UNIVERSITÀ DEGLI STUDI DI ROMA
"LA SAPIENZA"
DIPARTIMENTO DI MECCANICA E AERONAUTICA
Via Eudossiana, 18 – 00184 Roma

Roma, March 5, 2005

# Workshop on "Constructal Theory of the Generation of Optimal Flow Configurations"

**Roma, School of Engineering, "Aule del Chiostro", 17th and 18th of March, 2005**

Constructal Theory is a new research development aimed at the identification of the most efficient "structure" that a flow of mass, energy, or 'anything that moves' can take. The theory is validated by comparisons with natural phenomena, since it is generally accepted that systems in nature evolve to the most "efficient" configuration under the prescribed constraints. Constructal theory is being considered for analysis of the thermal management of components and systems, for system analysis of intrinsically energy-efficient vehicles, for traffic management, for networks for distribution and collection, etc. The approach shows potential for significant applications in land, air, sea and space systems, its generality being founded on its theoretical basis of "thinking about design as a science". The objective of the workshop is to assess the status and limitations of present technologies for developing the necessary systems of systems; current developments in new technologies; potential applications to future system developments; research directions for future investment.

The Workshop has been jointly organised by the University of Roma 1 "La Sapienza", Duke University and the United States Air Force Research Laboratory. It has been sponsored and funded by the European Office of Aerospace Research and Development, Air Force Office of Scientific Research and by the University of Roma 1.

The Organising Committee:
Adrian Bejan (Duke University)
David Moorhouse (AFOSR)
Enrico Sciubba (U. of Roma1)

# REPORT DOCUMENTATION PAGE

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ABSTRACT (Maximum 200 words)

Contains collected presentations from the Workshop on Constructal Theory Application to Aerospace advanced vehicles considered as Complex Energy Conversion Systems, 16-18 March 2005. This was an interdisciplinary workshop and was by invitation only. Topics include evaluating the possibility of applying 'Constructal Theory' (CT) to the optimization of complex energy conversion systems, with specific regard to advanced aerospace vehicles. The workshop included discussions of configuration optimization procedures that are possible with CT. The workshop goal was toward delivering a set of general guidelines as to the practical design topics in which CT can be applied in the near term.

**14. SUBJECT TERMS**

EOARD, Optimization, Energy conversion, Constructal theory, Exergy

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# Program

**Thursday, March 17 (Sala Grande del Chiostro)**

| | | |
|---|---|---|
| 9.30 - | Welcome address | (E. Sciubba, D. Moorehouse, A. Bejan) |
| 10.00 - | Constructal Theory: Shape & Structure, from engineering to nature | Adrian Bejan |
| 10.45 - | Requirements on methods for system-level analysis of efficient Aerospace flight vehicles | David Moorhouse |
| 11.30 - | Tree-shaped networks for distribution, collection & cooling | Sylvie Lorente |
| 12.15 - | Constructal Theory & variational principles for the Navier-Stokes equations: is there a link? | Enrico Sciubba |
| 13.00 - | Lunch break | |

| | | |
|---|---|---|
| 15.00 - | Aerosol particle deposition, and shape in inanimate/animate systems | Antonio F. Miguel |
| 15.45 - | Flow architectures of lungs and river basins | A. Heitor Reis |
| 16.30 - | Optimal geometry for a rectangular slab with internal convection cooling | Adrian Bejan, Mauro Robbe |
| 17.15 - | Discussion | A.Bejan, D.Moorhouse |

| | | |
|---|---|---|
| 20.00 - | Workshop Dinner, Restaurant "La Piazzetta" | |

**Friday, March 18 (Sala Piccola del Chiostro)**

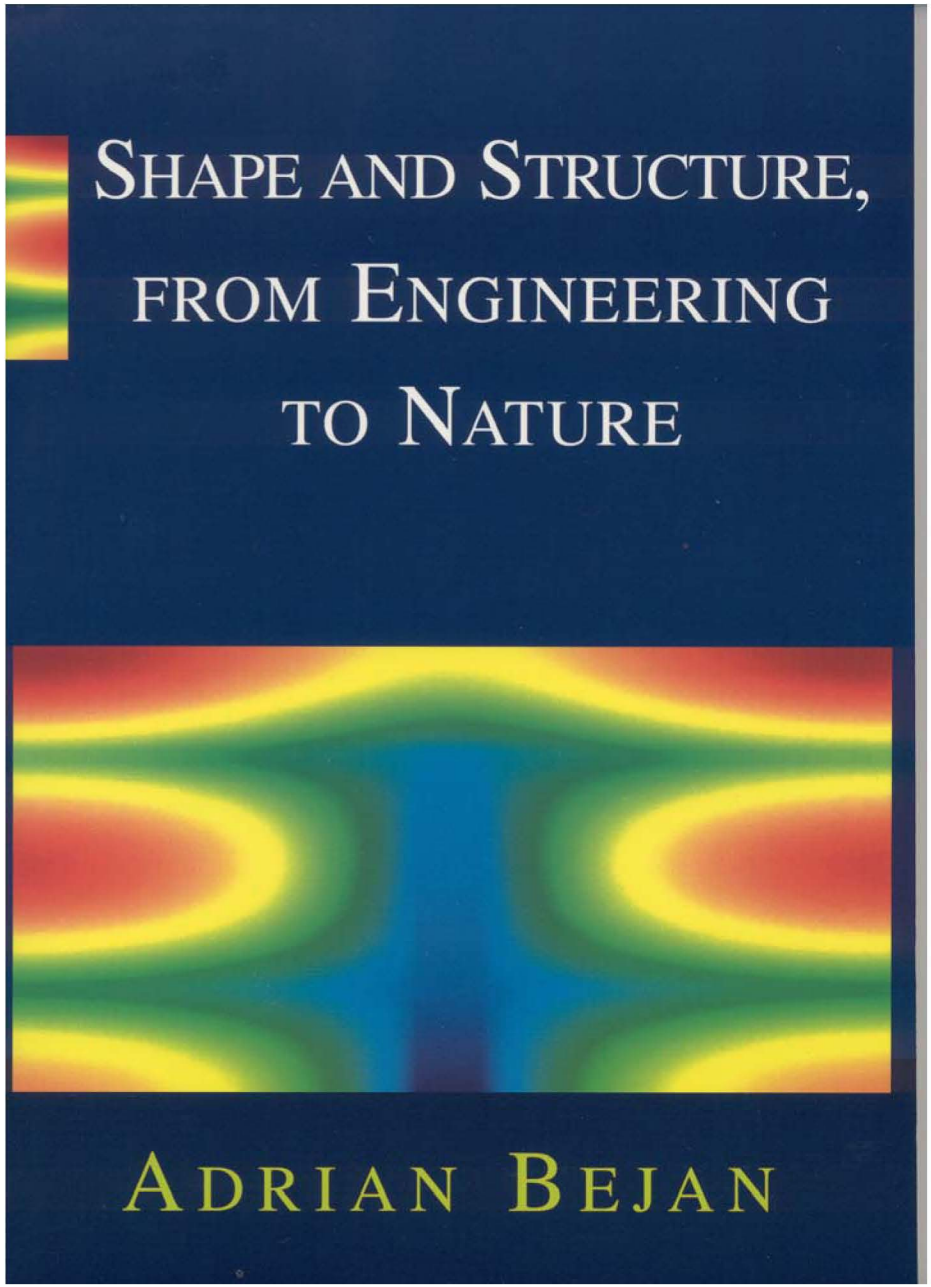
| | | |
|---|---|---|
| 9.30 - | Performance improvement of a tubular Solid Oxide Fuel Cell stack through the study of its configurational design | Vittorio Verda |
| 10.15 - | Numerical simulations of the fluid & heat flow in disc-shaped compact heat exchangers with dendritic flow structure | Mauro Robbe |
| 11.00 - | Energy usage in Aircraft Equipment Systems | Lester Faleiro |
| 11.45 - | On the synthesis of complex energy systems with several heat transfer interactions | Andrea Lazzaretto |
| 12.30 - | Thermal Management of Aircraft Systems | Dave Pratt |
| 13.15 - | Lunch | |

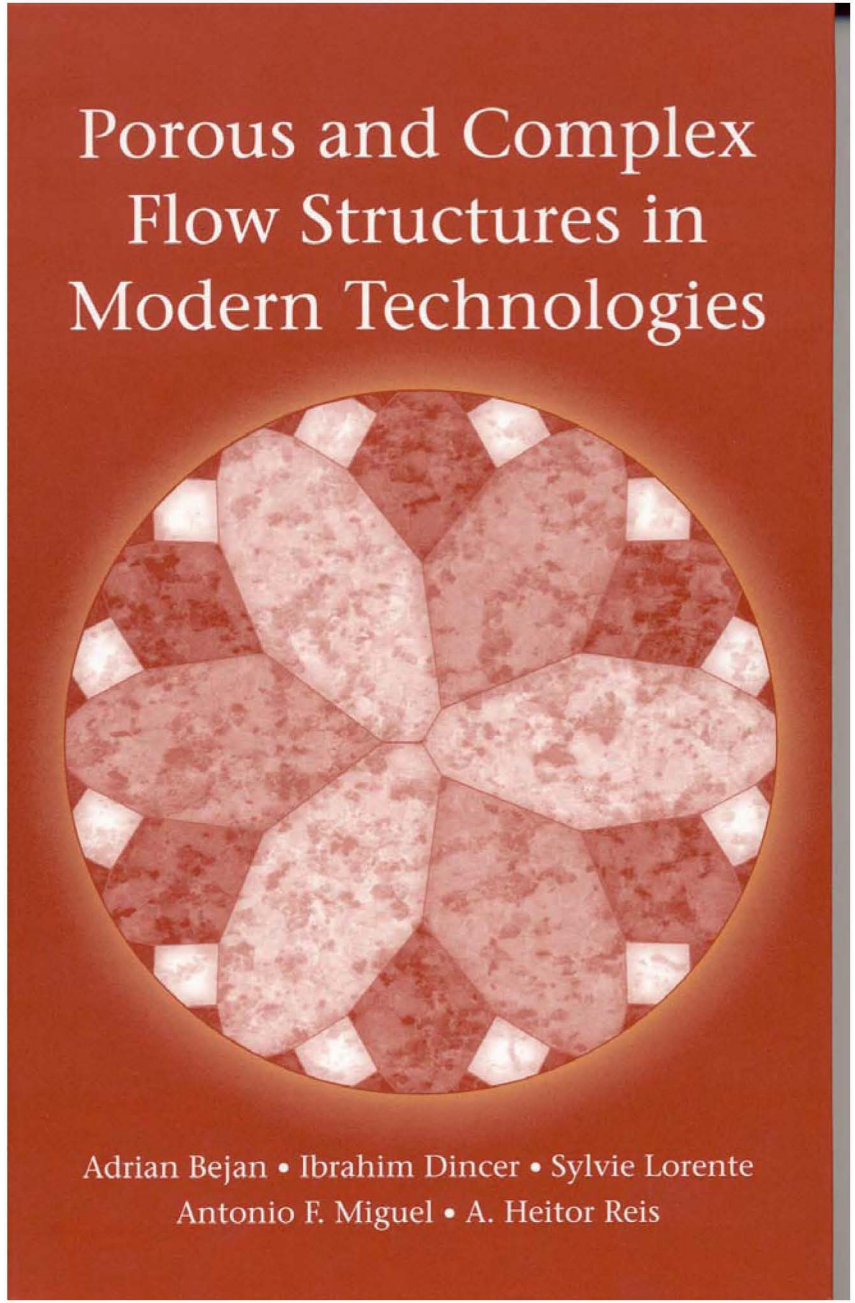
| | | |
|---|---|---|
| 15.00 - | Panel discussion | E. Sciubba |
| 15.45 - | General discussion, closure & recommendations for future work | A.Bejan, D.Moorhouse E.Sciubba |

# Constructal Theory:
# Shape and Structure,
# from Engineering to Nature

**Adrian Bejan**

J. A. Jones Distinguished Professor
of Mechanical Engineering
Duke University
USA


SHAPE AND STRUCTURE,
FROM ENGINEERING
TO NATURE
ADRIAN BEJAN


Porous and Complex
Flow Structures in
Modern Technologies
Adrian Bejan • Ibrahim Dincer • Sylvie Lorente
Antonio F. Miguel • A. Heitor Reis

1. Constructal theory:  current progress

2. Aircraft research and design:  needs, current work

3. Opportunities for constructal theory in aircraft development

Constructal theory (1996)

Internal spacings

Tree-shaped flow structures

Multiple scales, nonuniformly distributed

Multiple objectives

Complex engineering flow systems:  flight

Transportation, economics

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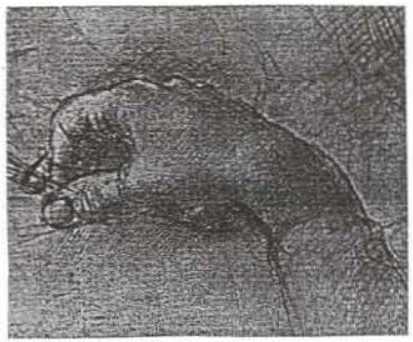
Engineering + Physics + Biology + Economics

## Biomimetics

Nature → Engineering

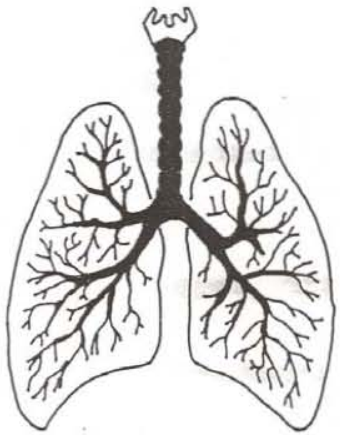
Time

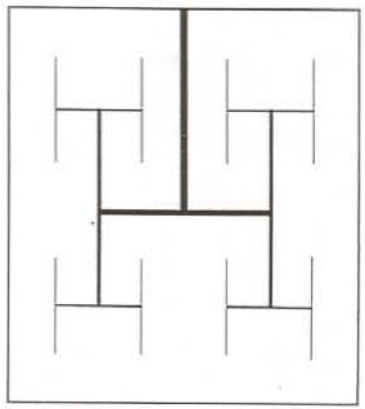


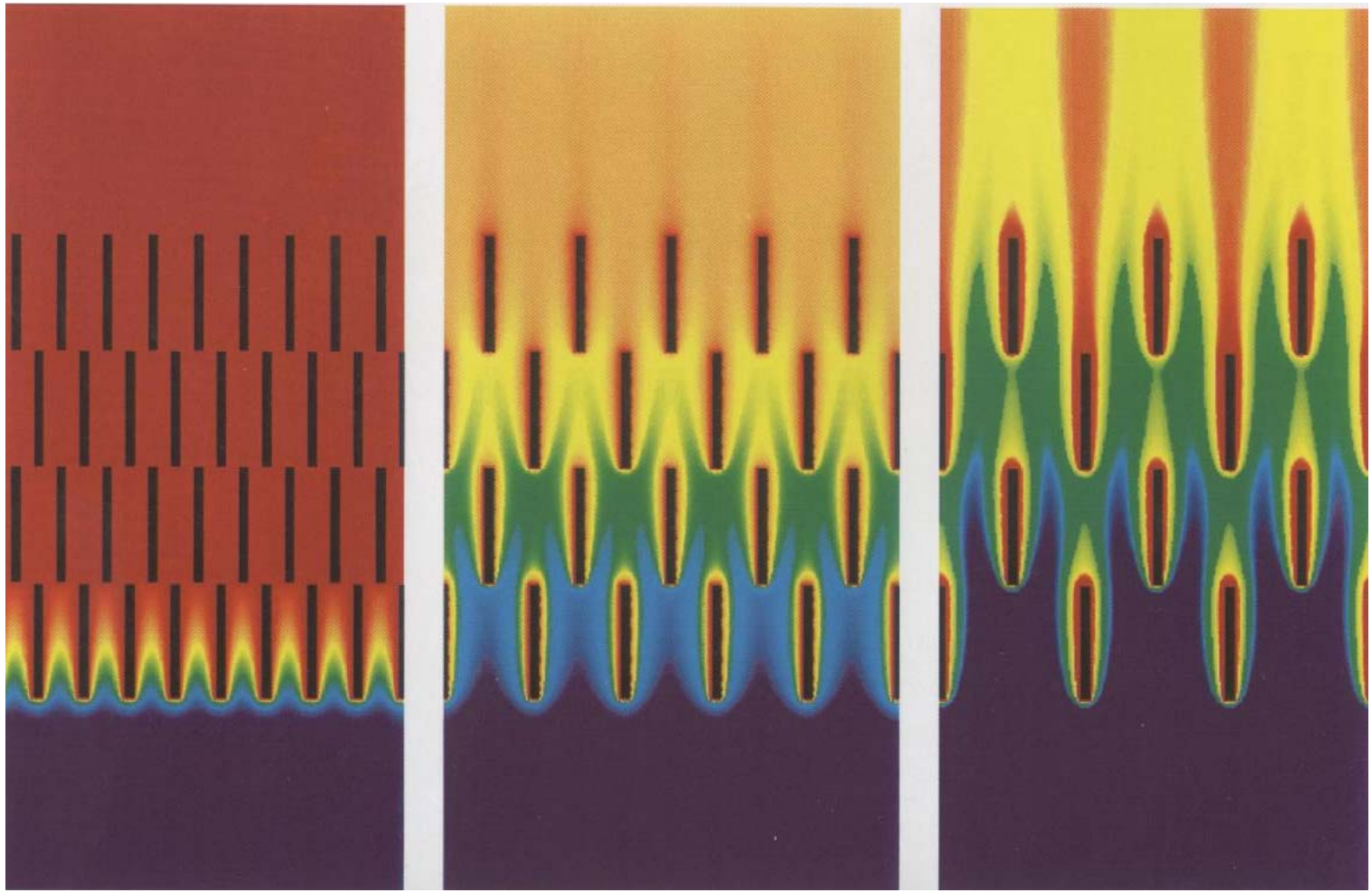
## Constructal theory

Nature ← Principle

Time





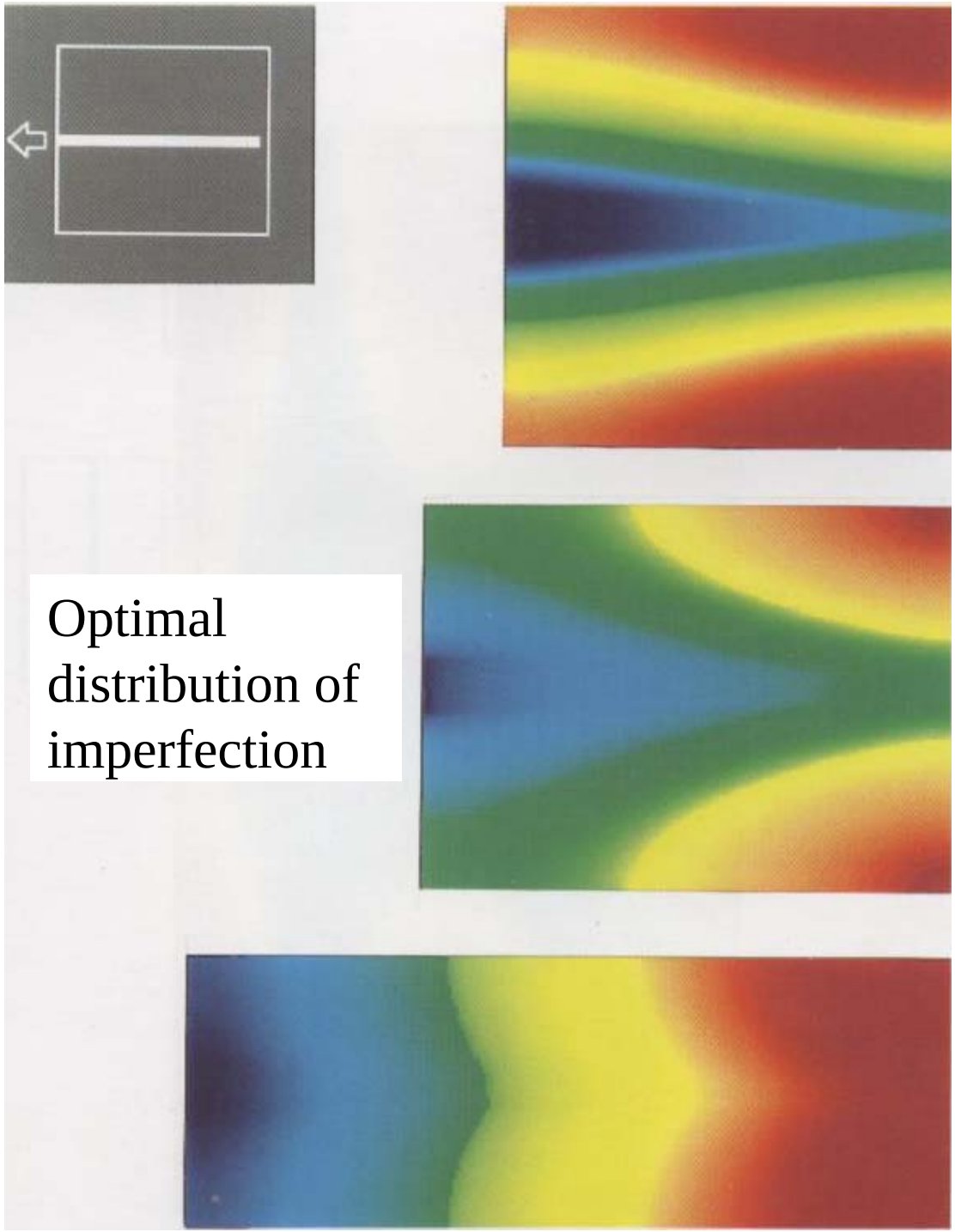


Large resistance to fluid flow

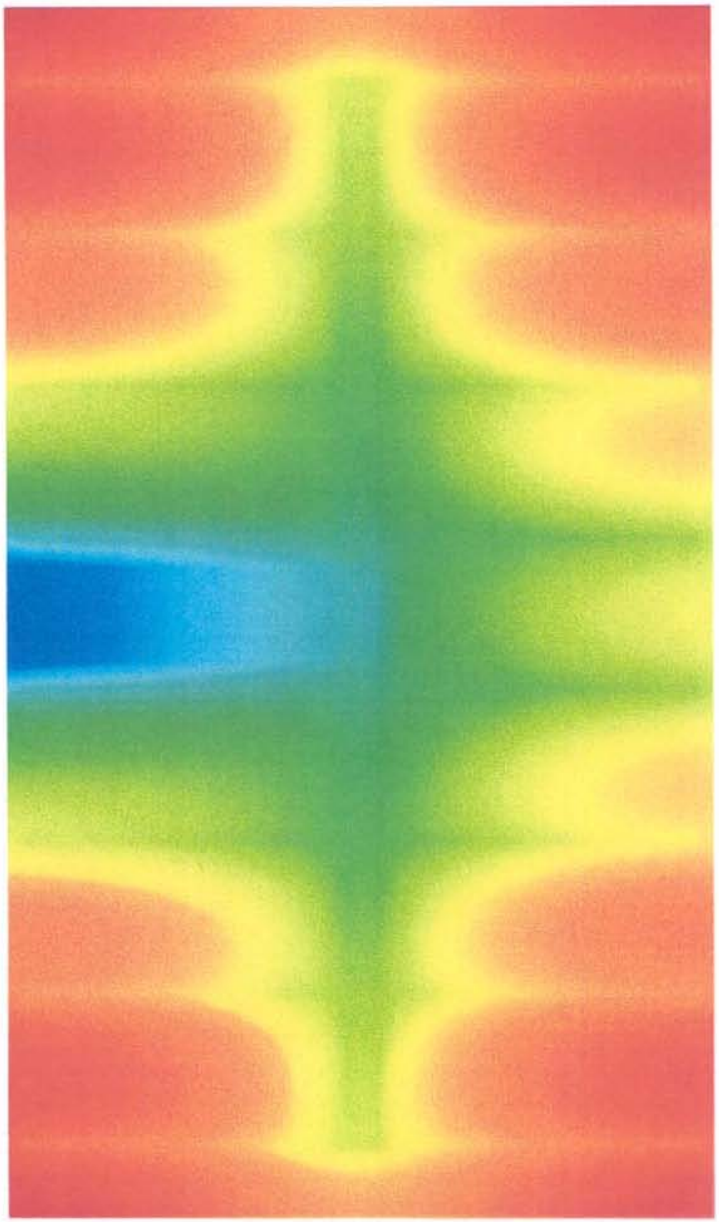
Balanced resistances

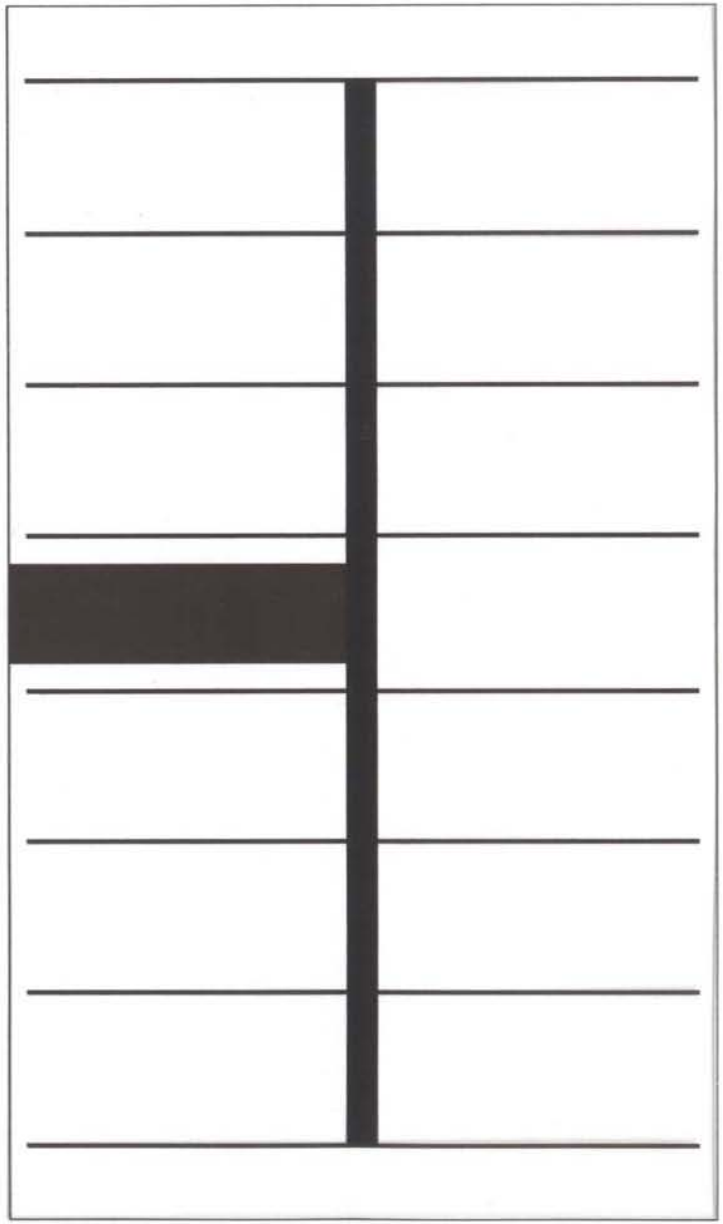
Large resistance to heat flow

Optimal distribution of imperfection


Optimal distribution of imperfection
Large vertical resistance
Balanced resistances
Large horizontal resistance

