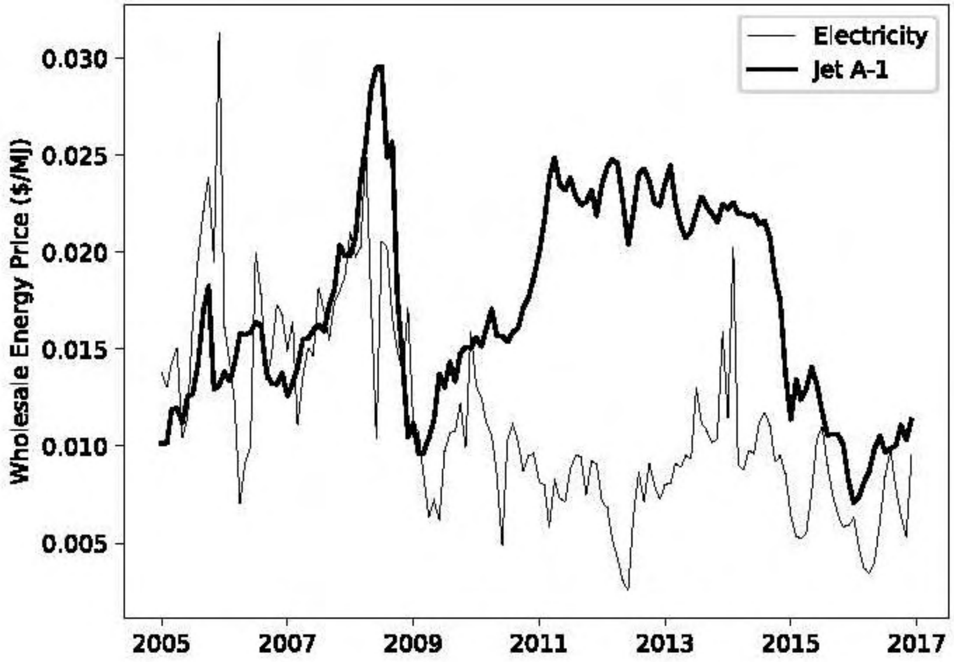
- **ELECTRIC POWER MAY BE USED TO DRIVE FANS TO ASSIST TAKE-OFF (AND CLIMB)**
- **REDUCED WING AREA → WEIGHT → THRUST → FUEL → etc.**
- **SPECIFIC POWER CONTROLLING (TAKE-OFF)**

5a. OTHER LIMITATIONS OF ELECTRIC AIRCRAFTS

- **BATTERY VOLUME ENERGY DENSITY ~ 1/10 OF JET FUEL → WEIGHT → THRUST → ENERGY → etc.**
- **RISK FIRES (BOEING 787)**
- **10 – 20% BATTERY CHARGE RELEASED AS HEAT → RADIATORS → WEIGHT, DRAG → etc.**

5b. COST ELECTRIC ENERGY *AND* BATTERIES

- COST kWhe + $\frac{COST\ ELECTRIC\ BATTERIES\ per\ kWhe}{no.\ of\ cycles}$
- e.g., 0.03 + 100/1000 = 0.13 » COST JET-A1
- PLUS EFFICIENCIES, DISPOSAL/RECYCLING EXHAUSTED BATTERIES



← Brelje 2019
multipy by 3.6 to get units of $/kWh

6. CONCLUSIONS

- **PRESENT TECHNOLOGY →**

→ LIMITED RELIEF ENVIRONMENTAL IMPACT

→ AEAs MORE COSTLY

- **HYDROGEN-FED TEAs GIVE NO CO_2, VERY LITTLE CONTRAILS AND NO_x, BUT …**

- **DECADES NEEDED TO BUILD INFRASTRUCTURES**

- **HYDROGEN PRODUCED BY RENEWABLES**

- **REQUIRE DECISE POLICY SHIFT**

8.6 PUT EVERYTHING IN PROPER CONTEXT...