$L_2$
$D_2$
$H_2$
$k_2, q'''$
$k_2, q'''$
$H_1$
$D_1$
$L_{1,opt}$
$q'''H_1L_1W$
$H_1/2$
$-H_1/2$
y
0
0
$k_p$
$k_1, q'''$
$k_1, q'''$
$D_1$
$D_0$
$H_0$
$L_1$
$L_{0,opt}$
x
$q'''H_0L_0W$
y
$H_0/2$
$k_0, q'''$
$D_0$
0
0
$L_0$
x
$k_p$
$k_0, q'''$
$-H_0/2$





| | | |
|---|---|---|
| Tree-shaped flow structure | — | deduced from principle |
| Round cross-sections, ducts | | not seen in nature first |
| Cross-sections of rivers | | not assumed |
| . | | not ‘simulated’ based on an |
| . | | assumed (e.g., fractal) algorithm |
| . | | . |
| . | | . |
| . | | . |
| Flow geometry | | deduced from principle |

**How, not what**

| **Application** | **What flows** | **How** | |
|---|---|---|---|
| | | **Interstices high resistance at the smallest (fixed) scale** | **Channels low resistance at larger scales** |
| Electronics packages | Heat | Low-conductivity substrate | High-conductivity inserts (blades, needles) |
| River basins | Water | Darcy flow through porous media | Rivulets and rivers |
| Lungs | Air | Diffusion in alveoli, tissues | Bronchial passages |
| Circulatory systems | Blood | Diffusion in capillaries, tissues | Blood vessels, capillaries, arteries, veins |
| Turbulent flow | Momentum | Laminar, viscous diffusion | Streams, eddies |
| Urban traffic | People | Walking in urban structure | Street traffic |
| Economics | Goods | Hand delivery and collection | Freight, rail, truck, air, ship |

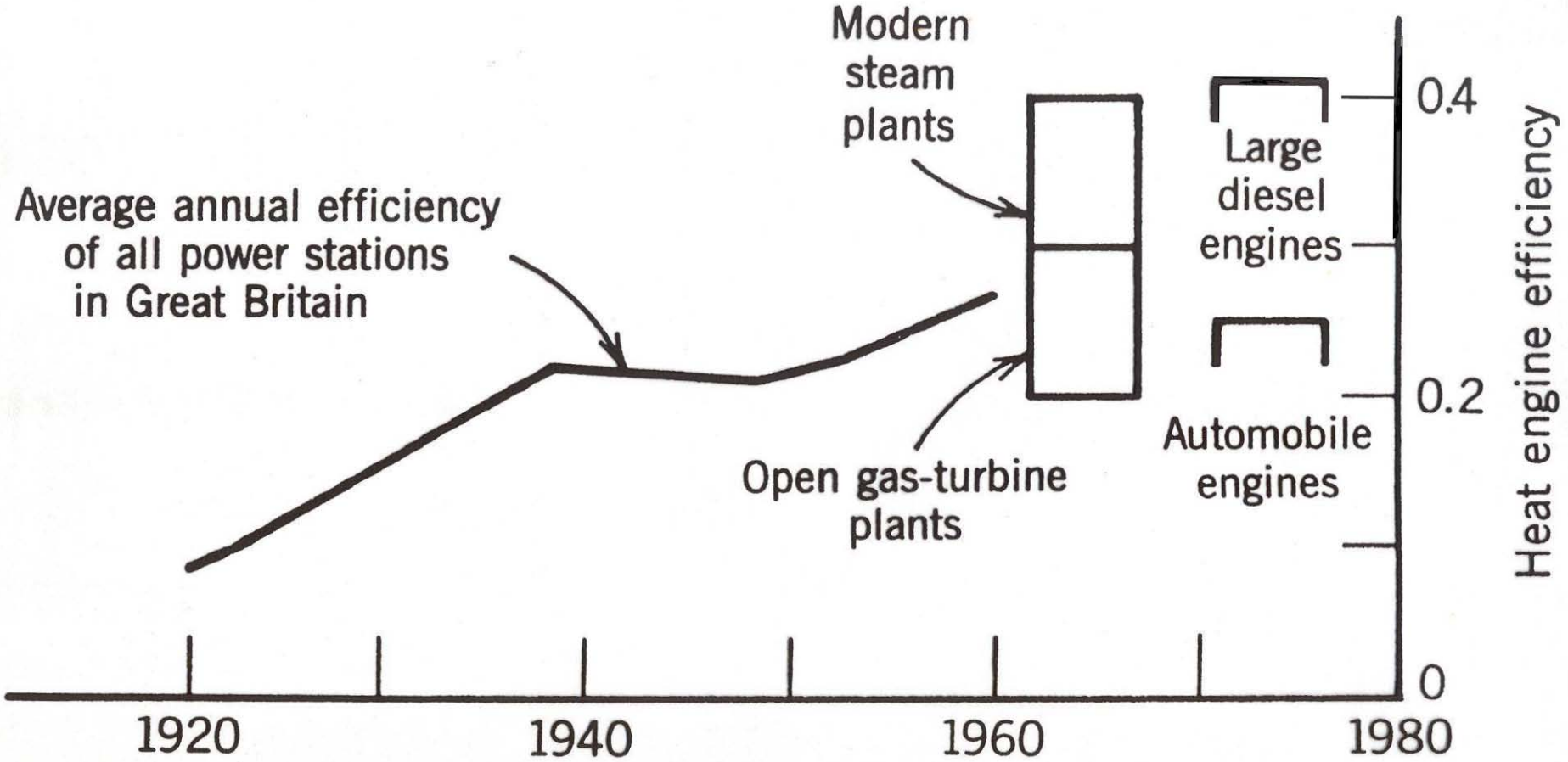
Constructal law (1996):

> “For a finite-size open system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it”.

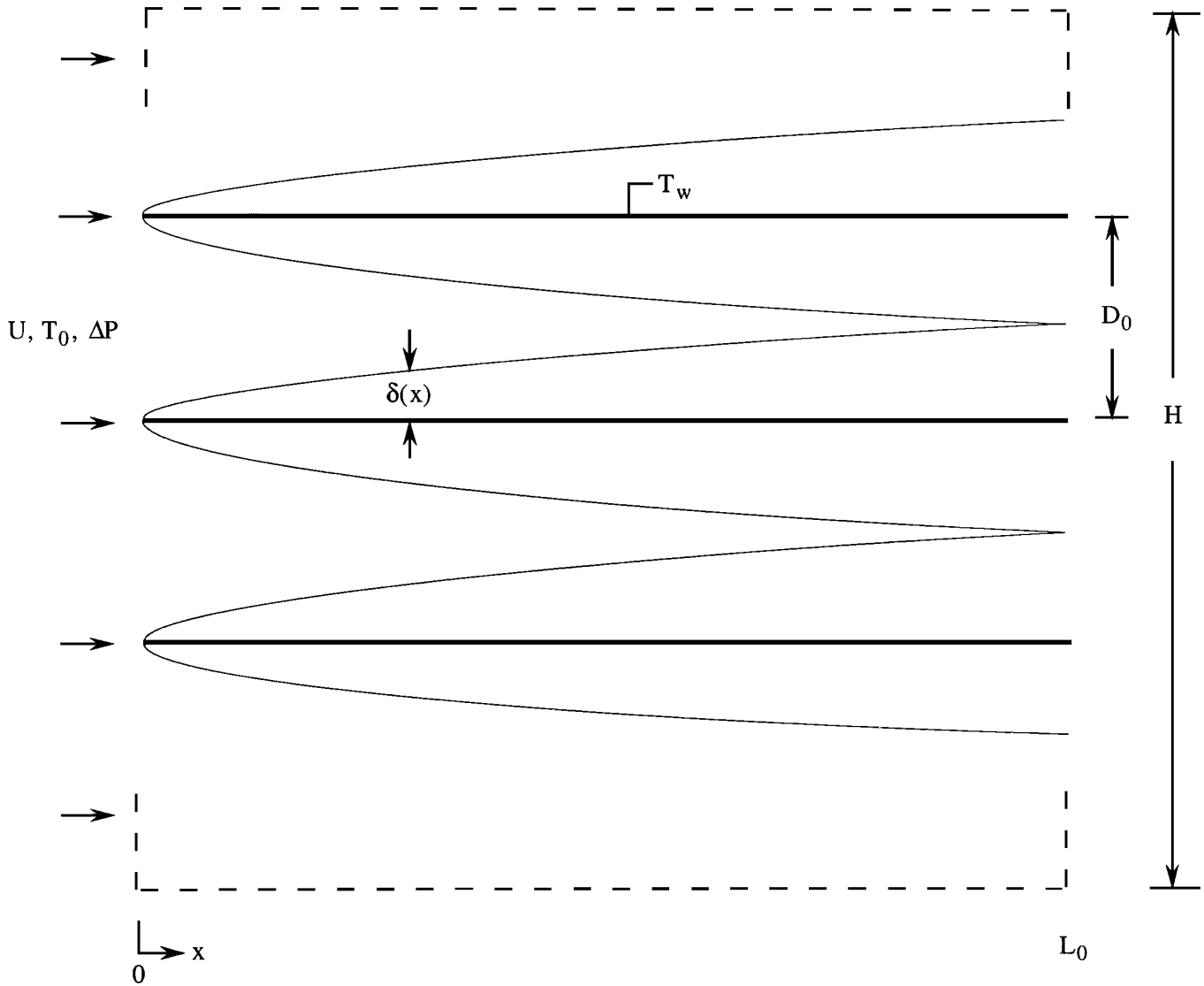
or the ‘physics’ behind:

Darwin’s observations

fractal algorithms

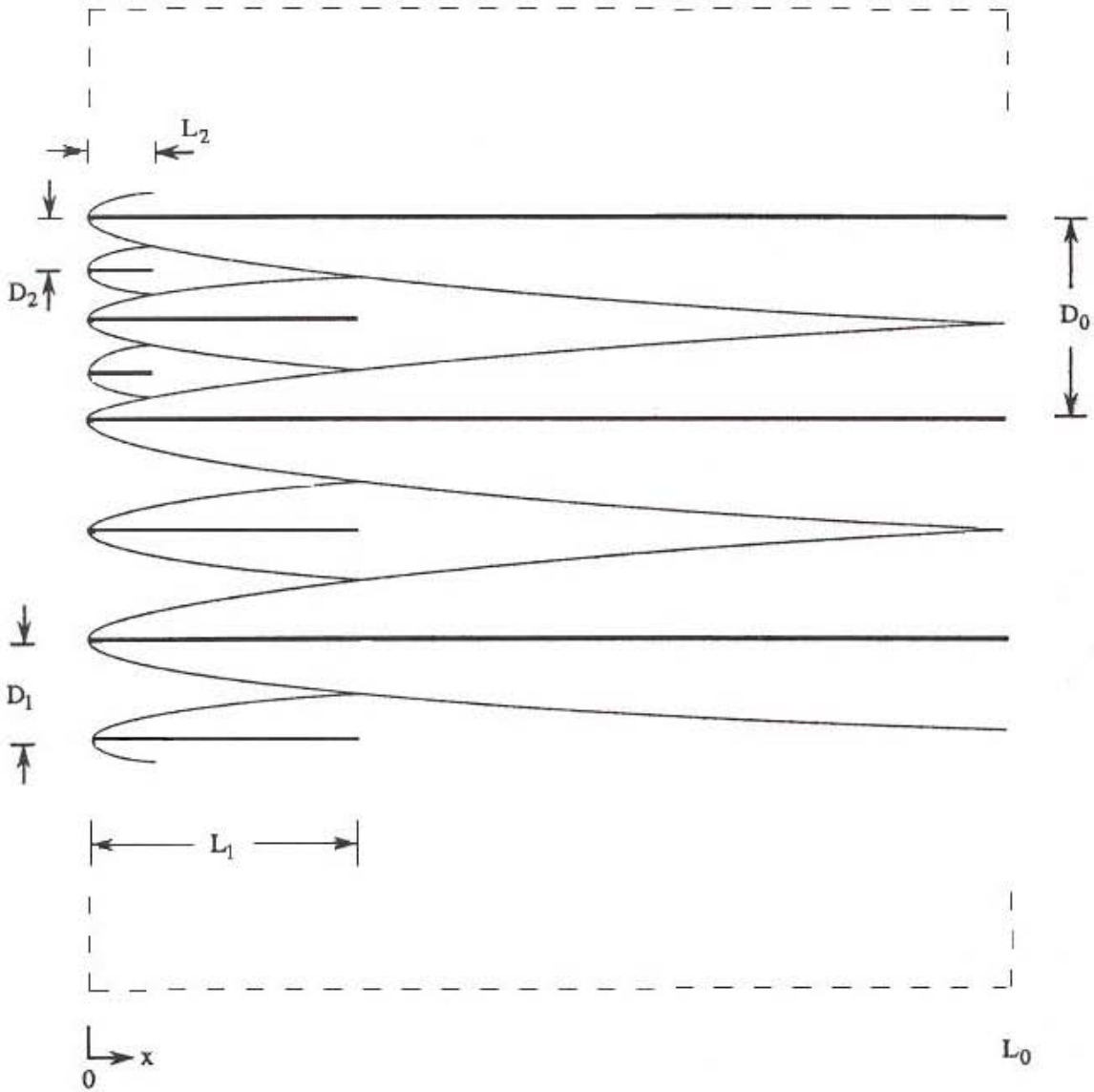

Modern steam plants
Average annual efficiency of all power stations in Great Britain
Open gas-turbine plants
Large diesel engines
Automobile engines
0.4
0.2
0
Heat engine efficiency
1920
1940
1960
1980

# Constructal Multi-Scale Structures




Package of parallel plates with **one spacing**.

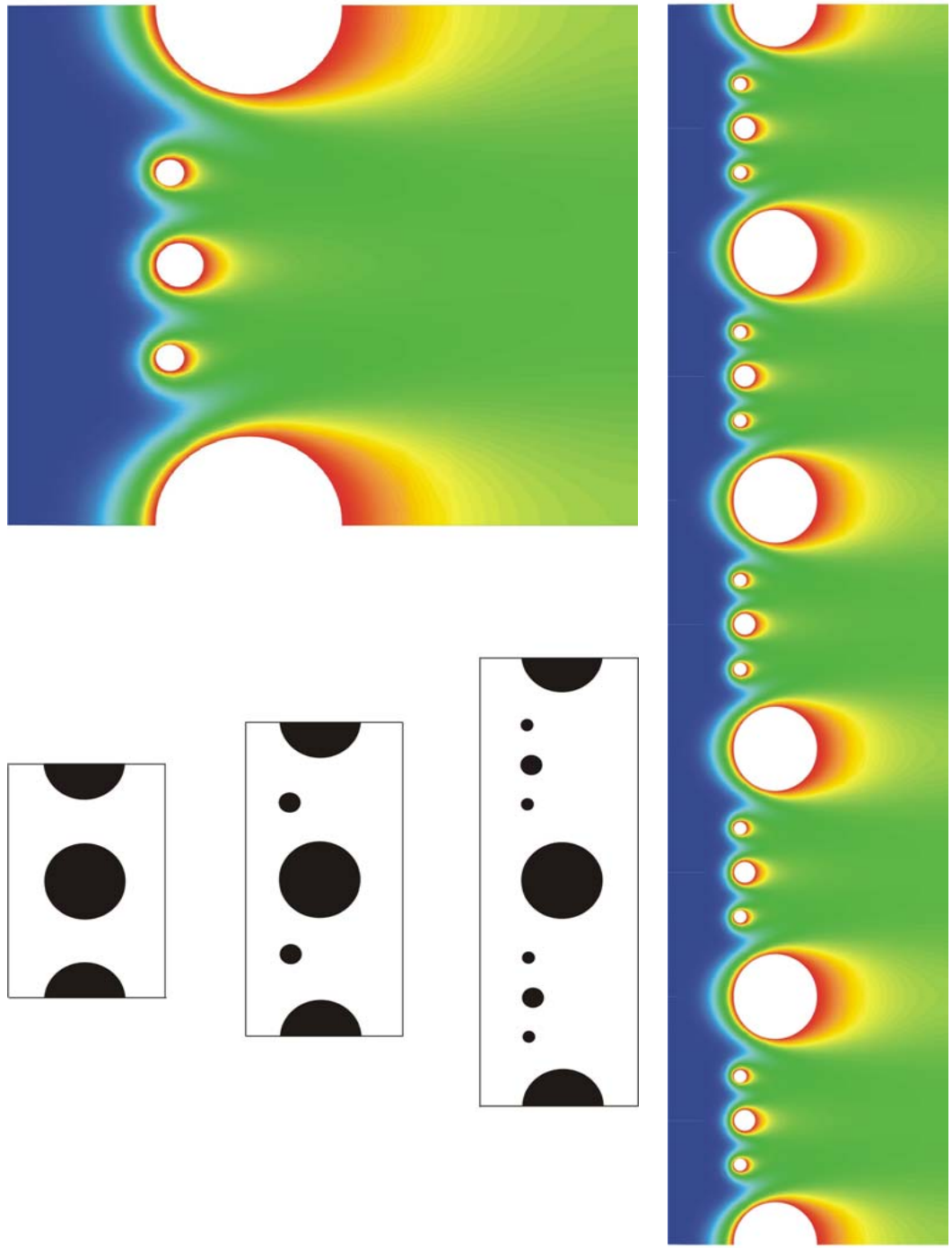
# **Multi-scale** hierarchical structures



T. Bello-Ochende and
A. Bejan,

Constructal multi-scale cylinders in cross flow,

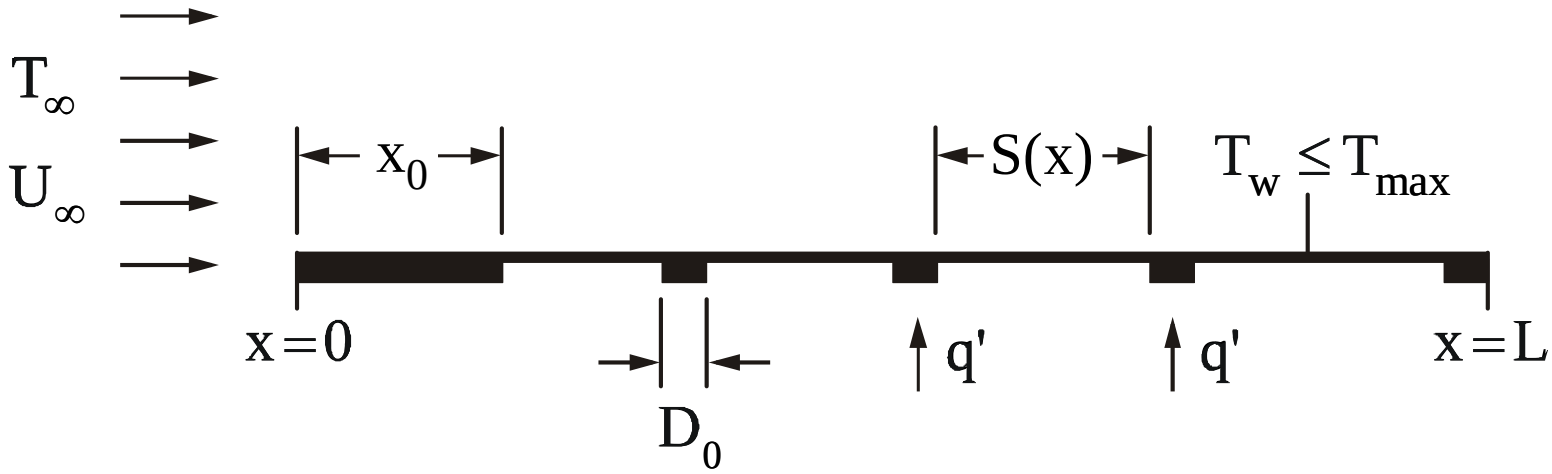
*Int. J. Heat and Mass Transfer* **48** (2005) pp. 1373-1383.



A. K. da Silva, S. Lorente and A. Bejan,

Optimal distribution of discrete heat sources on a plate with laminar forced convection,

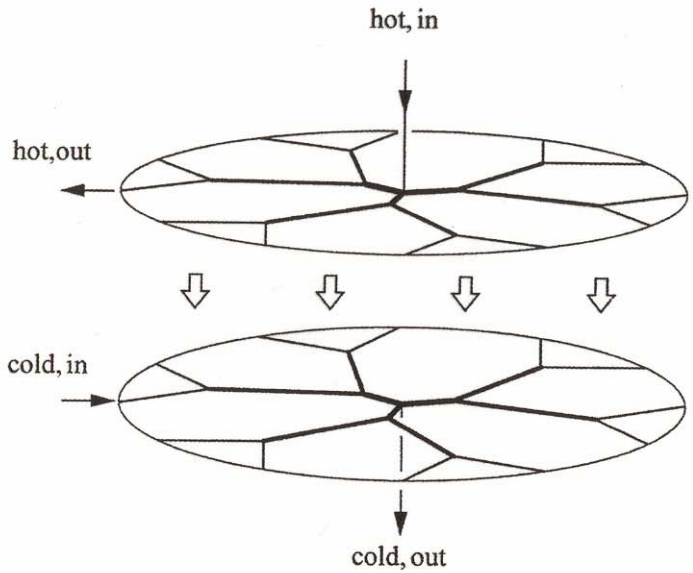
*Int. J. Heat Mass Transfer* **47** (2004) 2139-2148.

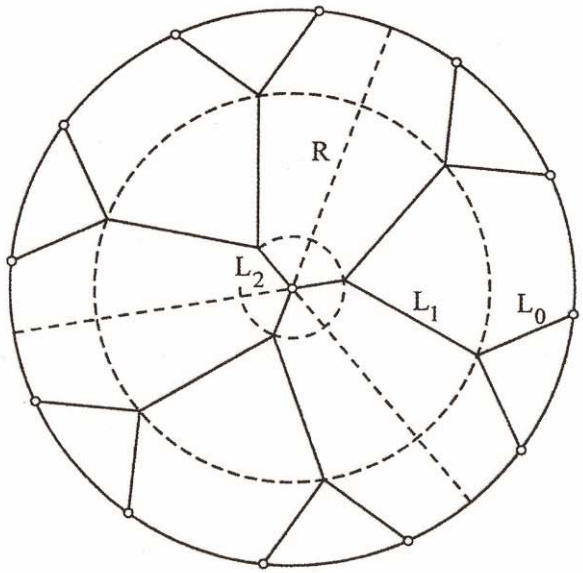


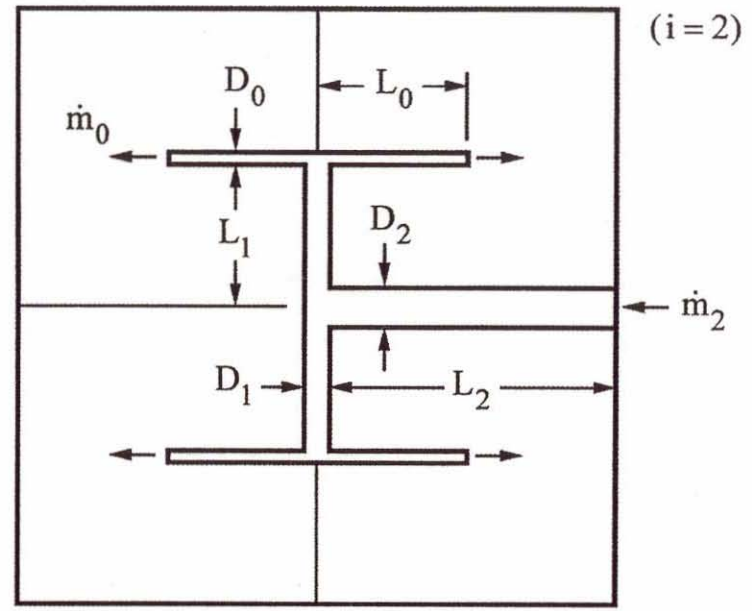
A. K. da Silva, S. Lorente, A. Bejan,

Constructal multi-scale tree-shaped heat exchangers,

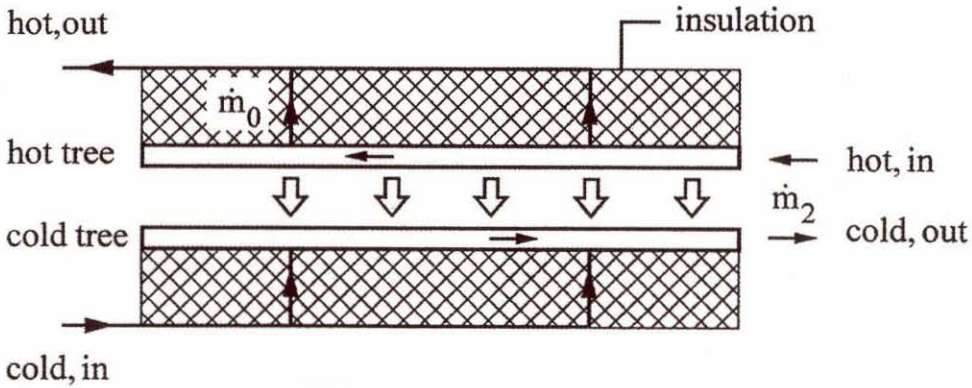
*J. Appl. Phys*. **96**(3), 1 August 2004, pp. 1709-1718.



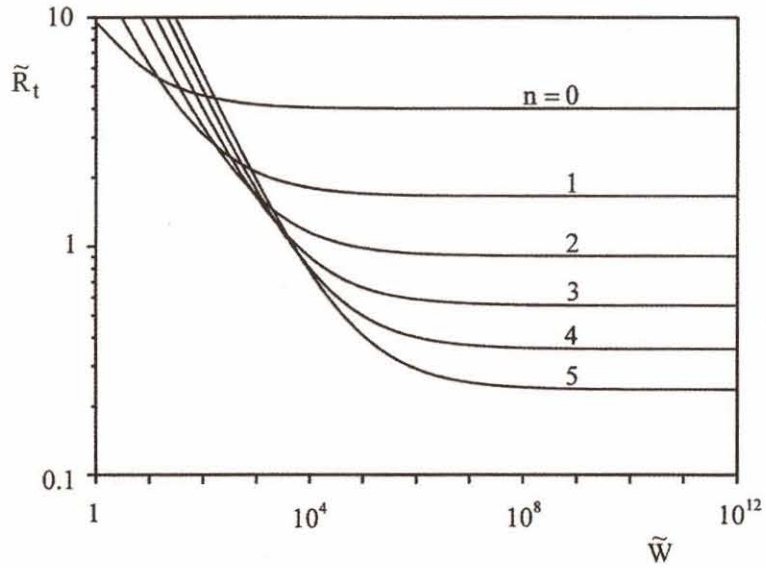





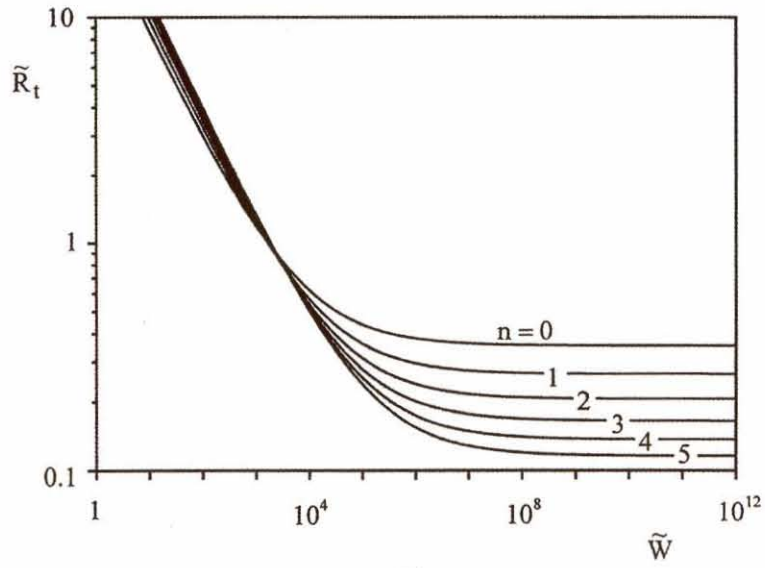

View from above



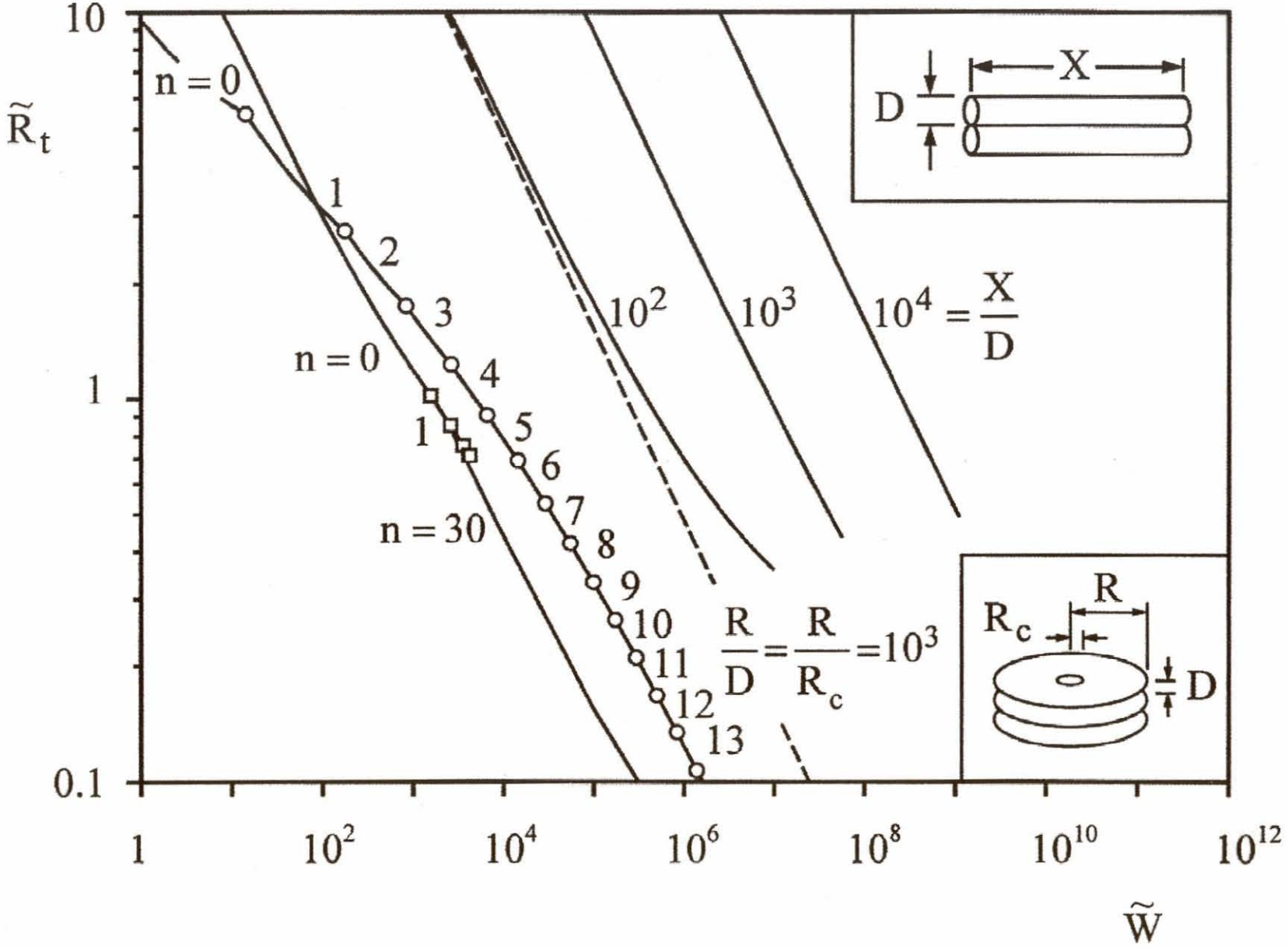

View from the side

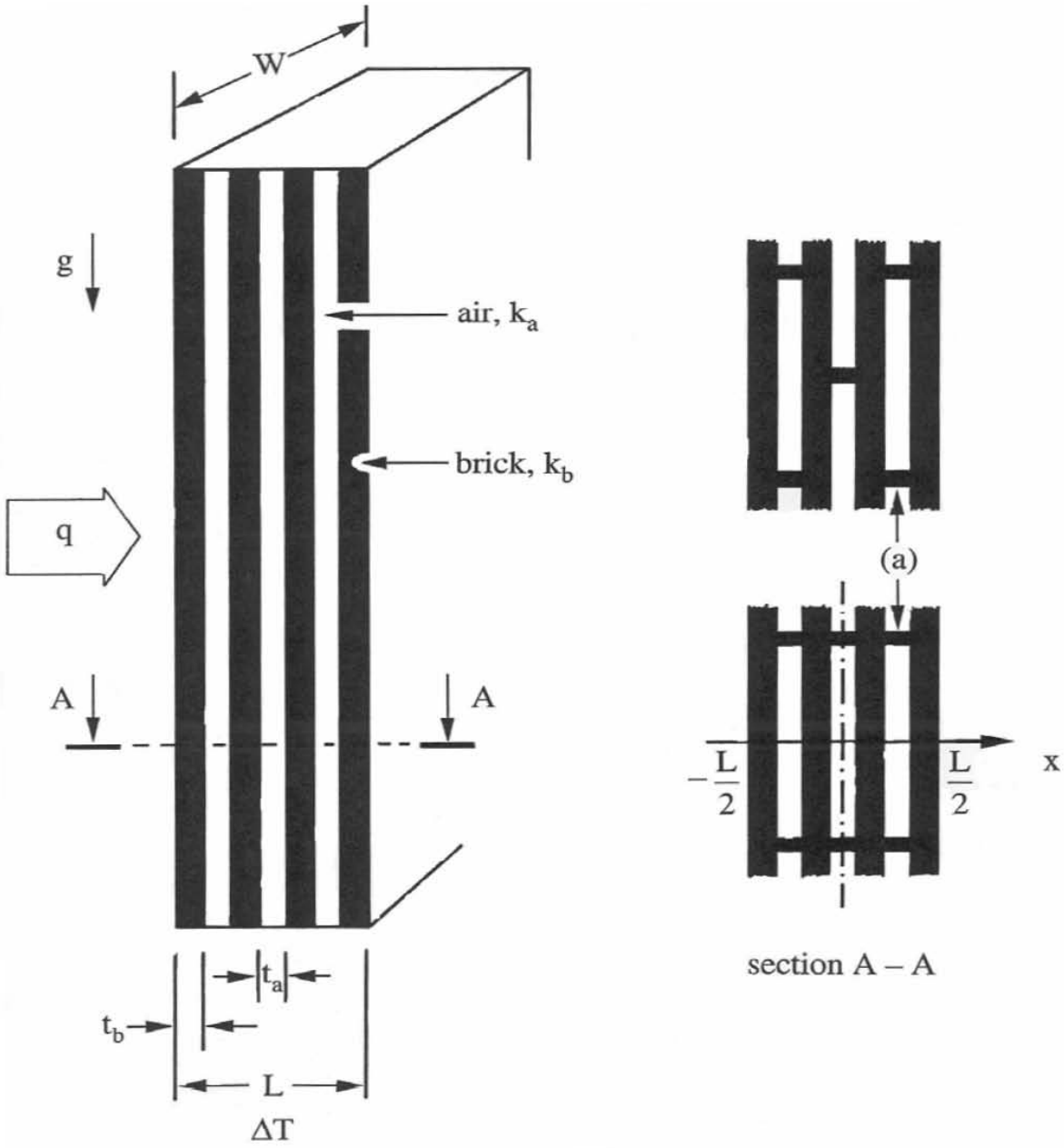

10
1
0.1
$\widetilde{R}_t$
n = 0
1
2
3
4
5
1
$10^4$
$10^8$
$10^{12}$
$\widetilde{W}$

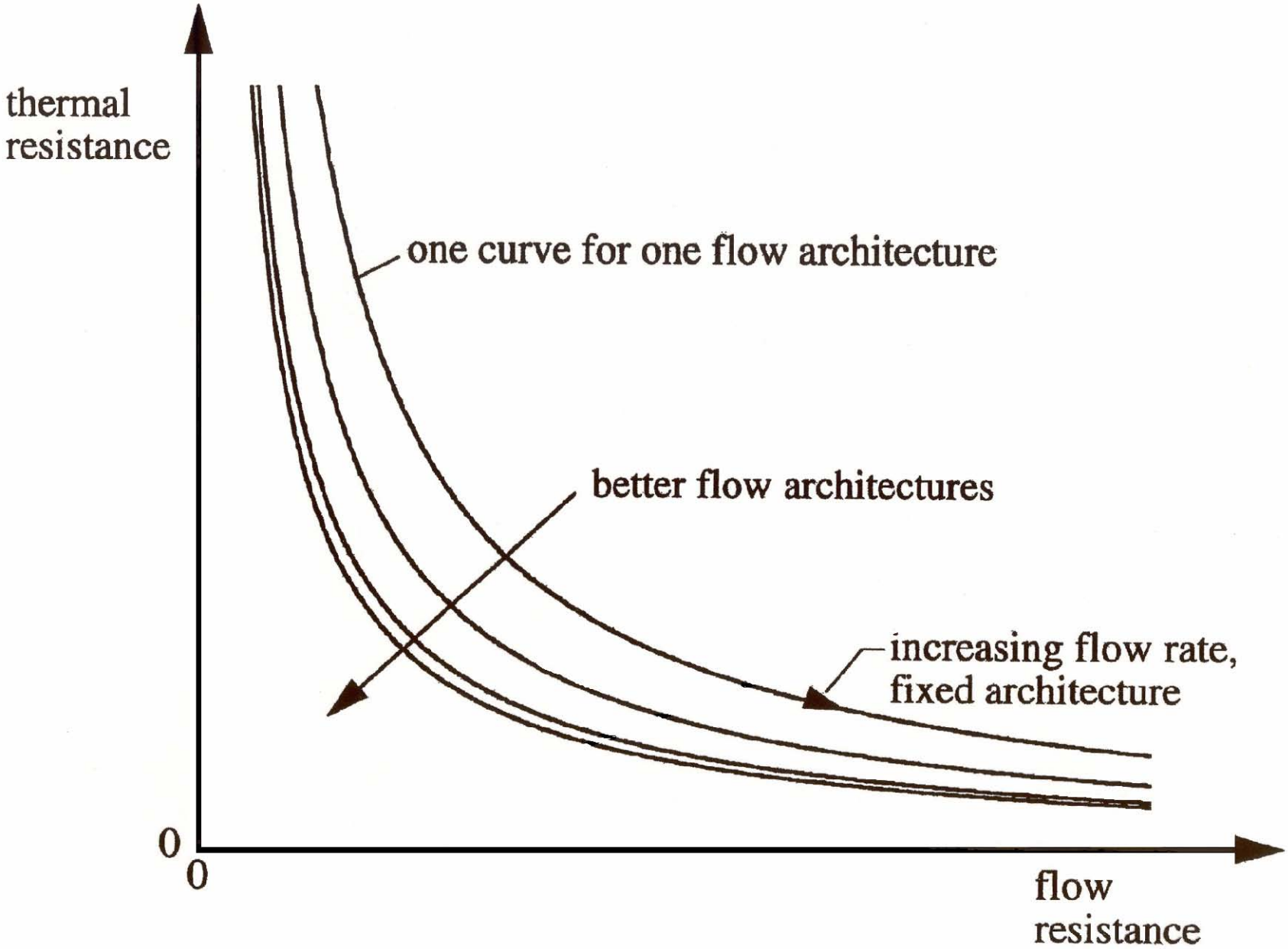
(a)

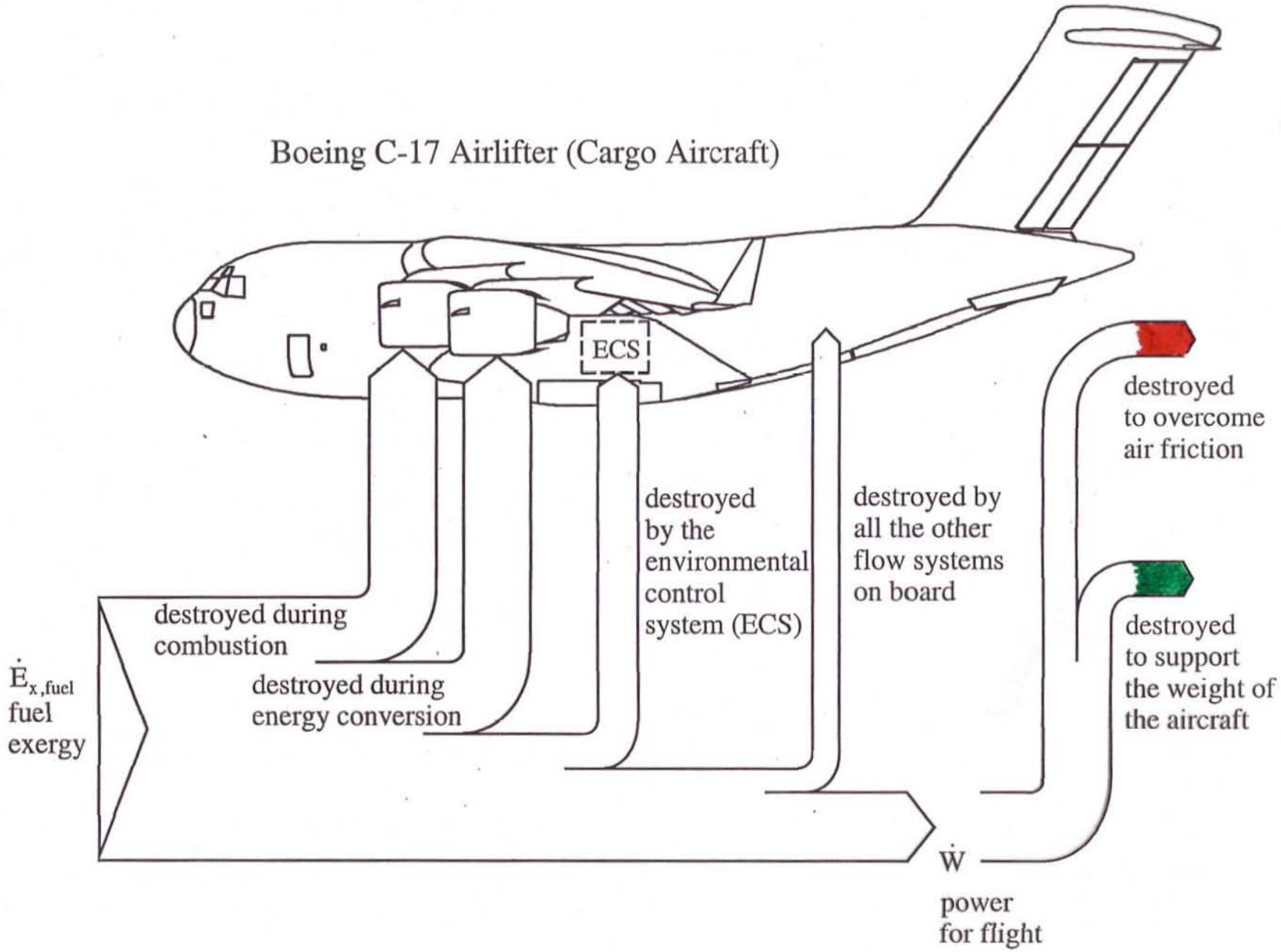

10
1
0.1
$\widetilde{R}_t$
n = 0
1
2
3
4
5
1
$10^4$
$10^8$
$10^{12}$
$\widetilde{W}$

(b)


10
1
0.1
$\widetilde{R}_t$
n = 0
1
2
3
4
5
6
7
8
9
10
11
12
13
n = 0
1
n = 30
$10^2$
$10^3$
$10^4 = \frac{X}{D}$
$\frac{R}{D} = \frac{R}{R_c} = 10^3$
X
D
R
$R_c$
D
1
$10^2$
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$\widetilde{W}$


W
g
air, $k_a$
brick, $k_b$
q
A
A
$t_a$
$t_b$
L
ΔT
(a)
$-\frac{L}{2}$
$\frac{L}{2}$
x
section A – A


thermal
resistance
one curve for one flow architecture
better flow architectures
increasing flow rate,
fixed architecture
0
0
flow
resistance


Boeing C-17 Airlifter (Cargo Aircraft)
ECS
destroyed during combustion
destroyed during energy conversion
destroyed by the environmental control system (ECS)
destroyed by all the other flow systems on board
destroyed to overcome air friction
destroyed to support the weight of the aircraft
$\dot{E}_{x,fuel}$ fuel exergy
$\dot{W}$ power for flight

# Minimization of work/distance

induced drag | friction drag

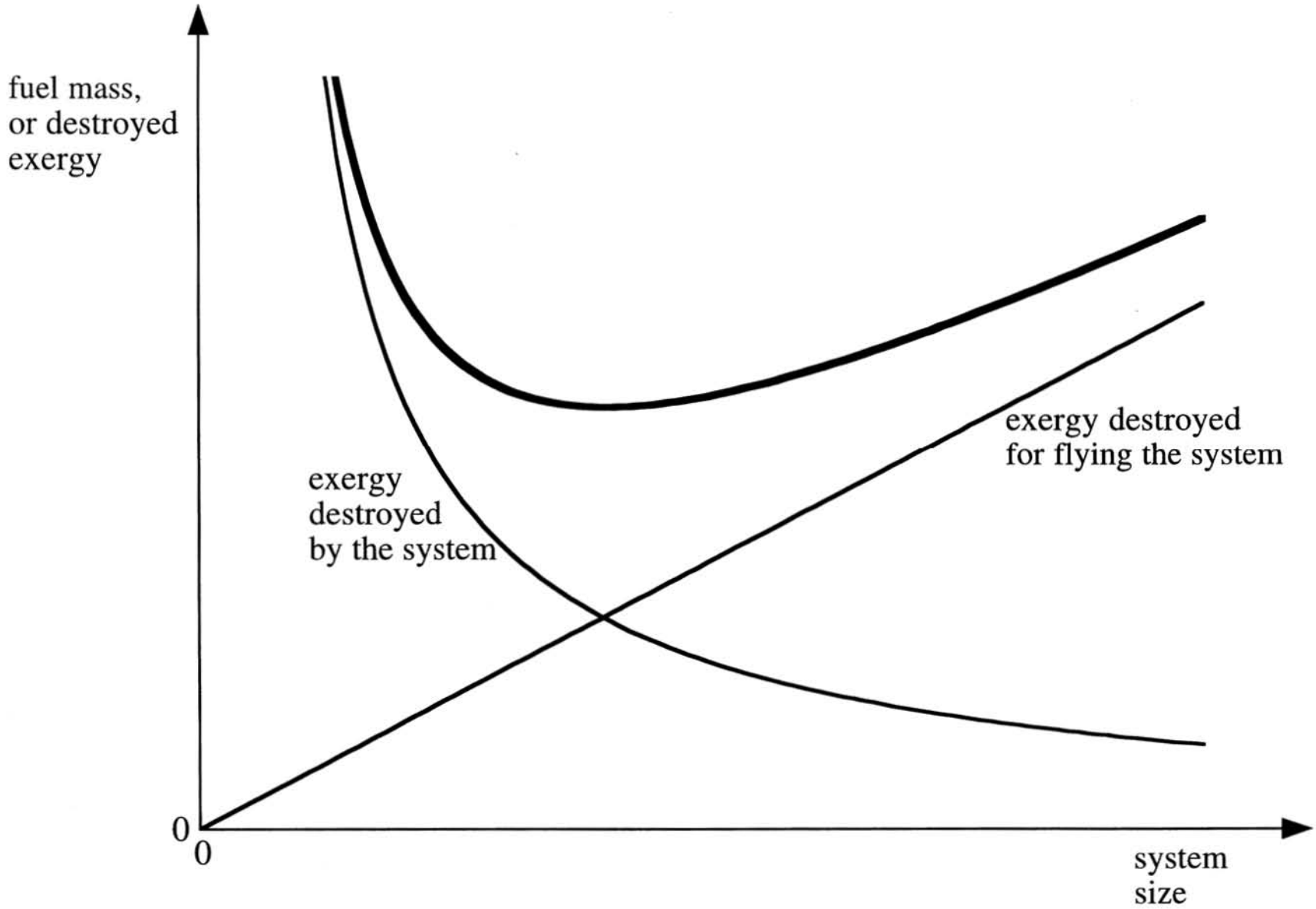
$$\frac{W}{L} \sim \frac{\rho_b^2 g^2 D^4}{\rho_a V^2} + \rho_a D^2 V^2$$

## Balance of losses, optimal distribution of imperfection

$$\left(\frac{W}{L}\right)_{min} \sim 2g\rho_b D^3 \sim 2gM$$

$$V_{opt} \sim \left(\frac{\rho_b}{\rho_a} gD\right)^{1/2}$$

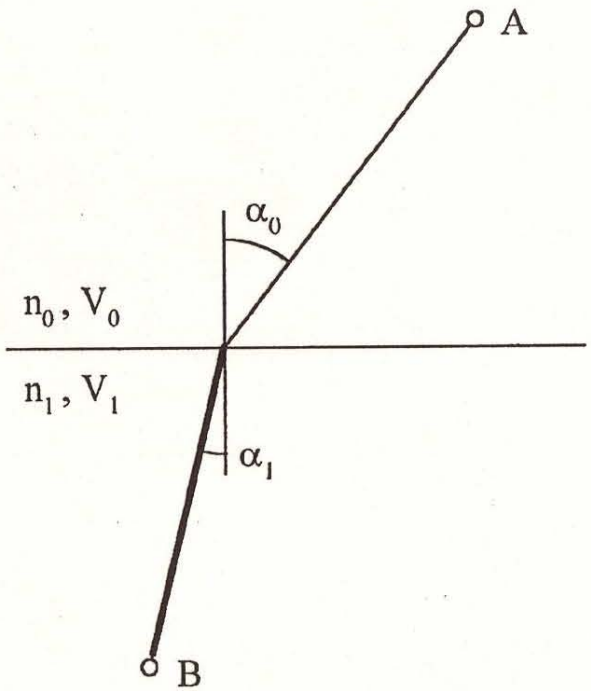
$$\text{speed} \sim (\text{mass})^{1/6}$$


fuel mass,
or destroyed
exergy
exergy
destroyed
by the system
exergy destroyed
for flying the system
0
0
system
size

V (m/s)
1
10
100
300
M (kg)
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
10
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
House fly
Meat fly
Honeybee
Hornet
Bumblebee
Dung beetle
Goldcrest
Ruby-throated hummingbird
Magnolia warbler
House wren
Sand martin
Barn swallow
Skylark
House sparrow
Blue jay
Sparrow hawk
Partridge
Peregrine falcon
Pheasant
Blue heron
Black vulture
White stork
Gannet
Golden eagle
Canada goose
Wandering albatross
Mute swan
Piper Warrior
Beech Bonanza
Beech Baron
Beech King Air
Leerjet 31
F-16
Mig-23
Fokker F-28
F-14
Boeing 737
Airbus A310
Douglas DC-10
Boeing 747
Insects
Birds
Airplanes

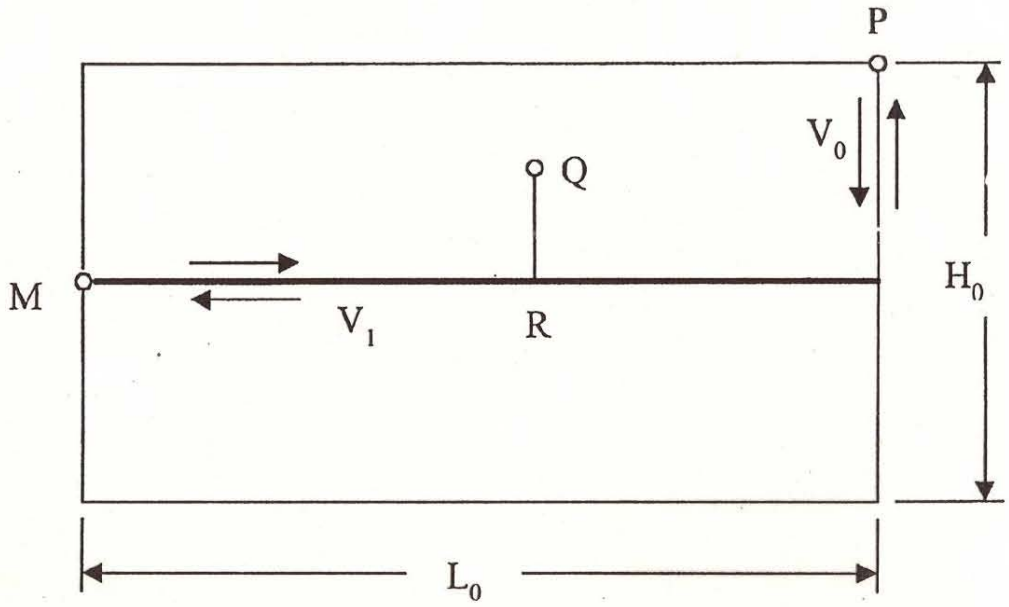
## Fermat law

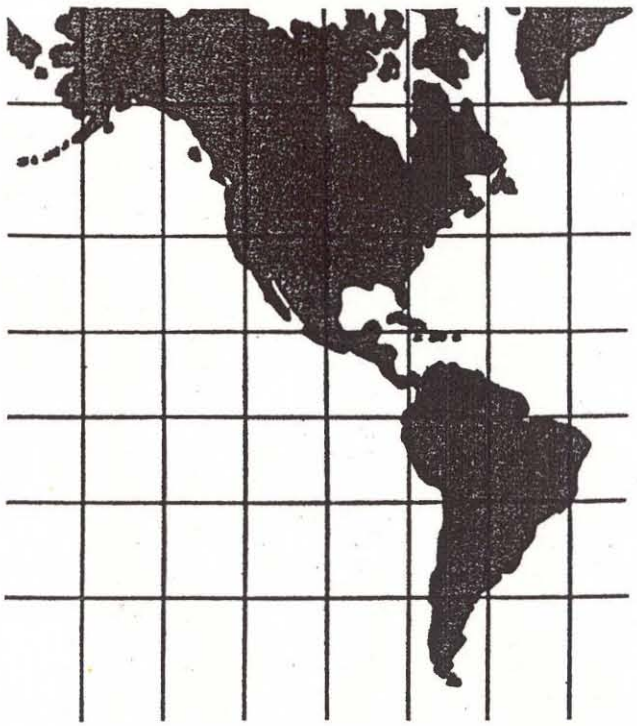
point-point flow

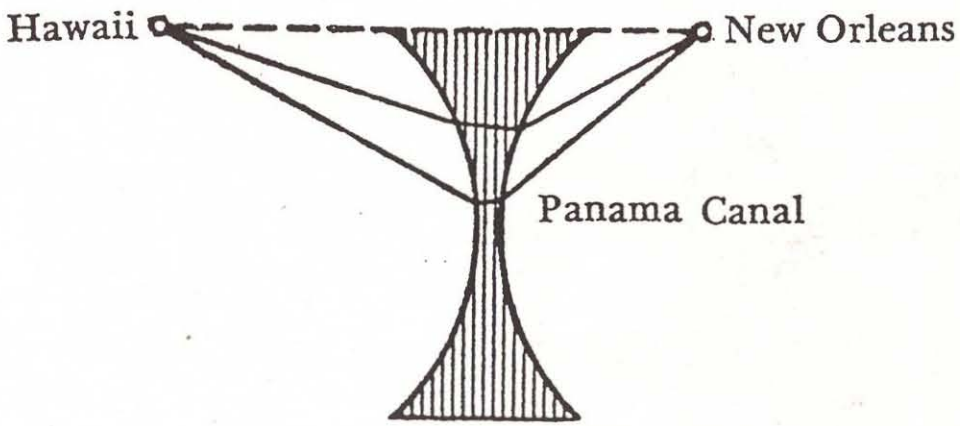


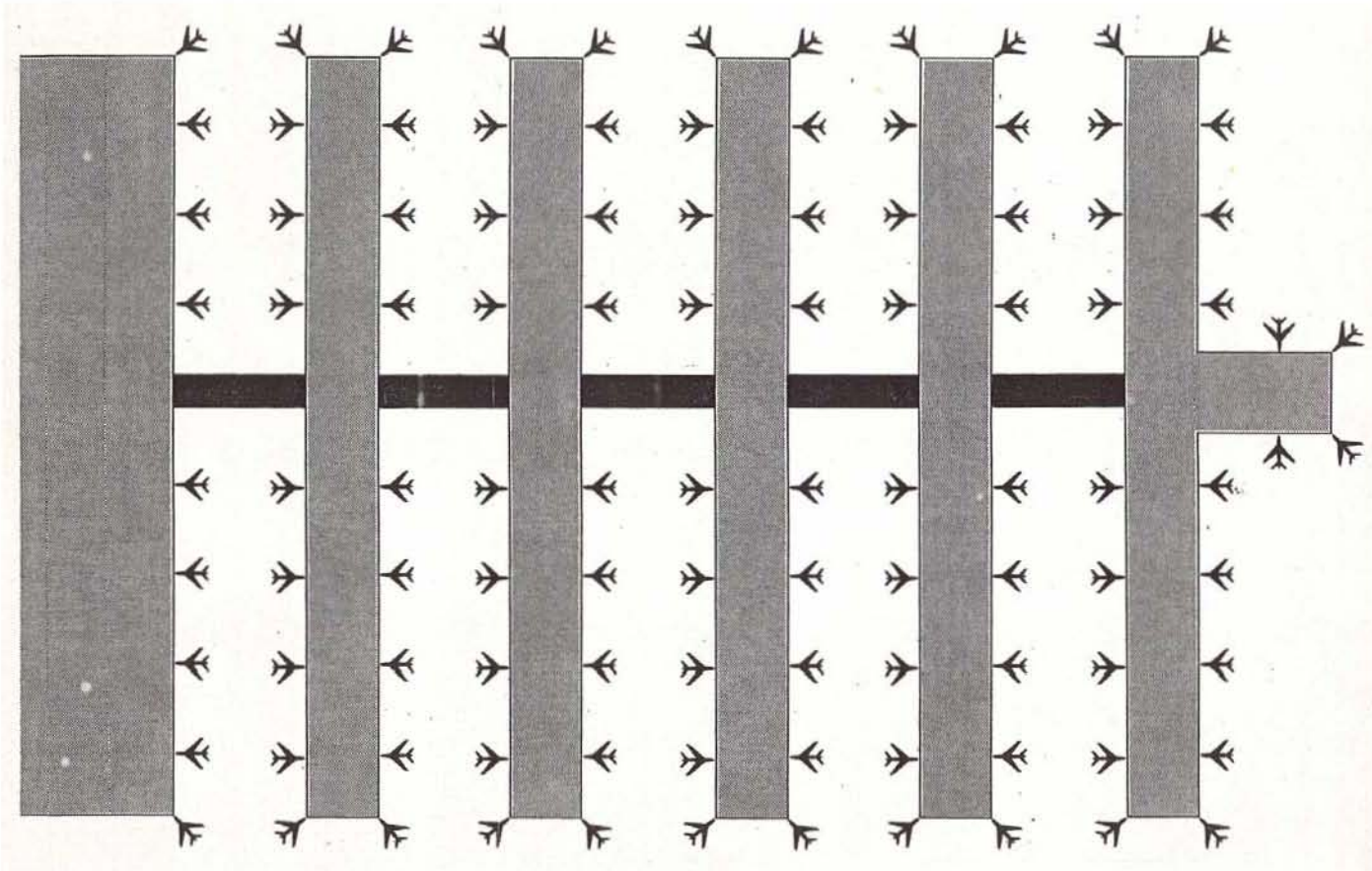

## Constructal law

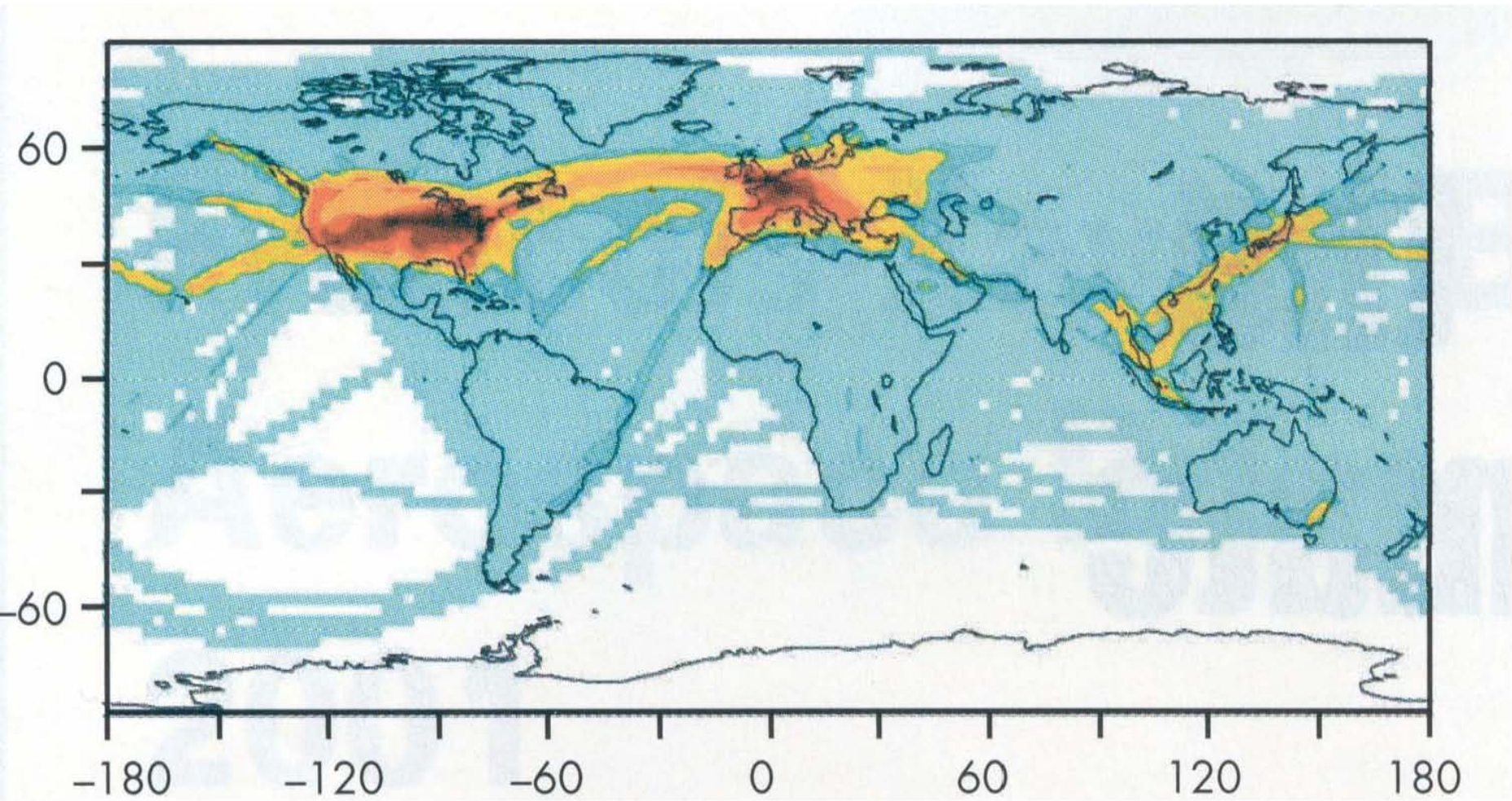
volume-point flow






Hawaii
New Orleans
Panama Canal

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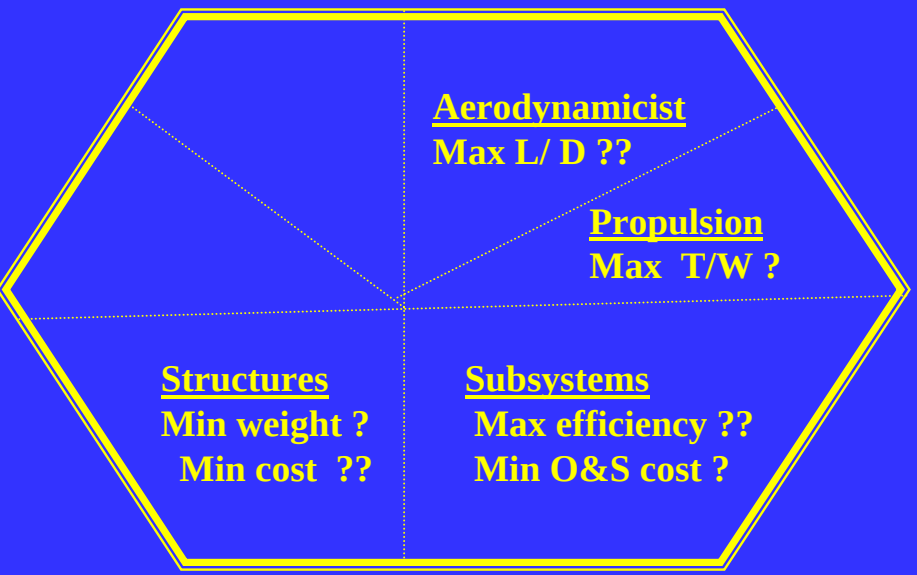
# Requirements on Methods for System-Level Analysis & Design of Efficient Aerospace Flight Vehicles ~ Exergy- Based or Constructal Theory or ???

Dr. David J Moorhouse
Air Force Research Laboratory
Wright-Patterson AFB USA

# The MultiDisciplinary Engineer in a Concurrent Environment

## TRADITIONAL DEVELOPMENT




## SYSTEM DESIGN OPTIMIZATION

**Integration of:**
**Airframe & propulsion**
**+ fully adaptive structures**
**+ propulsion & power systems**
**+ aerodynamics & controls**
**+ etc, etc**

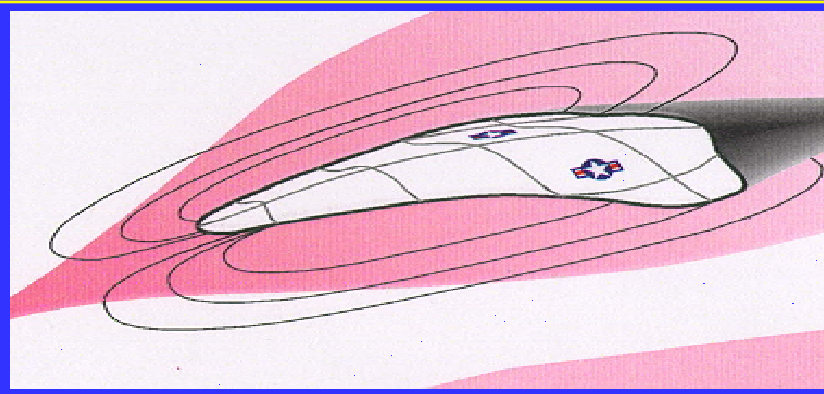
**Design for Synergistic Interactions**

***What is the Common Measure for Comparison ??***

# Why Develop New Methods ???

**Technology Challenges:**

- Accurate prediction/design tools
- Integration of airframe & propulsion
- Control of flow fields with plasma
- Energy extraction/power distribution



A Flight Vehicle Interacts Combustion Energy + Mechanical Work + Thermal + Kinetic + Potential Energies + + +

- **1st Law Principles → Energy conservation only**
- **2nd Law Principles → Entropy can only be created**

Minimizing Exergy Consumption Should Give an Efficient Design

**What Will Constructal Theory Provide ????????**

# Energy-Based Design

Special Section, AIAA Journal of Aircraft, Jan-Feb 2003:

Moorhouse, "Proposed System-Level Multidisciplinary Analysis Technique Based on Exergy Methods"

Chandrasekaran et al, "Optimization of an Aircraft Power Distribution Subsystem"

Paulus & Gaggioli, "Rational Objective Functions for Vehicles"

Munoz & von Spakovsky, "Decomposition in Energy System Synthesis/Design Optimization for Stationary and Aerospace Applications"

Bejan, "Constructal Theory: Tree-Shaped Flows and Energy Systems for Aircraft"

Figliola & Tipton, "Exergy Approach to Decision-Based Design of Integrated Thermal Systems"

Roth & Mavris, "Generalized Model for Vehicle Thermodynamic Loss Management" + "Method for Propulsion Technology Impact Evaluation via Thermodynamic Work Potential"

# Exergy-Based Design
## Task required

**Integration Framework for System-Level Optimization of Aerospace Vehicles**

A flight vehicle is a ‘device to do work’. The complete set of vehicle design requirements can be specified as an energy system. The mission can be stated in terms of work to be done by the exergy available from the fuel. The propulsion and every system are then components in minimizing the exergy consumed. This will provide the necessary understanding to allow decomposition into appropriate energy systems together with appropriate interactions. The exergy-based framework will support the design of a truly energy-efficient vehicle, although a realistic flight vehicle will also be subject to other constraints.

# Mission Requirements

- Define weight specific energy as kinetic + potential energies per unit weight:

$$E = h + \frac{1}{2g} U^2$$

- **Customer Work** – includes generating the specific energy of the **payload** and overcoming drag and power requirements:

$$\frac{dw_c}{dt} = W_p \frac{dE}{dt} + P_P + D_P U \quad \rightarrow \quad \textbf{REQUIRED}$$

- **Overhead Work** – Sum of the work consumed and drag caused by every component of the system which has to carry the payload:

$$\frac{dw_o}{dt} = \sum \left( W_i \frac{dE}{dt} + D_i U \right) \quad \rightarrow \quad \textbf{TO BE MINIMIZED}$$

AIAA Journal of Aircraft, Vol. 40, No. 1, Jan/Feb 2003

# System Level Efficiency

The customer and overhead work integrated over the entire mission represents the the total work that has to be supplied by the exergy of the fuel.

Conservation of Energy in time interval dt is:

$$-\eta H \frac{dW}{dt} = \frac{dw_c}{dt} + \frac{dw_o}{dt}$$

*H* is energy content of the fuel/weight, η is overall efficiency, $dW/dt < 0$.

Design problem is to minimize overhead work and maximize overall efficiency

# Aerospace Vehicle Design
## Exergy as a System-Level Metric

Design Mission Stated in Terms of Work to be Done

How precise does this need to be ?

Comes From the Exergy of the Fuel Consumed

Propulsion System Converts Fuel Into:

Mission Work, Including Power to Drive Mission Equipment

+

Mission Overhead

- Power to Lift Itself and Required Fuel
- Overcome Vehicle Drag
- Power for Other Subsystems

+

Waste due to Inefficiencies in Operation & Thermal Performance

# Exergy-Based Design Methods
# Potential System Energy Balance

| OVERHEAD | positives | negatives * |
|---|---|---|
| Actuation | essential functions | weight + power used |
| Structure | carries payload | weight |
| Adaptive structure | minimize drag, provide control | weight + power used |
| Controls | trim/stability/control | weight + cause drag + power used |
| Flow control | reduce drag | weight + power used + waste |
| ECS | essential cooling | weight + engine bleed + waste |
| Propulsion | supplies thrust + power | weight + waste |
| Fuel | supplies exergy + cooling | weight |

* weight now reflects work that needs to be done

# Exergy-Based Design
## Task required

Conventional high-speed vehicles have a requirement to protect the structure from elevated temperatures or provide active cooling, BUT:

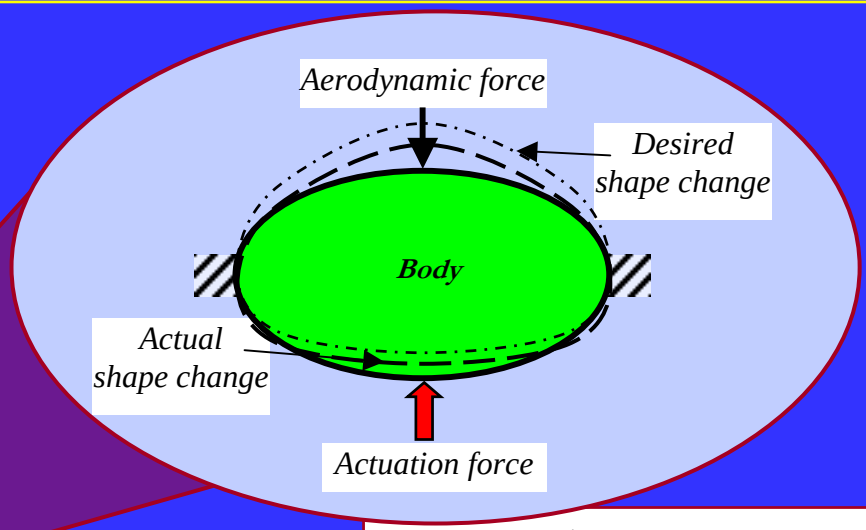
**Structures as an Energy System**

Current efforts are utilizing structural deformation requiring actuation power as a flight control effector, i.e. wing twist for roll control. In high-speed vehicles, the structure will have to be designed as a fully-integrated part of the system. In these vehicles the structure may distribute energy between other systems, it may store energy for use as and when required, and it may be a user of exergy for tailoring different characteristics. For the future, with the advent of active structures technology, there is a need to develop an understanding of the vehicle structure as an energy system.

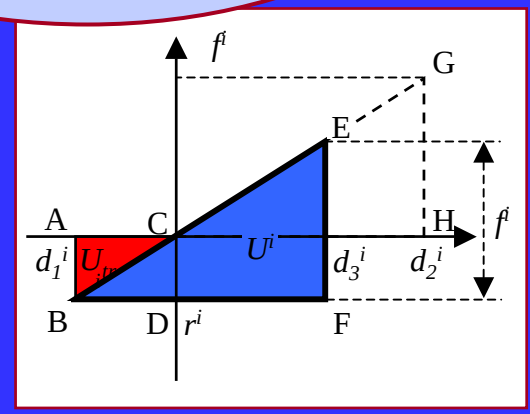
# Adaptive Structure Design

## Approach

- Develop a theoretical framework to identify energy flow inside of the body (input energy, transferred energy, stored energy and etc.) for efficiency calculation




$$\eta_{loaded} = \frac{Useful\ energy}{Input\ energy}$$




- Exergy-based framework to facilitate the design & system optimization of efficient systems

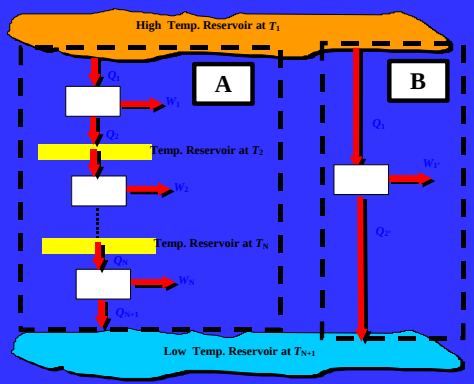
Total input energy = stored energy + transferred energy

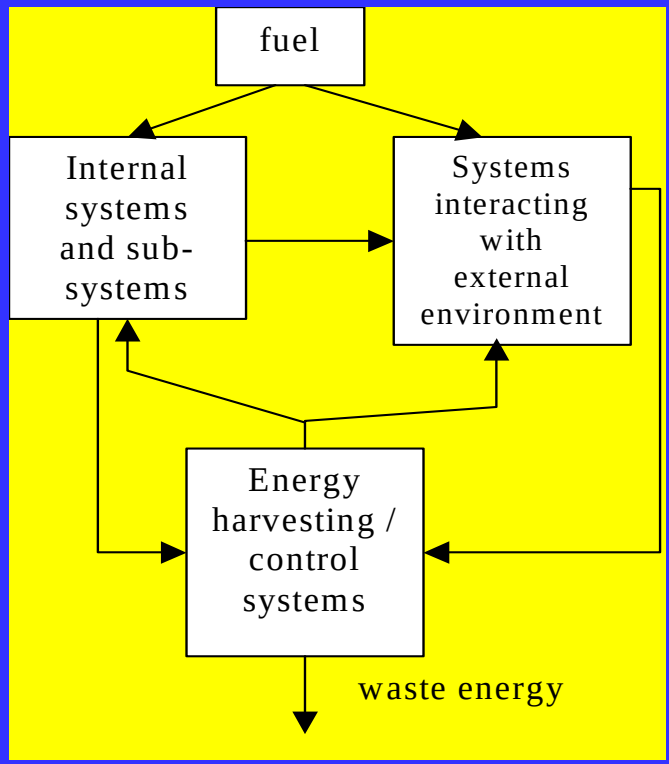
# Energy Based Design Structure as an Energy System

$$Exergy = (u - u_o) - T_o(s - s_o) + \frac{P_o}{J}(v - v_o) + \frac{V^2}{2gJ} + \frac{g}{g_c J}(z - z_o) + \sum_c (\mu - \mu_o)N_c + \ldots$$

## Energy Harvesting

### Basic Research

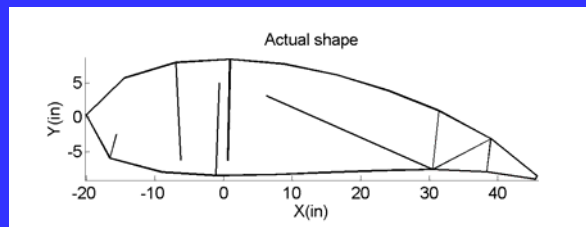



## Shape Control

### Basic Research

### Design Example



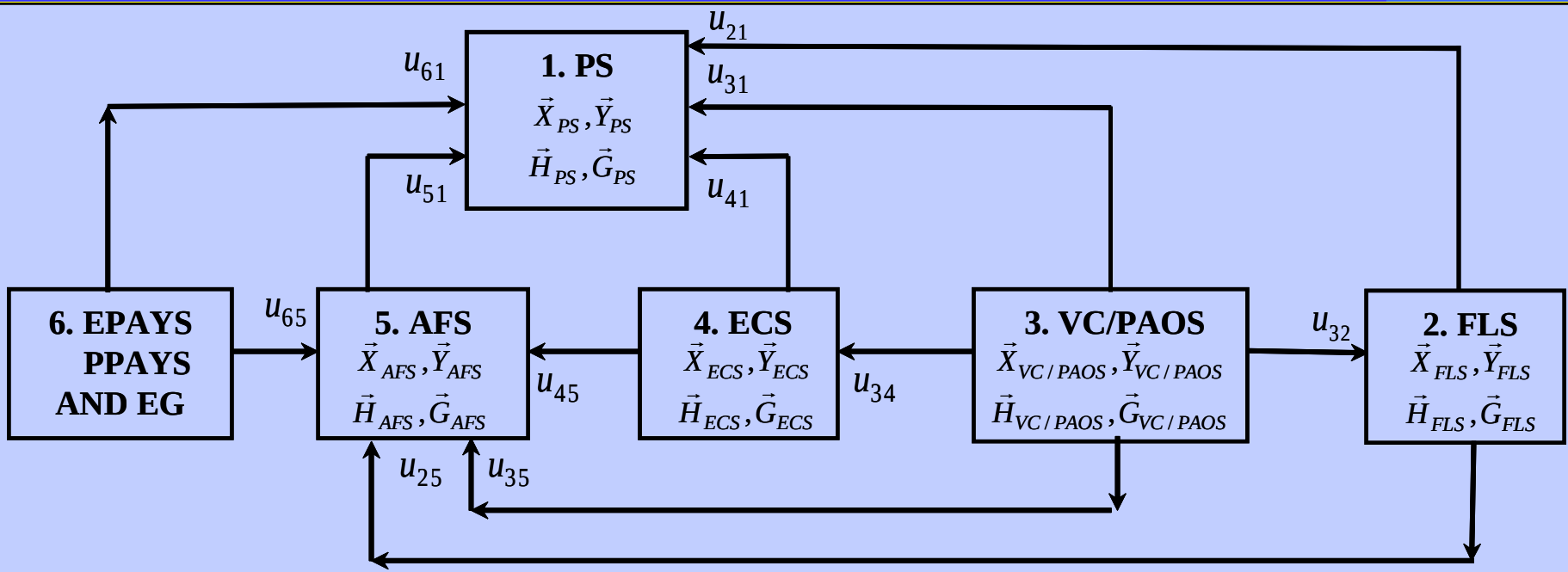
# Exergy-Based Design
## Task required

In current aircraft, the engine obviously supplies the direct power, cooling air, etc for all the aircraft subsystems. The definition of a turbine engine as an exergy component with airframe weight and drag has been done.

**Propulsion as an Integrated Energy System**

A high-speed vehicle will require new forms of propulsion and airframe system integration. It may power a device to reduce airframe drag as opposed to providing thrust to overcome the drag. There must be a credible way to perform the design trades. We need to develop the understanding of how the hypersonic propulsion system and all the other required systems can be designed to common metrics and optimization criteria.

# Sub-system Coupling Functions




| | | | |
|---|---|---|---|
| $u_{15}$ | **Weight of the PS** | $\vec{u}_{35}$ | **VC/PAOS weight** |
| $\vec{u}_{21}$ | **Momentum drag, FLS weight, power** | $\vec{u}_{41}$ | **Momentum drag, ECS weight, bleed air** |
| $\vec{u}_{25}$ | **FLS weight** | $\vec{u}_{45}$ | **ECS weight** |
| $\vec{u}_{31}$ | **Momentum drag, VC/PAOS weight, power** | $\vec{u}_{51}$ | **Drag, weight of the AFS** |
| $\vec{u}_{32}$ | **Heat rejection** | $\vec{u}_{61}$ | **PPAY, EPAY, EG weight** |
| $\vec{u}_{34}$ | **Heat rejection** | $\vec{u}_{65}$ | **PPAY, EPAY, EG weight** |

# Future ~ Required Task

A conventional flight control system is a user of exergy in the form of actuation power, and can impact vehicle drag which consumes exergy.

**<u>Future task required</u>: Control Strategies for Energy Systems**

- The control design problem is magnified when we consider the control requirements and associated subsystems of future vehicles

*Develop an Understanding of How the Total Vehicle Control System can be Designed to Exergy-Based Principles.*

*Develop an Understanding of How to Control the Distribution or Transfer of Energy Between the Different Systems in Order to Produce an Optimum Vehicle Control System.*

# Exergy-Based Design
## Task required

**Scaling Laws for Energy Systems**

There is a need to understand how the results of a laboratory test will have to be applied in the design of a full-scale vehicle. This will become increasing critical as we attempt to design a full-scale hypersonic flight vehicle using components with no previous flight experience.

Need to integrate mechanical work, thermal energy, rate of change of momentum, etc, etc

This requires research to develop an understanding of the appropriate scaling laws for energy systems.

# Exergy-Based Design
## Task required

A common problem area with flight vehicle development involves the full-scale characteristics not matching the predicted models. In many areas of design it is common practice to design for uncertainties, e.g. sensitivity analyses, robust control theories.

**Uncertainty Analysis of Energy Systems**

Currently, there is no database on the expected accuracy or errors in modeling some of the new energy systems that will be used in a hypersonic flight vehicle. It is probable that each system will interact with every other one. The propagation of uncertainties through an interactive system must also be addressed. There is a need to develop an understanding of the uncertainties in modeling these systems and the ramifications of using the models in full-scale design.

# Exergy-Based Design
## Task required

**Optimization Techniques for a System of Energy Systems**

It is not guaranteed that conventional optimization techniques are the most appropriate for the envisioned system of energy systems. It is also possible that a system of energy systems will be subject to new and unforeseen constraints.

**The understanding must be developed of how to minimize <u>total</u> entropy generation in a complex integrated system, plus the appropriate constraints.**

# Exergy-Based Design Methods Summary

Energy Consideration is NOT New, BUT The Uses Have Been Implicit, Disconnected and Indirect
- e.g. the Breguet range equation ~ work against drag
- e.g. propulsion system design

We Considered Explicit Use of Entropy & Exergy Principles to Develop System-Level Design/Analysis Methods Based on the Laws of Thermodynamics:

- Mission Requirements in Terms of Work to be Accomplished
- Energy/Exergy Terms Flow Down to Every Component
- Computation of Entropy Generation Rate -> Exergy Destroyed
- Minimize Available Work that is Wasted, i.e. Fuel Required

# System-Level Design Methods Summary

Is **Constructal Theory** the Natural Energy Flow for Mechanical Systems ?

Does Natural Selection Apply for Constrained Optimization ??

How do We Need to Model Flight Vehicles & Systems ???

What are the Constraints for Efficient Energy Usage ????

Will This Approach Give Us Better Practical Solutions ?????

What Further Research Is Required ?

# Tree-Shaped Networks for Distribution, Collection & Cooling

**Sylvie Lorente**
**Lab. Materials and Durability of Constructions**
**National Institute of Applied Sciences (INSA),**
**Toulouse, France.**

Workshop on Constructal Theory of the Generation of Optimal Flow Configurations, Roma.

Adrian Bejan, Duke University, North Carolina, USA

1996

"*For a finite-size open system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it* ".

# Tree architectures

everywhere in nature and engineering

# Introduction

Purpose → to make
a flow connection between
one point and an infinity of points

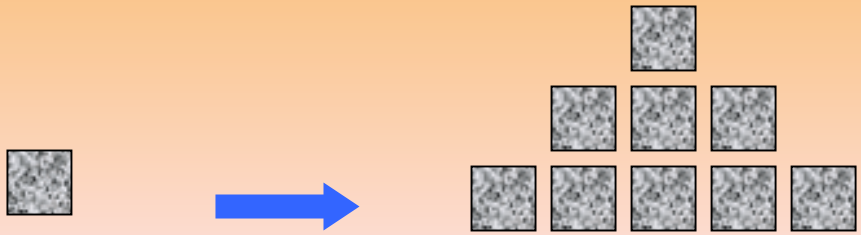
Complex flow structures with multiple scales
: tree-shaped networks

The flow resistances cannot be
eliminated. They can be rearranged,
assembled ...

To minimize their influence on
performance = optimization

method

integration of an increasing number of smaller and smaller flow components



elemental area

constructs

**Shape** (or geometry) is the result of the minimization of imperfections, or the optimal distribution of imperfections.

# Contents


- Introduction
- Networks at human scales
  - Tree-shaped networks of insulated pipes for the distribution of hot water
- Networks at small scales
  - Tree-shaped networks in a disc-shaped body
  - Comparisons
    - Minimal pipes length
    - Fractal-like structure
  - Tree networks with loops
- Concluding remarks

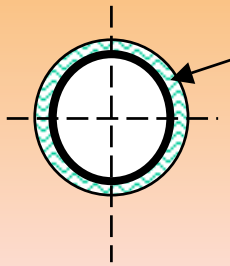
# Networks at human scale

Tree-shaped networks of insulated pipes for the distribution of hot water uniformly over a given territory (area A)

| | |
|---|---|
| objectives | Maximum delivered temperature<br>Minimum pumping power |
| constraints | Total amount of insulation<br>Total volume of the pipes |

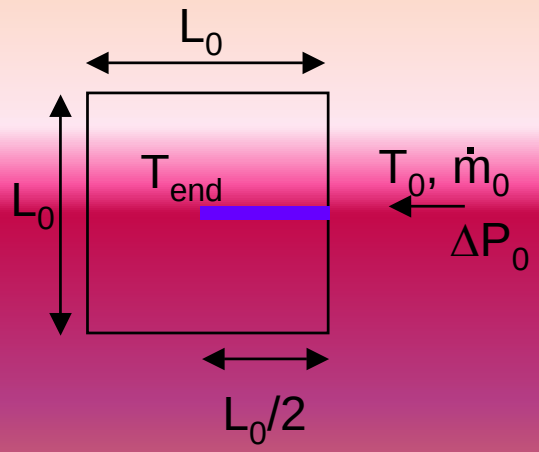
# Construction of the network

## Elemental System



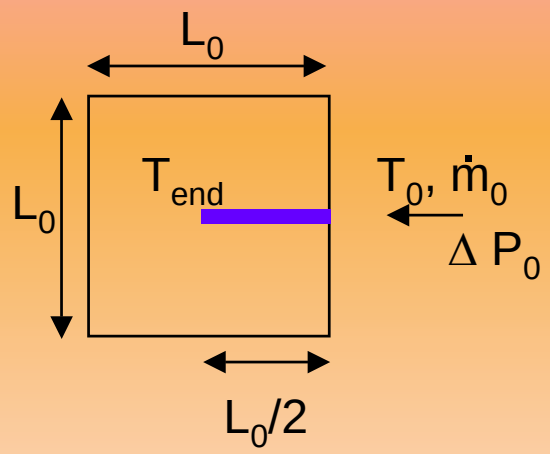

$r_i$ inner radius of the pipe

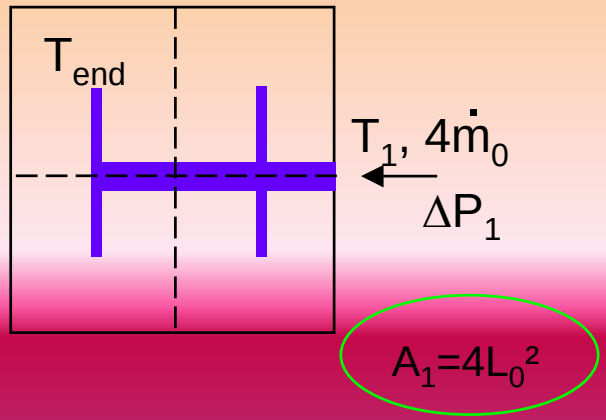
$r_o$ outer radius of the (pipe + insulation)

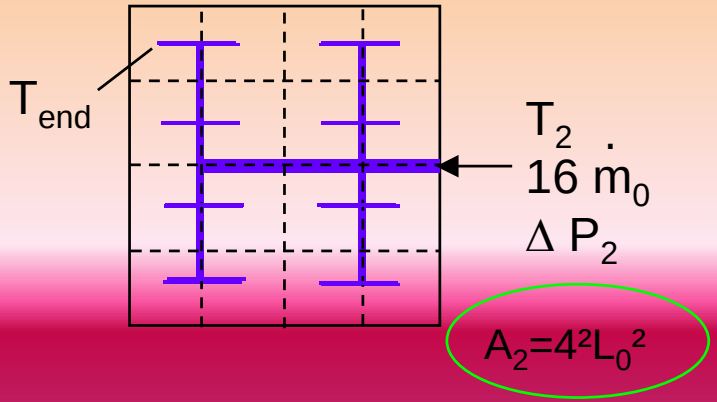


# Different configurations

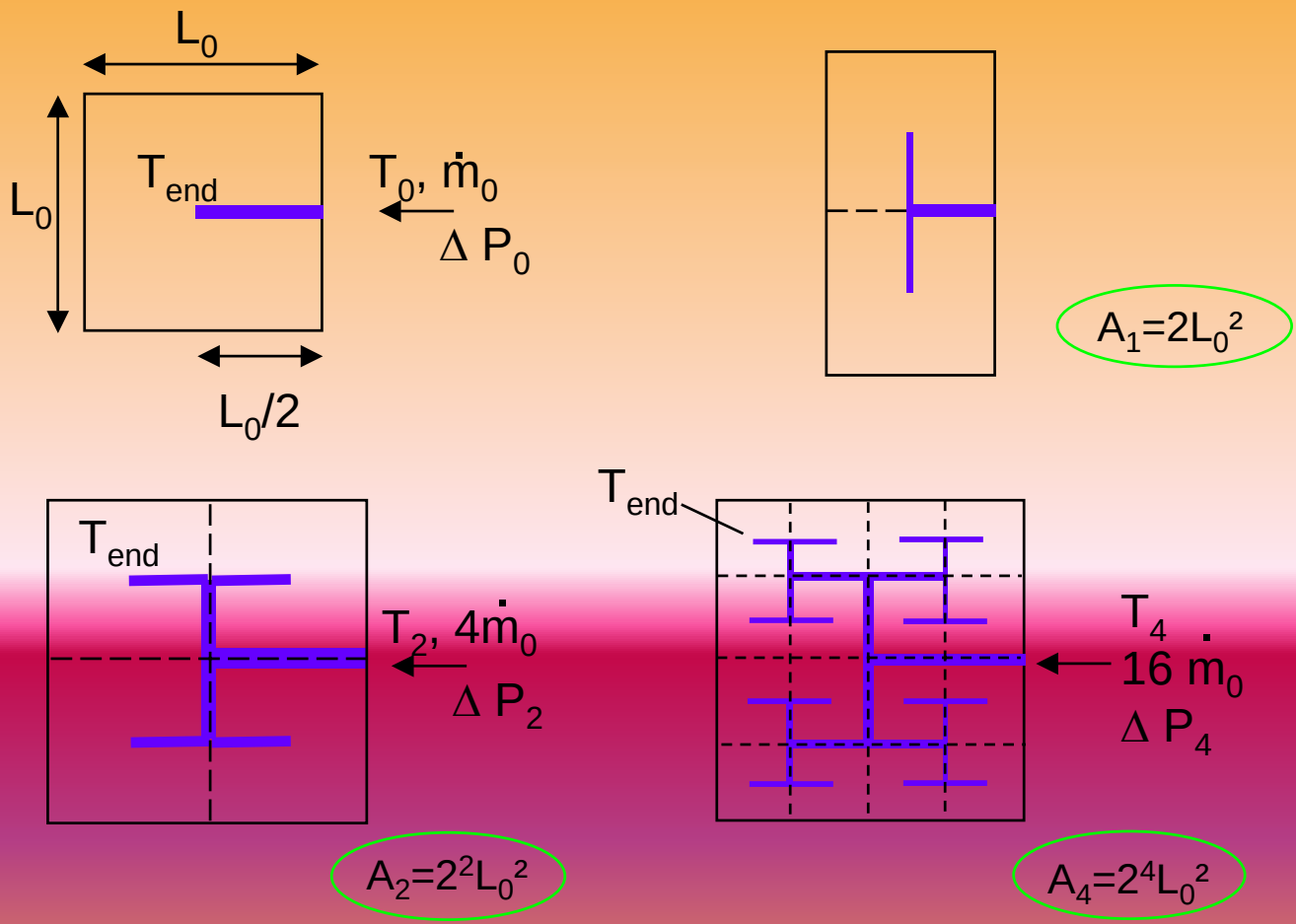
Case 1: every construct covers a square area



## Case 2: the new construct is obtained by pairing the previous ones



## Constraints

- Total volume occupied by the ducts

*Fluid Mechanics aspect*

objective: minimization of the pressure drops

minimization of pumping power

- Total amount of insulation wrapped around the pipes

objective: minimization of the heat losses

*Heat Transfer aspect*

maximization of the temperature

of the hot water received by the end user

# METHOD

Pressure drops and heat losses are minimized at every step

Set of equations:

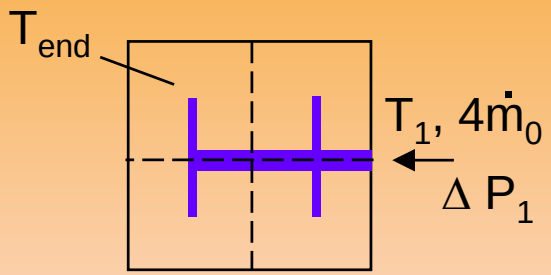
*Fluid Mechanics aspect*

- $\Delta P = C \frac{L \dot{m}^2}{r_i^5}$ fully turbulent flow (rough)

- elemental system $\Delta P_0 = C \frac{L_0}{2} \frac{\dot{m}_0^2}{r_{i_0}^5}$

**example of case 1:**

1st construct




$$\Delta P_1 = C\frac{L_0}{2}\frac{(4\dot{m}_0)^2}{r_{i_1}^5} + CL_0\frac{(2\dot{m}_0)^2}{r_{i_1}^5} + C\frac{L_0}{2}\frac{\dot{m}_0^2}{r_{i_0}^5}$$

$$\Delta P_1 = CL_0\dot{m}_0^2\left[\frac{12}{r_{i_1}^5} + \frac{1}{2r_{i_0}^5}\right]$$

- total volume occupied by the ducts

$$\frac{3}{2} L_0 \pi r_{i_1}^2 + 2 L_0 \pi r_{i_0}^2 = \text{constant}$$

- minimization $\frac{\partial}{\partial r_{i_0}} \Delta P_1 = 0$ $\Rightarrow$ $\left( \frac{r_{i_1}}{r_{i_0}} \right)_{opt} = 2^{5/7}$

## *Heat Transfer aspect*

- heat losses to the ambient (per unit of pipe length)

$$q' = \frac{2\pi k}{\ln\left(\frac{r_o}{r_i}\right)}\left(T - T_\infty\right)$$

the pipe thickness is neglected
k: thermal conductivity of the insulating material

- energy conservation $\dot{m}C_p dT = q' dx$

$$\frac{T_{end} - T_\infty}{T_{initial} - T_\infty} = \exp\left(-\frac{N}{\ln R}\right)$$

with $R = \frac{r_o}{r_i}$ and $N = \frac{2\pi kL}{\dot{m}C_p}$ "number of heat loss units"

$$N=\frac{2\pi kL}{\dot{m}C_p}$$ "number of heat loss units"

a low N:

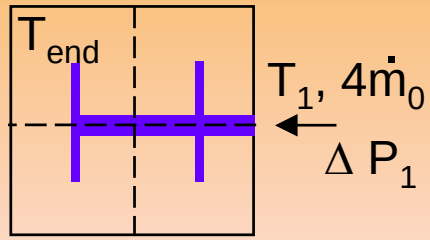
high performance materials (low k)

high mass flow rate

- elemental system $$N_0=\frac{2\pi k\frac{L_0}{2}}{\dot{m}_0 C_p}$$

## example of case 1:

➡ 1st construct




$$\theta_1 = \frac{T_{end} - T_\infty}{T_1 - T_\infty} = \exp\left( - \frac{N_0}{\ln R_0} - \frac{5N_0}{4 \ln R_1} \right)$$

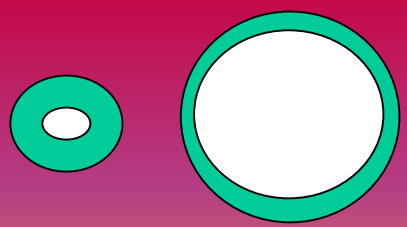
- total amount of insulation

$$\tilde{V}_1 = \frac{V_1}{\pi L_0 r_{i_0}^2} = \frac{3}{2}\left(\frac{r_{i_1}}{r_{i_0}}\right)^2\left(R_1^2 - 1\right) + 2\left(R_0^2 - 1\right)$$

Fluid Mechanics optimization

- maximization of $\theta_1$

$$\frac{R_1 \ln R_1}{R_0 \ln R_0} = \left(\frac{5}{6}\right)^{1/2}\left(\frac{r_{i_0}}{r_{i_1}}\right)_{opt} \quad \rightarrow \quad R_{1_{opt}} < R_{0_{opt}}$$



$$R = \frac{r_o}{r_i}$$

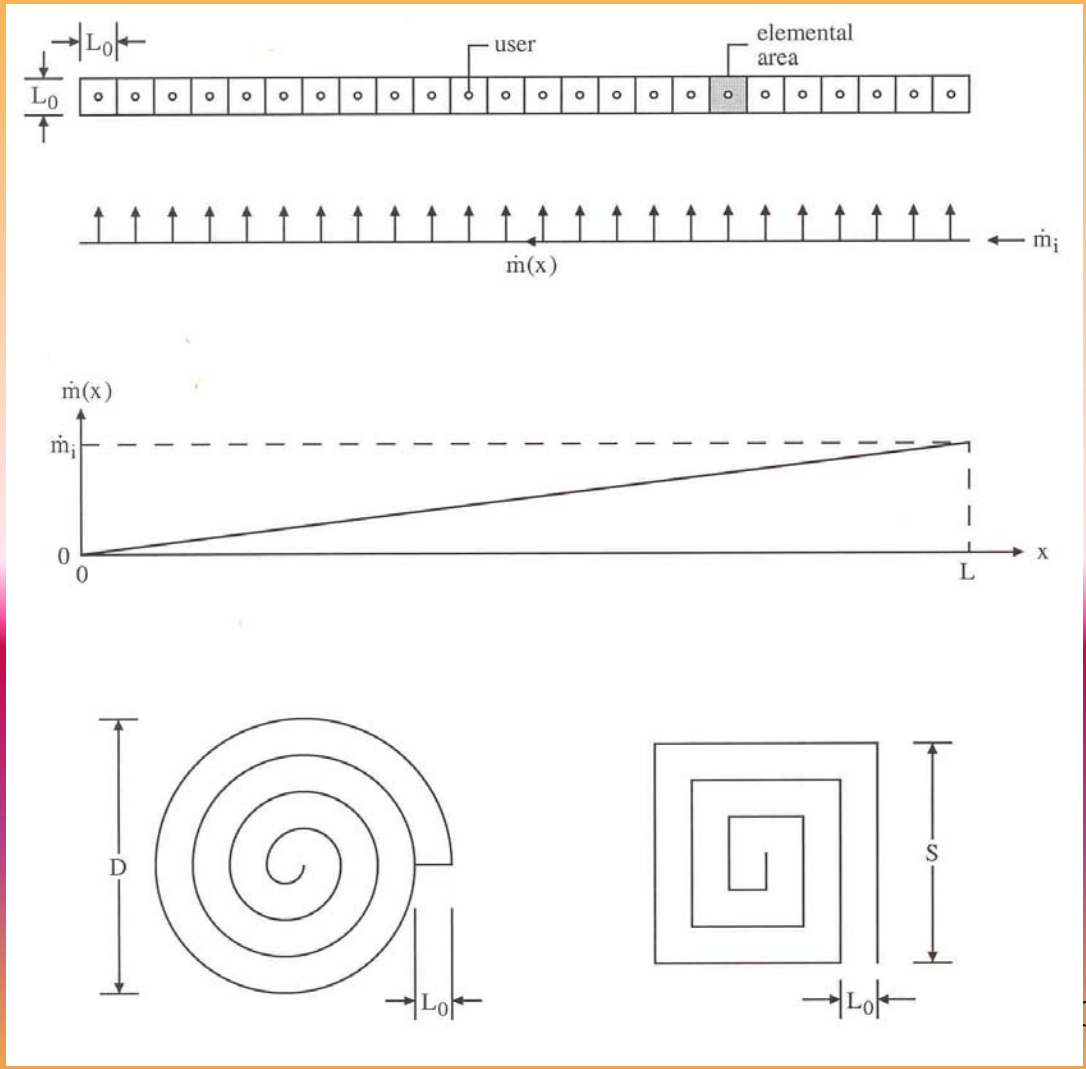
The insulation shell is relatively thicker over the smaller ducts

## Comparison of the different systems

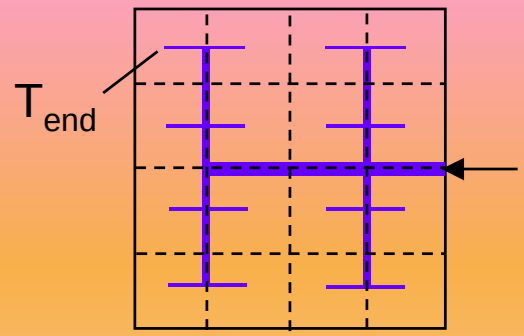
? *Which network serves the farthest user better*

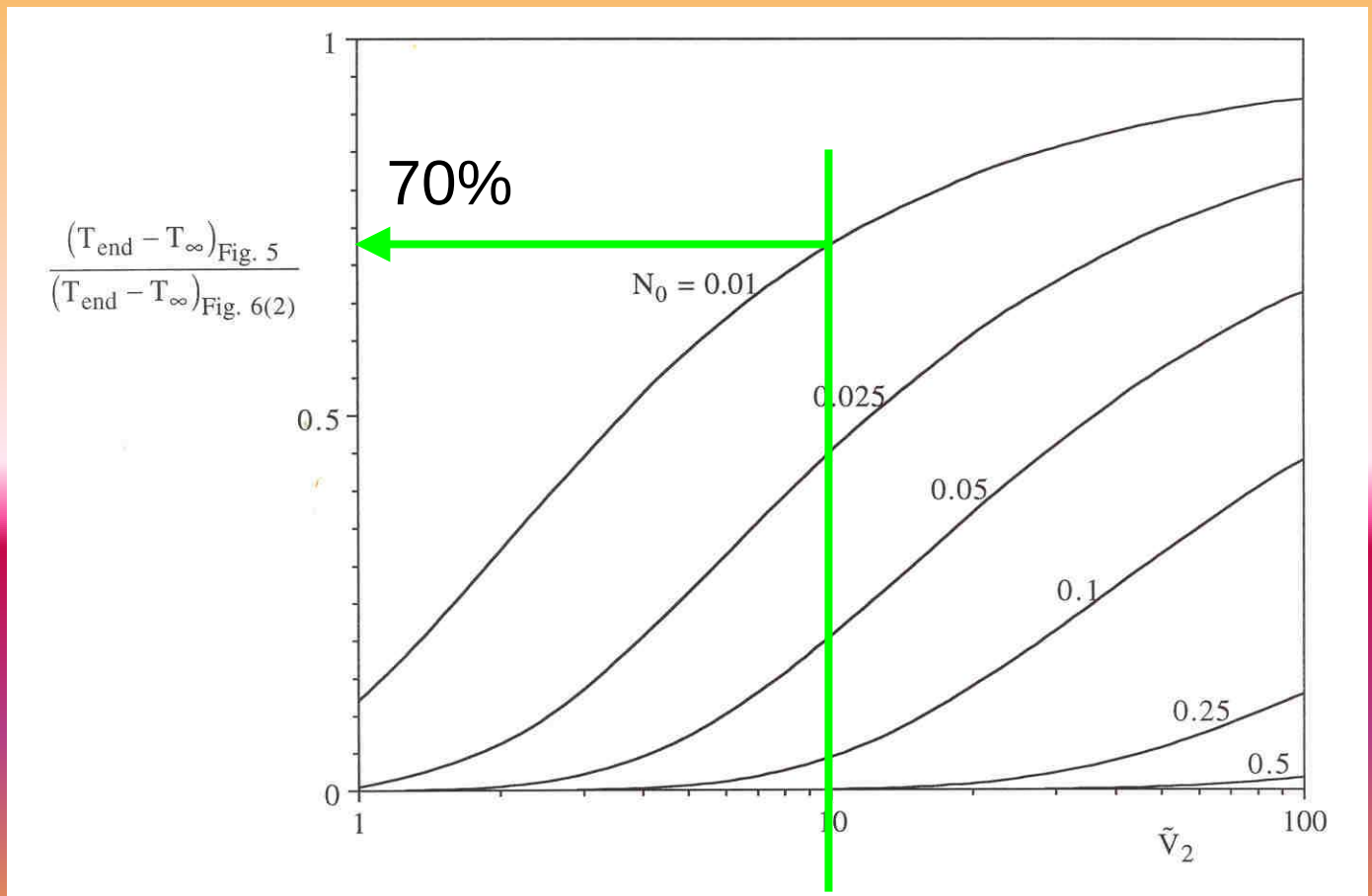
$$q' = \frac{2\pi k}{\ln(r_0 / r_i)}\left(T(x) - T_\infty\right)$$

$$\frac{T(x) - T_\infty}{T_i - T_\infty} = \exp\left(-N \int_x^L \frac{dx}{x \ln(r_o / r_i)}\right)$$

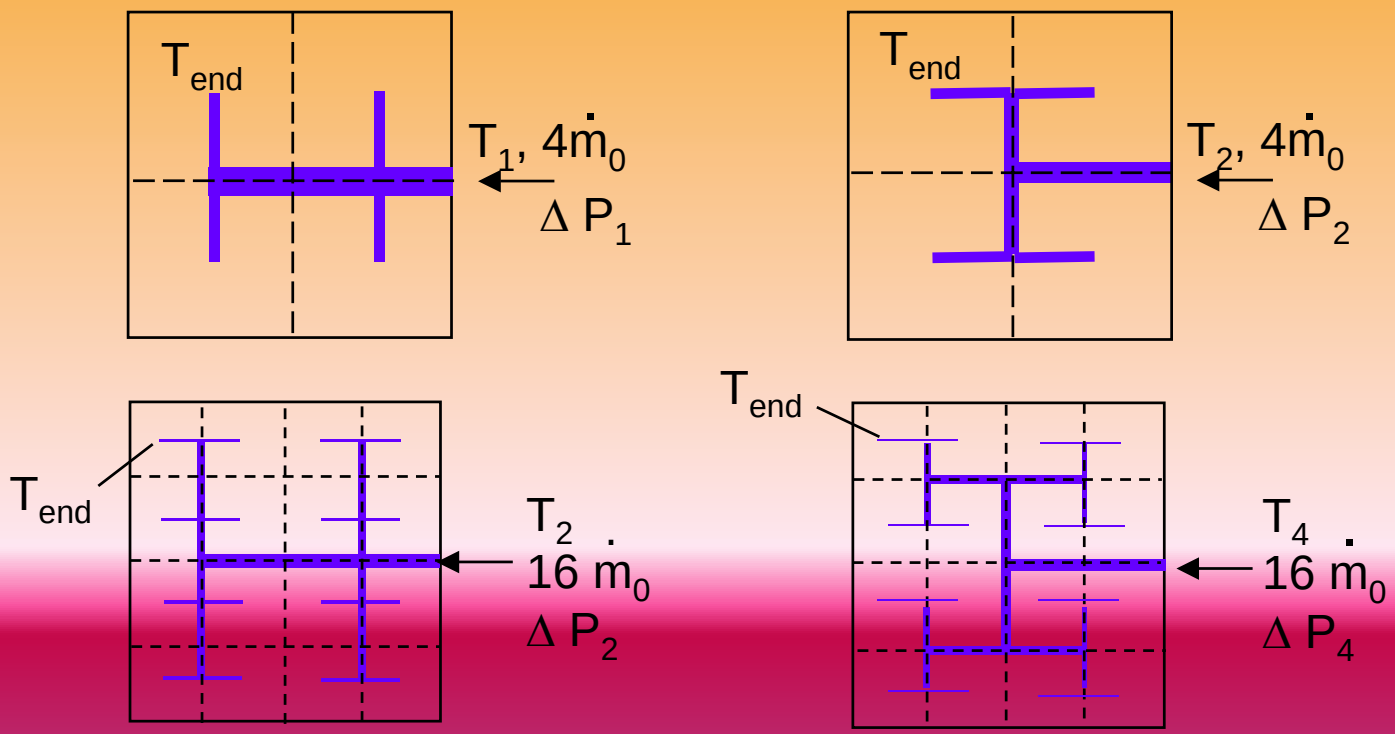



Configurations, Roma.

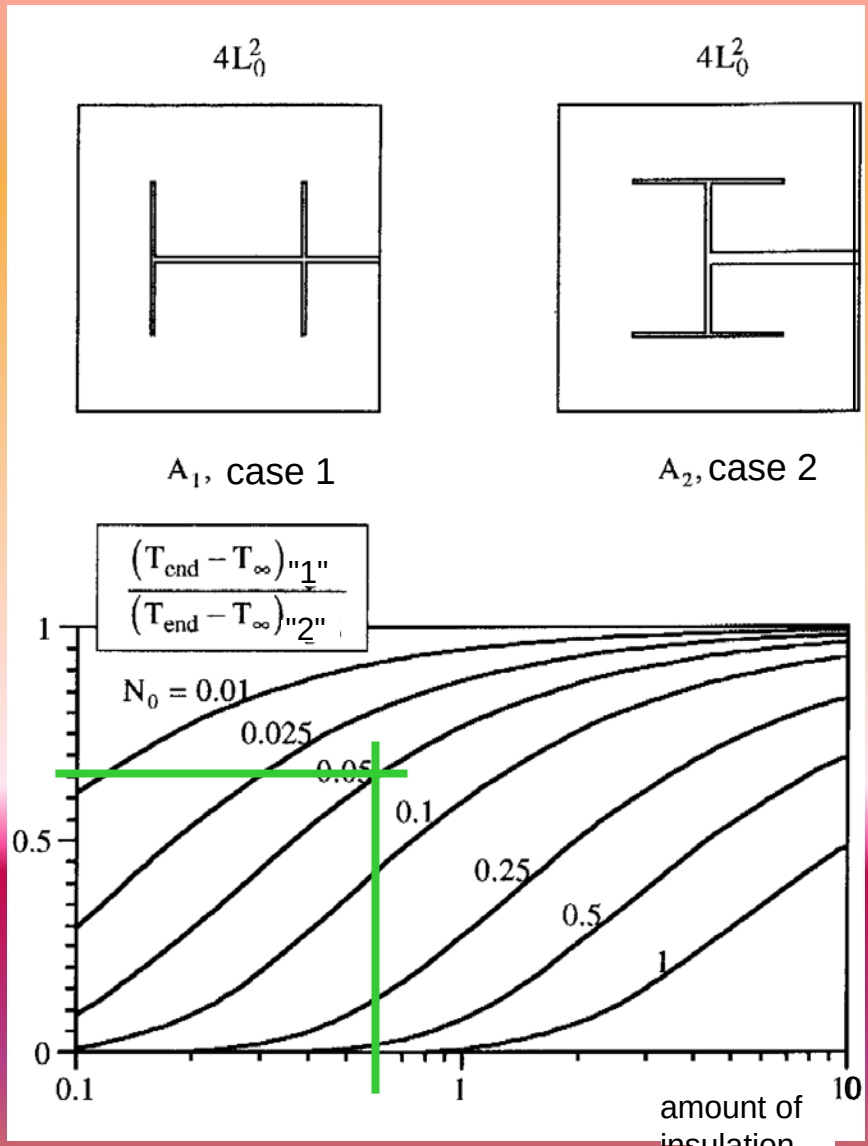

$T_{end}$

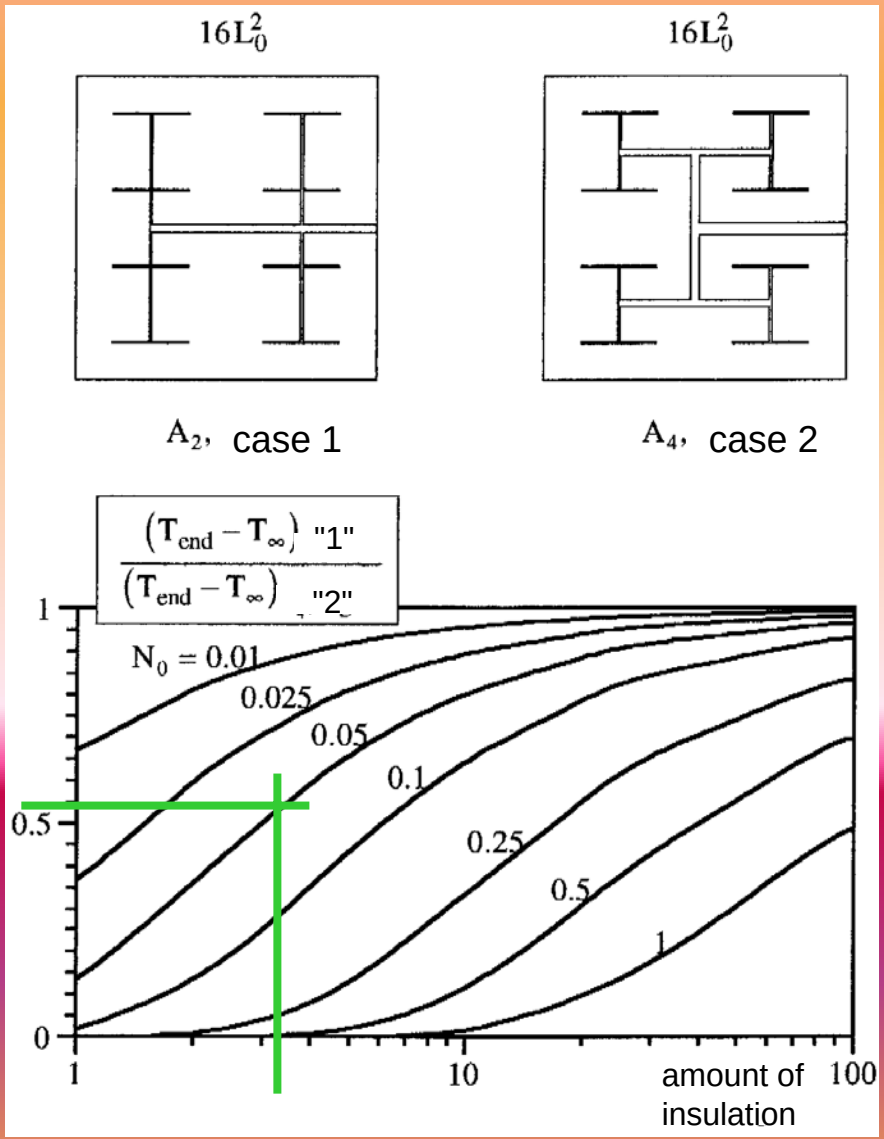

70%
$\frac{(T_{end} - T_\infty)_{Fig.\ 5}}{(T_{end} - T_\infty)_{Fig.\ 6(2)}}$
1
0.5
0
1
10
100
$\tilde{V}_2$
$N_0 = 0.01$
0.025
0.05
0.1
0.25
0.5

# 2 levels of comparison: square areas $4L_0^2$ and $16L_0^2$




the same | surface covered by the network
amount of insulating material


$4L_0^2$
$4L_0^2$
$A_1$, case 1
$A_2$, case 2
$\frac{(T_{cnd} - T_\infty)_{"1"}}{(T_{end} - T_\infty)_{"2"}}$
1
0.5
0
$N_0 = 0.01$
0.025
0.05
0.1
0.25
0.5
1
0.1
1
10
amount of insulation



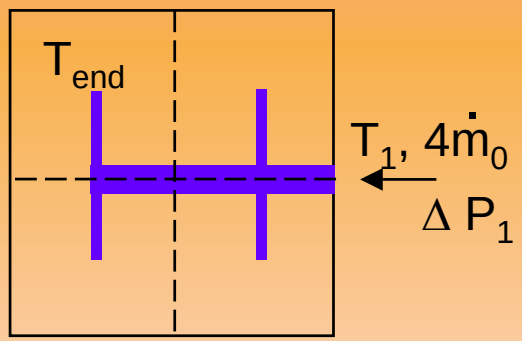

➡ "Case 2" performs best

⟶ $T_{end}$ is higher.

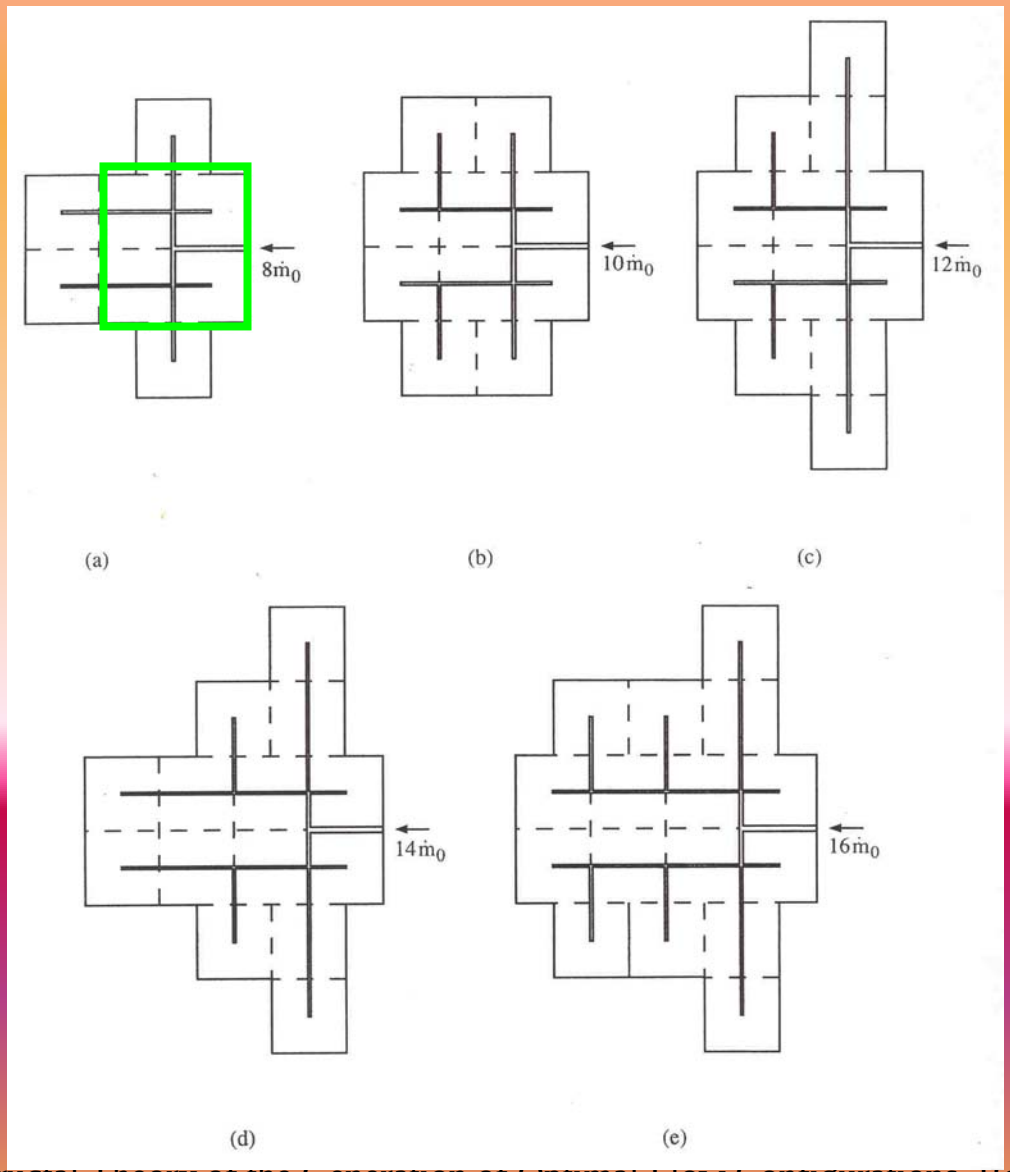
The difference decreases as the Structure becomes more complex

➡ "Case 2" ⟶ each user receives hot water at the same temperature

# The addition of new users to an existing network




« one-by-one » design less performant than the constructal one.
But, the gap shrinks for larger structures.



# Contents


Introduction

Networks at human scales

- Tree- shaped networks of insulated pipes for the distribution of hot water

Networks at small scales

- Tree shaped networks in a disc-shaped body
- Comparisons
  - Minimal pipes length
  - Fractal-like structure
- Tree netwoks with loops

Concluding remarks

# Networks at small scale

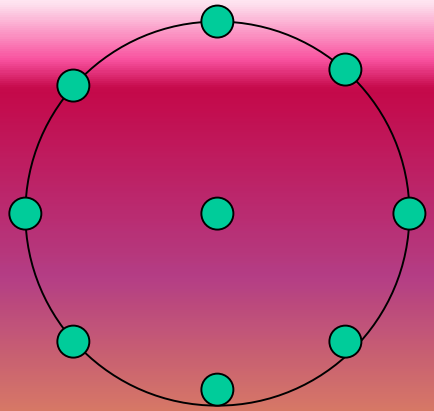
Tree-shaped networks in a disc-shaped body

Micro-channels
Electronics cooling

objectives

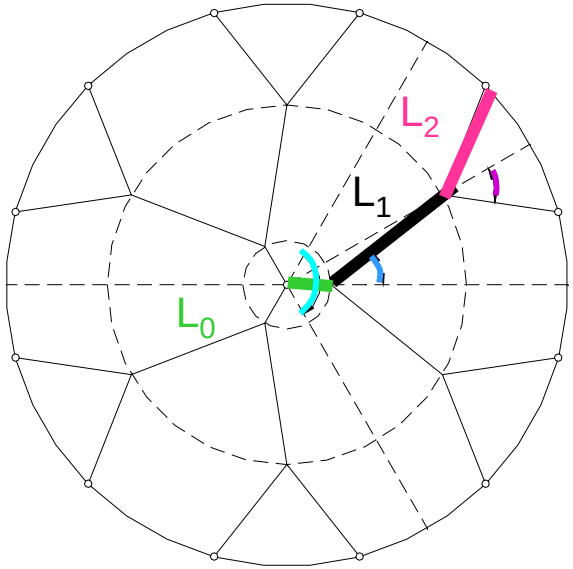
To deliver a fluid from a source to a given number of outlets (users)

→ Minimum $\Delta P$



constraints

Disc-shaped area
Number of outlets
Total volume of the tubes




2 levels of pairing
N = 12 outlets

$\alpha$

$\beta$

$\gamma$

Flow resistance (Hagen-Poiseuille regime)

$$\frac{\Delta P_i}{\dot{m}_i} = \frac{128\nu}{\pi} \frac{L_i}{D_i^4}$$

When the total volume of the tubes is constrained

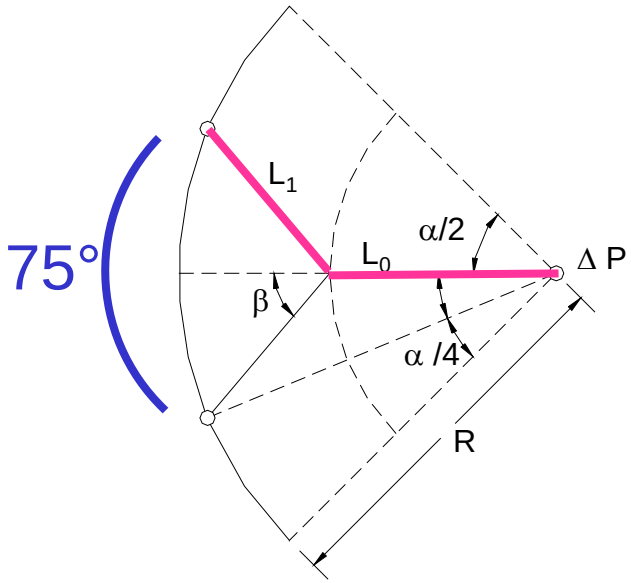
↘ Optimal tube diameters follow Murray's law

$$\frac{D_{i+1}}{D_i} = 2^{-1/3}$$

## First step

$$\Delta P = \Delta P_0 + \Delta P_1$$

$L_0$ and $L_1$ are expressed using the angles $\alpha$ and $\beta$




$$\frac{\partial \Delta P}{\partial \beta} = 0$$ Leads to

$\beta$=37.47°

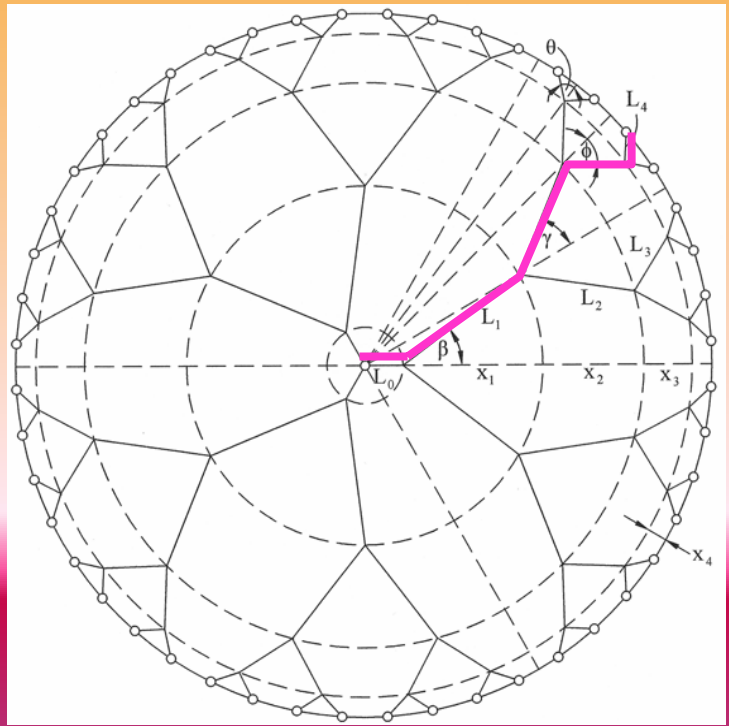
## Finally

$$\frac{\Delta P}{\dot{m}} = 8\pi\nu \frac{R^3}{V^2} f$$

With **f** a dimensionless resistance factor depending on tube lengths

We obtain the connecting angles

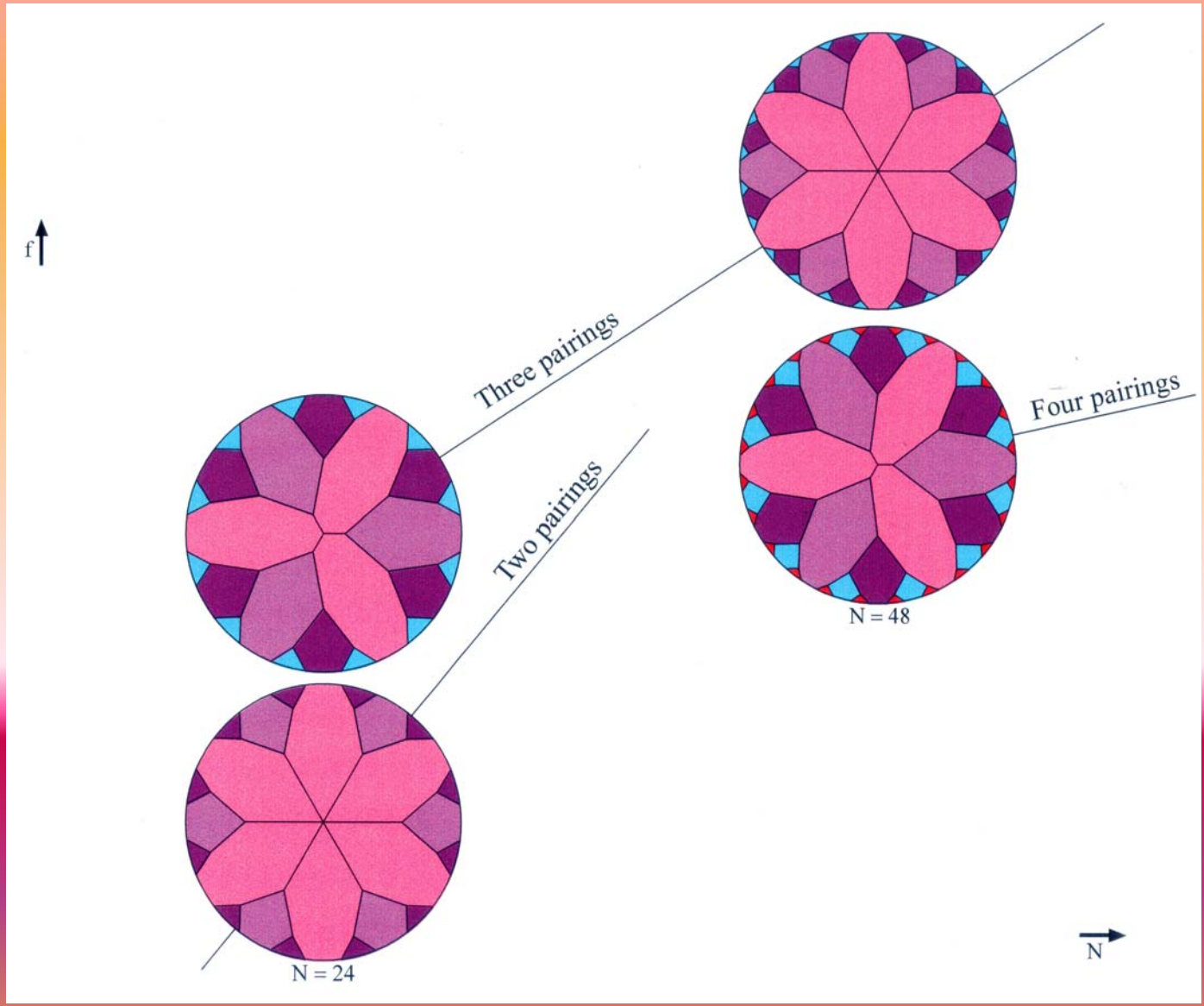
The shape of the network is the result.
It is « given » by the angles.




(48 outlets)

Resistance
factor

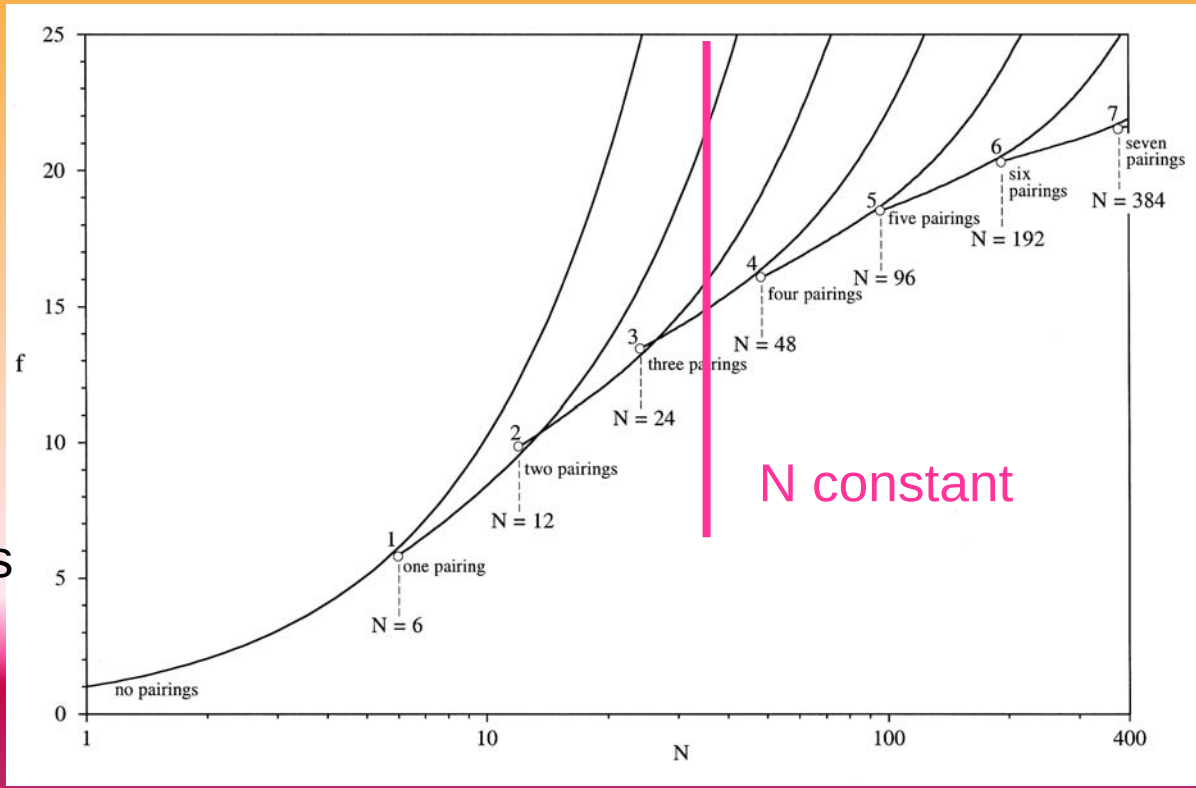
Details of the previous figure



# When optimized complexity is beneficial

N = constant
pairing is a useful feature
if N sufficiently large

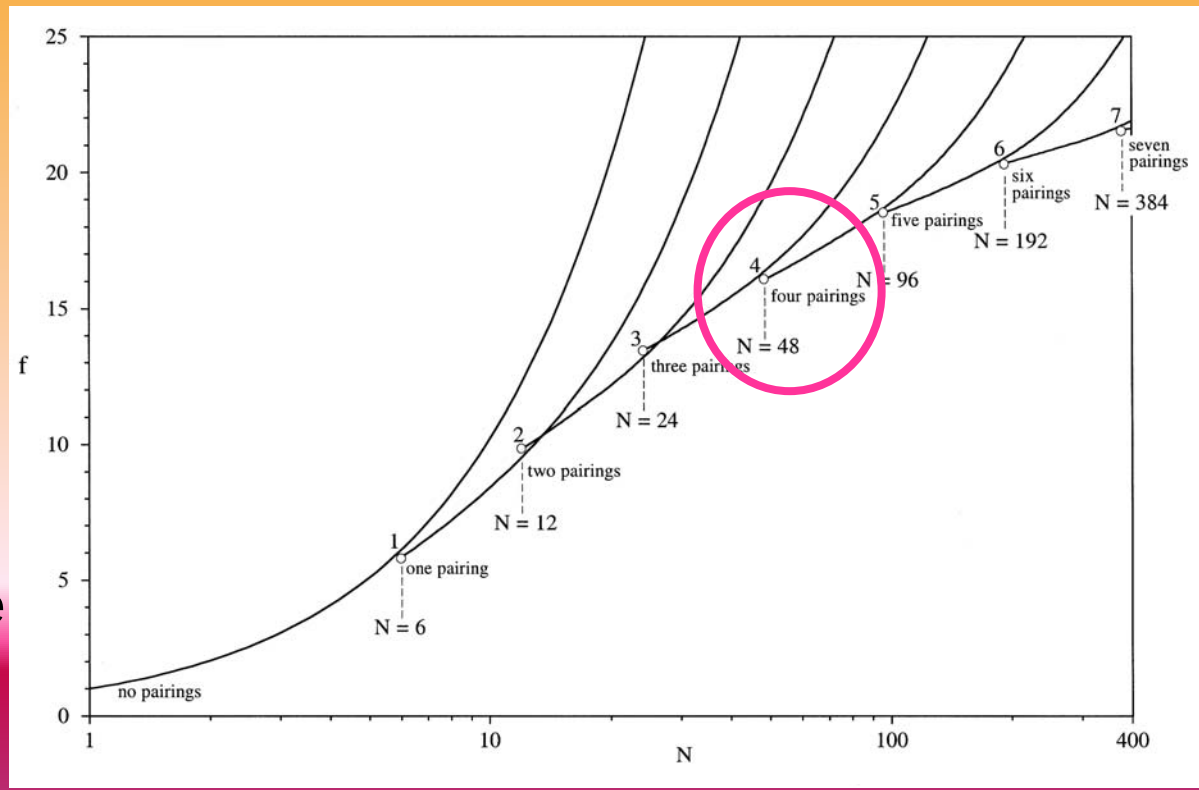
N increases ⟶ the level of pairing increases
⟹ complexity increases



By complexity, the dendritic flow assures its minimal resistance

The designer can choose between two structures

→ ≈ same resistance



# Contents


Introduction

Networks at human scales

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Minimal pipes length

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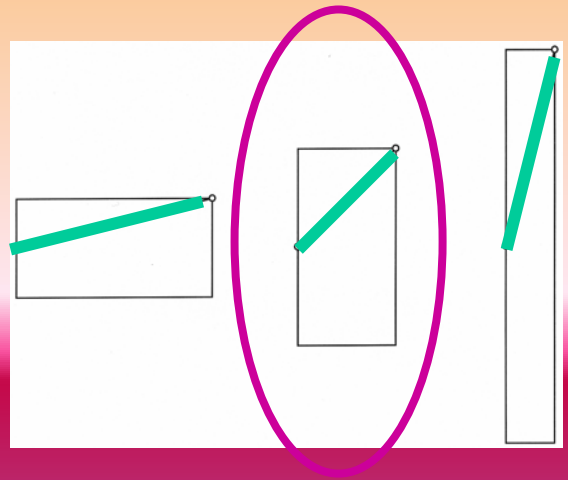
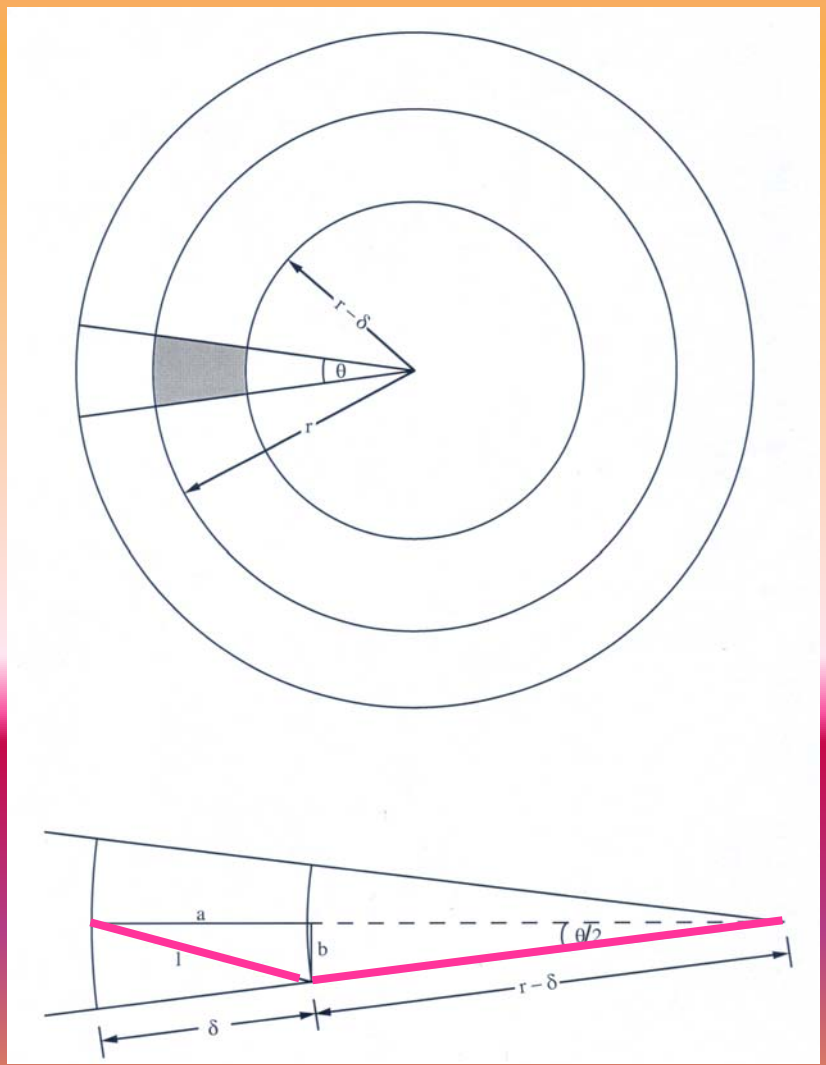
# Comparison: minimal length

- Every duct has a fixed area allocated to it
- On its area, the duct must have the shortest length possible (smallest $\Delta P$)

optimal rectangle shape



# Minimization of flow path lengths




Elemental curvilinear rectangle

Area of the element fixed

$$A = \frac{1}{2}\theta\left(2r\delta - \delta^2\right)$$

→ Minimize L

$$L^2 = a^2 + b^2$$

Result:

$$\frac{x}{\theta} = \frac{(1-x)^2 \sin\frac{\theta}{2}}{(2-x)\left(x - 1 + \cos\frac{\theta}{2}\right)}$$

with $x = \delta / r$

# Construction of the minimal path length

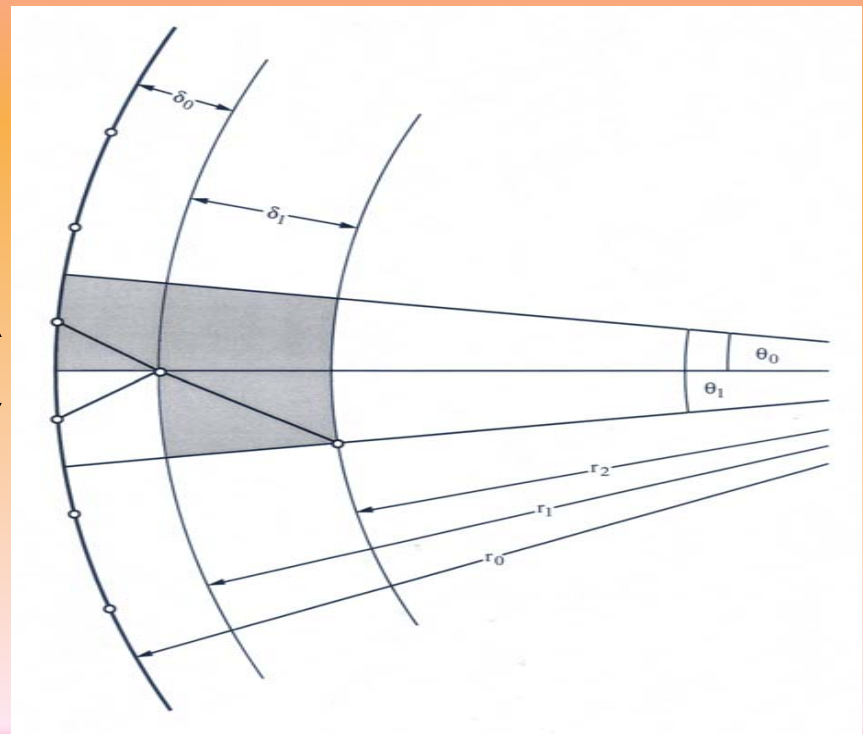
Outer circle

Starting point

$$\theta_0 = d/r_0 << 1$$

Selection of $\theta_0$: 0.1

$$\Rightarrow \left(\frac{x}{\delta}\right)_0$$




Next

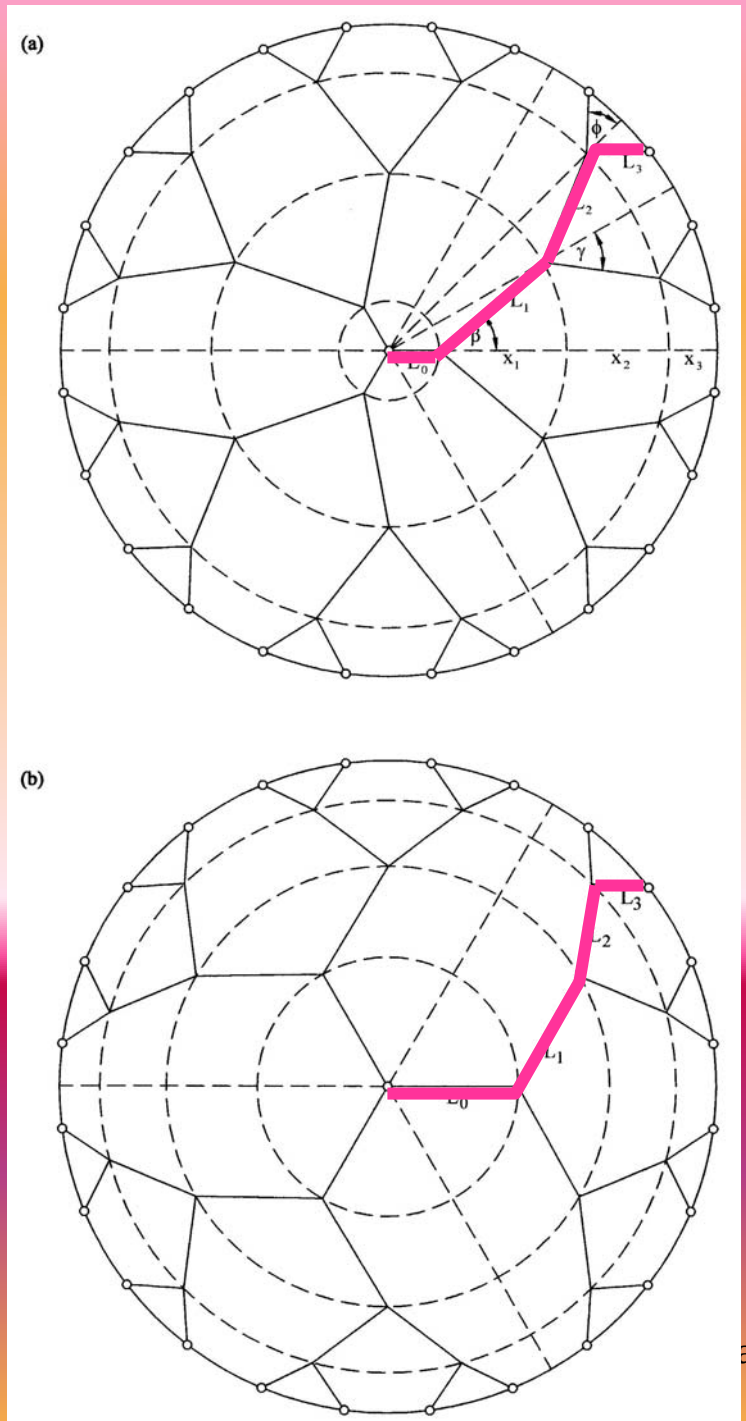
$$\theta_1 = 2\theta_0$$

$$\left(\frac{x}{\delta}\right)_1$$

Etc, etc ...

Stop $\theta_i > 2\pi$ or $r_i < 0$

Note: rectangle approximation poor when r $\longrightarrow$ 0

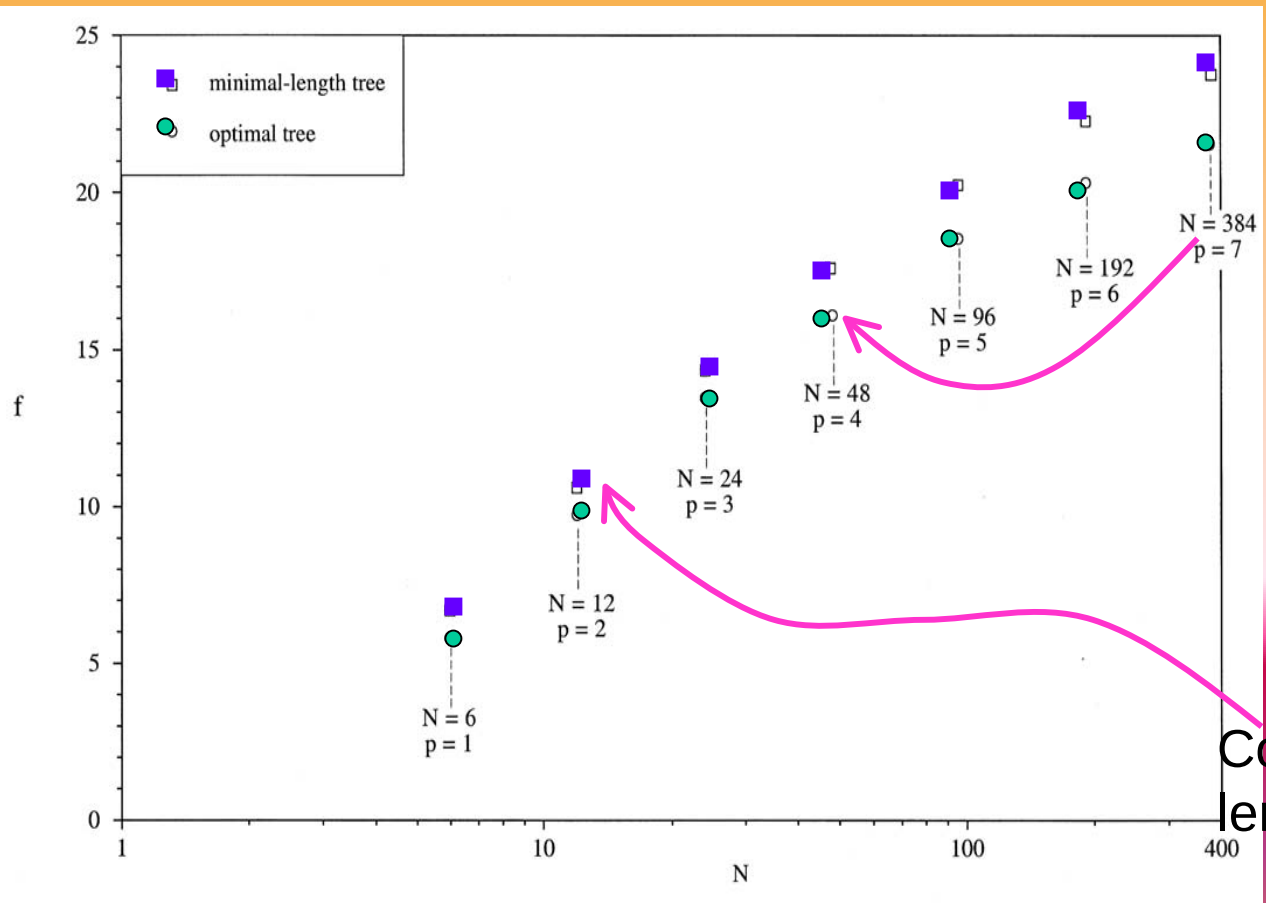



Every geometric detail is optimized

Minimization of flow path lengths

al Theory of the Generation of Optimal Flow Configurations, Roma.

# Global flow resistance

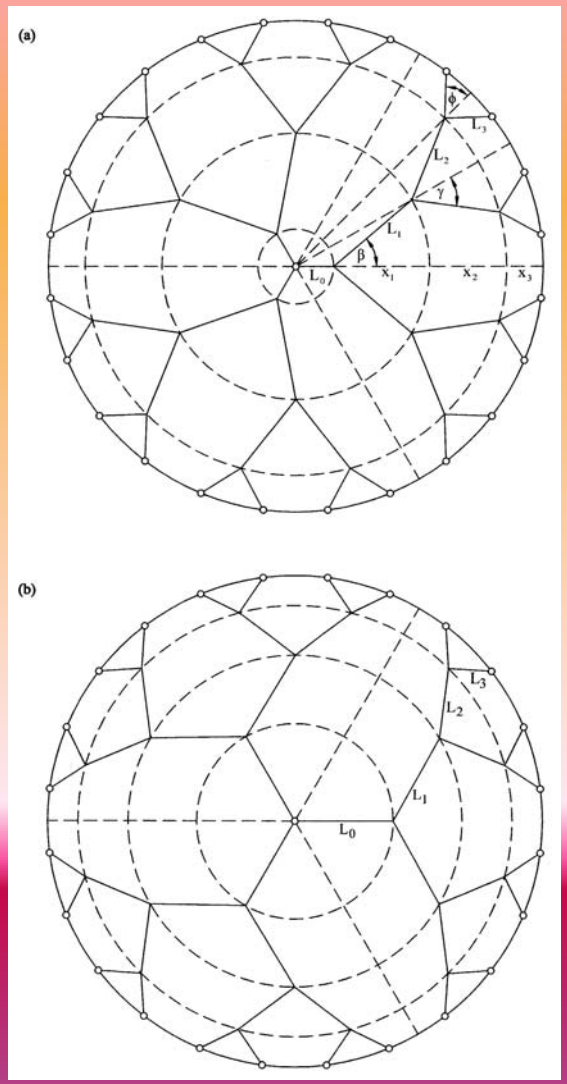



Construct obtained by optimizing every geometric detail

Construct obtained by the length-minimization algorithm

## Comparison

Performance of minimal length structures resemble closely the performance of fully optimized structure → **Effective shortcut**




Every geometric detail is optimized

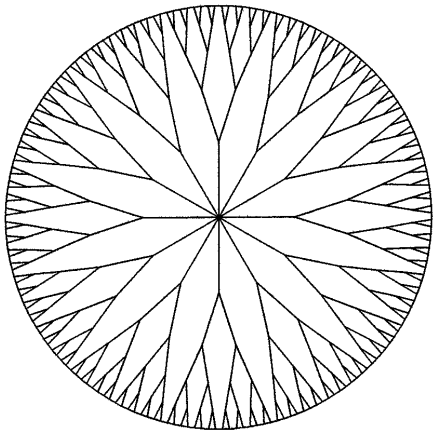
*Global optimization*

The optimized design is generated step by step

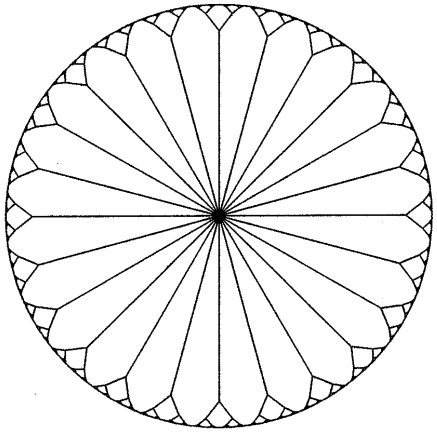
*Local optimization*

Assembling locally optimized pieces does not lead to fully optimized structures

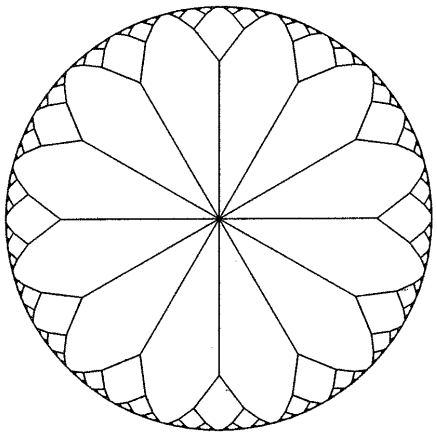
# Comparison: fractal-like structure



f = 36.89
four pairings, assumed
N = 192
$n_0$ = 12



f = 33.16
three pairings, optimized
N = 192
$n_0$ = 24



f = 23.61
four pairings, optimized
N = 192
$n_0$ = 12

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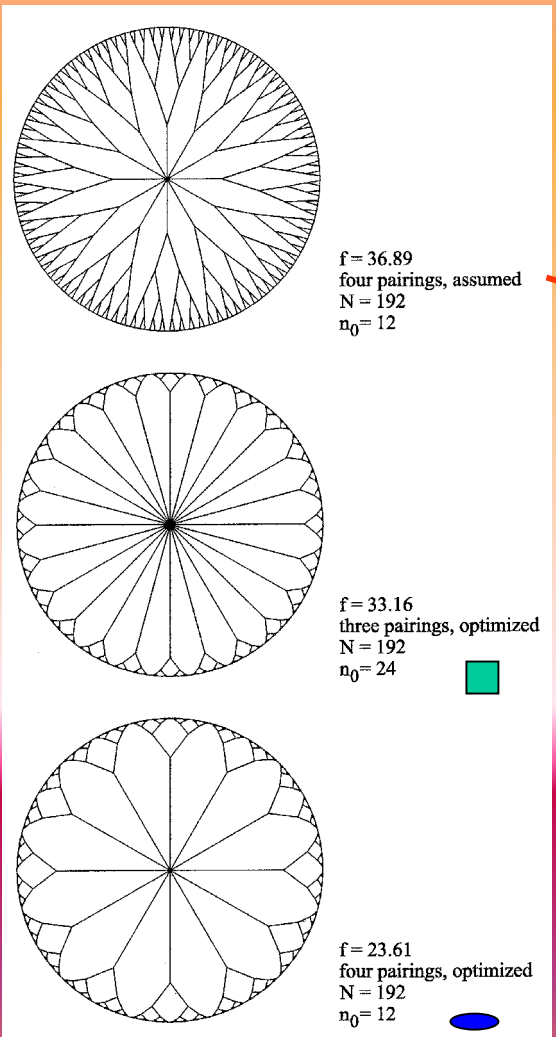
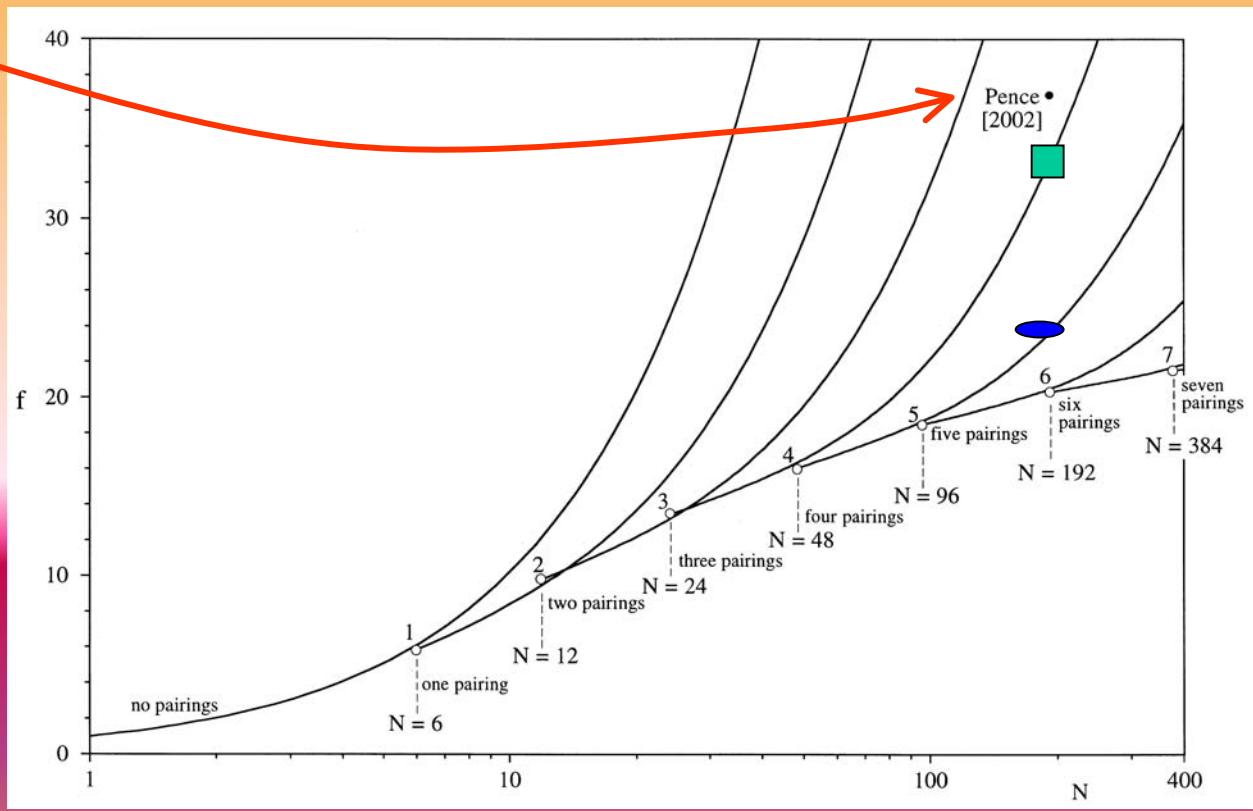
# Complexity does not mean performance



# Contents


Introduction

Networks at human scales

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# Tree networks with loops

## Limits of the previous approach

In case of accident along the ducts, interruption of the flow.

## Solution: look at nature

At a certain scale, loops appear

# The ginkgo leaf is the exception

Designed networks mimic nature:

The biggest networks have loops for the sake of security.

- Is an optimized network with loops much less efficient than a dendritic one?

- Does the result on the comparison between the two depend on the complexity level?

Constraints:

total surface (radius of the circle fixed)

total pipes volumes, V

Degrees of freedom

- number of tubes connected to the center
- tubes diameter and lengths
- pairing level
- number of outlets

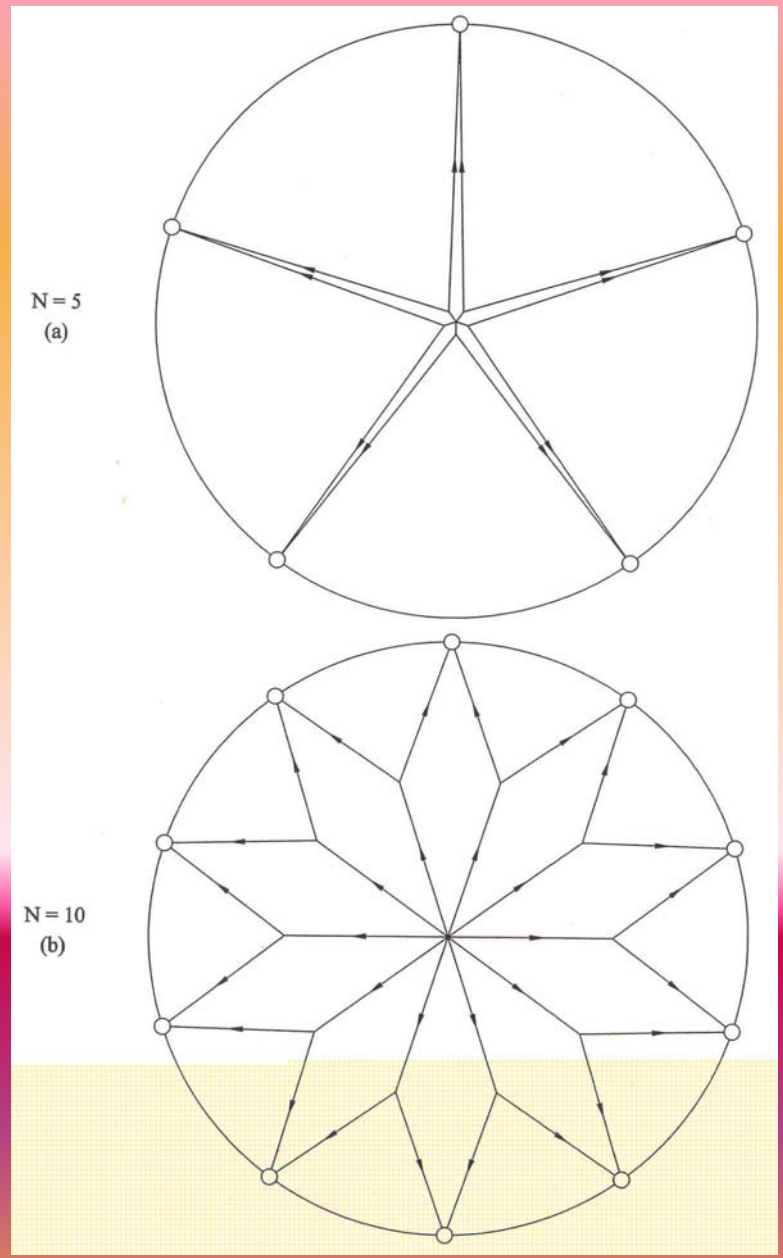
Laminar flow

Local losses are neglected

If N < 5, optimal solution: radial network

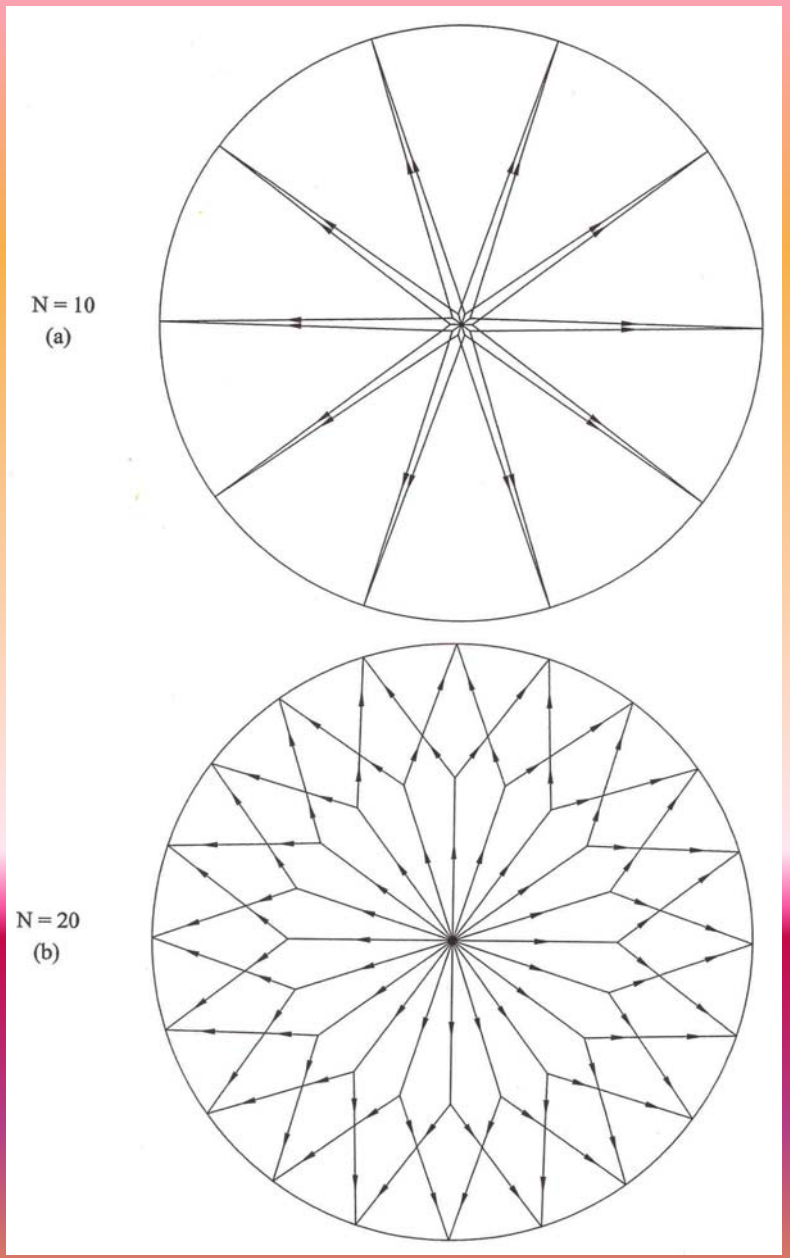
N > 5, the « one loop size » can be optimized

very high flow resistances



N > 10, the « two loop size » can be optimized

even higher flow resistances



Conclusion:

The price is heavy in terms of fluid mechanics

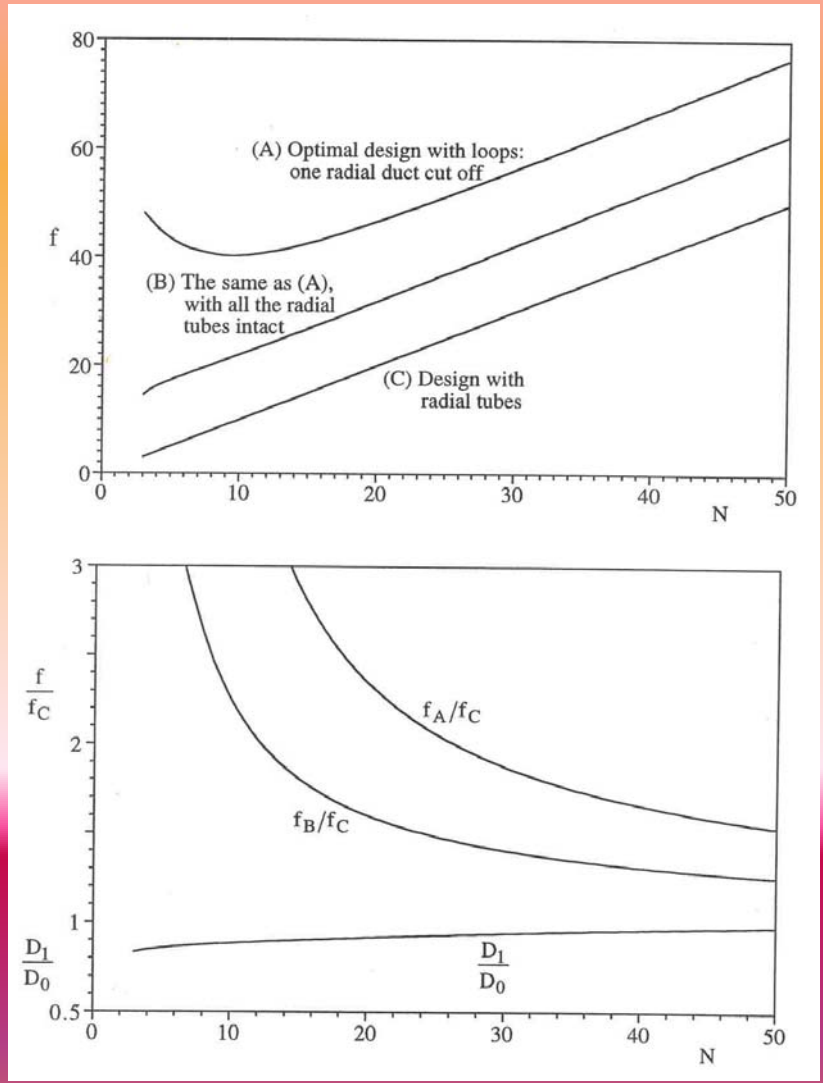
# Other possibility

Again, the flow resistances increase with security

Robustness of optimized complex flow structures

Impact of having loops decreases when complexity increases

Optimal diameter ratio (one tube is cut)
# insensitive to the increase of complexity



# Concluding remark

Several applications at differents scales

Urban hydraulics

Cooling of electronics

Complexity is an optimization result.

Optimized complexity must not be confused with maximized complexity.

**Workshop on**
**“Constructal Theory of the Generation of Optimal Flow Configurations”,**

**U. of Roma 1, 17&18 march 2005**

# Constructal Theory & variational principles for the Navier-Stokes equations: is there a link?

**Enrico Sciubba**

*enrico.sciubba@uniroma1.it*

**To practice Constructal Theory means "*to construct complex structures by connecting simple elements and to optimise each connection*" [Bejan 2000]**

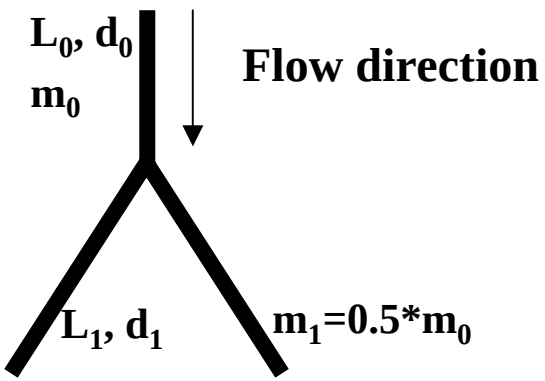
- **For fluid flow, "constructing structures" means to assemble flow paths**
- **Question: what is the objective function of the optimisation?**

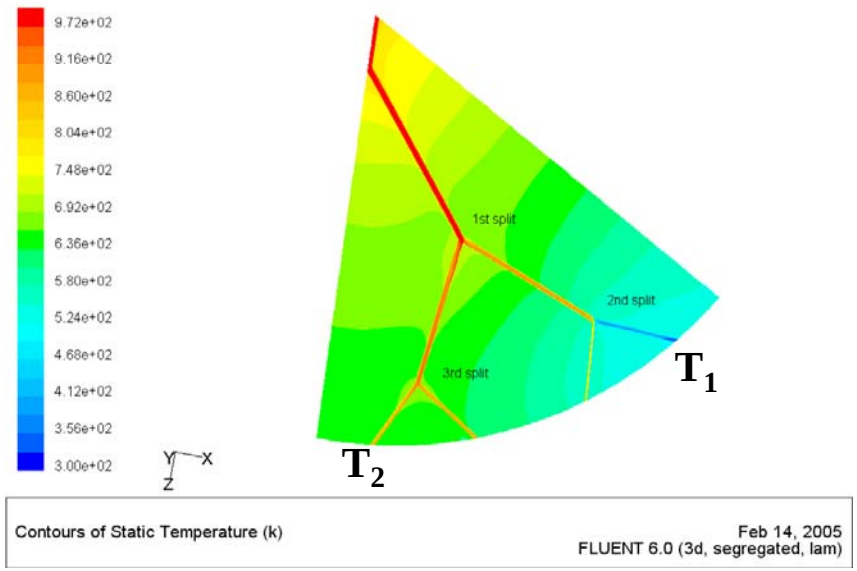
**For laminar liquid flow in pipes & channels, constructalists basically contend that:**

**a) There is an "optimal" diameter ratio at each bifurcation, given by biology-based "optimal volume" considerations [Murray 1926]**

**b) If no heat transfer is involved, the "structure" is optimised under the "minimal flow resistance" criterion (minimal $\Delta p_{tot}$)**

**c) If thermal transport is involved, the "maximum heat flow" becomes a suitable optimising criterion (there may be others)**



**My contention here is that the optimising criterion is always the minimum entropy generation compatible with the prescribed contraints, and that “Constructal Theory” ought to be viewed as an “entropy-based optimisation tool”**

**In this first attempt to put things in this particular perspective, I will limit my considerations to fluid flow only (no heat transfer)**

# 1) The standard derivation of the velocity profile in plane Poiseuille flow

- **Navier-Stokes equations**

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

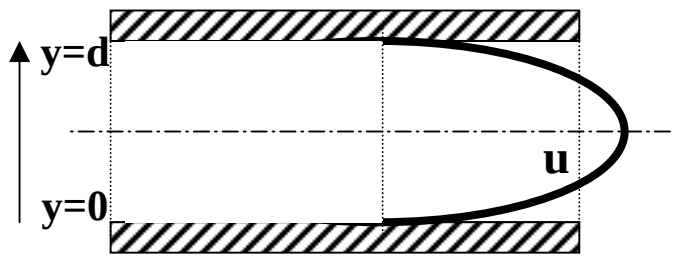
- **Physical assumptions: steady flow** ( $\frac{\partial}{\partial t} = 0$ );

  **fully developed** (v=0, $\frac{\partial}{\partial x} = 0$ , $\frac{\partial p}{\partial x} = \frac{\Delta p}{L}$ );

  **laminar**

- **Boundary conditions: u=0 at y=0**

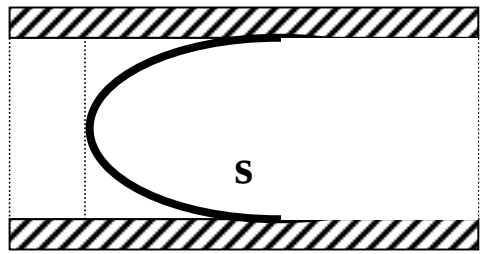
  **u=0 at y=d**




$$\Rightarrow \qquad u = \frac{d^2}{L}\frac{\Delta p}{2\mu}\left(\frac{y^2}{d^2} - \frac{y}{d}\right)$$

**Once the velocity profile is known, we can compute the entropy generation:**

$$s(y) = \frac{\mu}{T}\left(\frac{du}{dy}\right) = \frac{d^2}{L^2}\frac{(\Delta p)^2}{\mu T}\left(\frac{y^2}{d^2} - \frac{y}{d} + \frac{1}{4}\right)$$




- **And the entropy generation per unit channel length**

$$s_{L,d} = \left(\frac{\Delta p}{L}\right)^2 \frac{Ld}{12\mu T}$$

**The pressure gradient is linked to the mass flow rate by:**

$$\frac{\Delta p}{L} = \frac{12\nu\dot{m}}{d^3}$$

**So that the entropy generation per unit channel length becomes:**

$$s_{L,d} = \frac{12\nu\dot{m}^2}{\rho T}\frac{L}{d^5} = K_f\,\frac{m^2 L}{d^5}$$

- $s_{L,d}$ grows with L
- $s_{L,d}$ grows with decreasing d

## 2) Alternative derivation of the velocity profile of plane Poiseuille flow

- **Assume steady, laminar, fully developed flow**
- **Assume that the velocity profile is such that it minimises the viscous entropy generation in the flow**

$$s_v = \frac{\mu}{T}\left(\frac{du}{dy}\right)^2$$

unknown function of y

**The relevant variables in the optimisation are u, du/dx=0, du/dy. The Euler-Lagrange equations for this variation reduce to:**

$$\left(\frac{\partial s_v}{\partial u}\right) - \frac{\partial}{\partial x}\frac{\partial s_v}{\partial\left(\frac{\partial u}{\partial x}\right)} - \frac{\partial}{\partial y}\frac{\partial s_v}{\partial\left(\frac{\partial u}{\partial y}\right)} = \ldots$$

$$= -\frac{\partial}{\partial y}\frac{\partial s_v}{\partial\left(\frac{\partial u}{\partial y}\right)} = 0$$

**The boundary conditions on *u* and the additional constraint that the flow must transport a prescribed mass flow rate provide:**

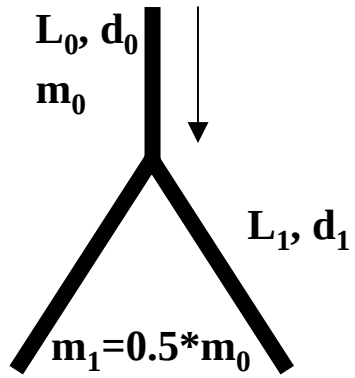
$$u = \frac{d^2}{L}\frac{\Delta p}{2\mu}\left(\frac{y^2}{d^2} - \frac{y}{d}\right)$$

**This result is indeed general: for viscous steady flow the Navier-Stokes equations admit of a variational formulation whose Lagrangian is the exergy destruction ($T_0$*ds/dt). There is no definitive proof yet that this is also the Lagrangian for thermal transport by convection, but it would seem reasonable to assume so.**

**The question is: since the entropy generation "governs" the structure of the flow in a channel, why should it not be the "Lagrangian" for the structure of more complex flow domains?**

**I shall now try to derive an "optimal" bifurcation structure from a "*minimum ds/dt*" principle**

**The relevant variables are: $m_0$, $m_1$, $L_0$, $L_1$, $d_0$, $d_1$, and the fluid properties.**




a) $m_0$ is supposed prescribed
b) $m_1 = 0.5\, m_0$
c) The flow is isothermal

$$\dot{s}_{tot} = K_f \left( \frac{m_0^2 L_0}{d_0^5} + 2\frac{m_1^2 L_1}{d_1^5} \right) =$$

$$= K_f \frac{m_0^2 L_0}{d_0^5} \left( 1 + \frac{L_1 d_0^5}{L_0 d_1^5} \right)$$

**We want to minimise $s_{tot}$ w.r.t. $L_0$, $L_1$ and to the ratio $d_1/d_0$**

**In general, for a prescribed global geometry, $L_0$ and $L_1$ will be functionally linked:**

$$L_1=f(L_0)$$

**It follows:**

$$\dot{s}_{tot} = K_f \frac{m_0^2 L_0}{d_0^5}\left(L_0 + \frac{f(L_0)}{\delta^5}\right)$$

**where $\delta=d_1/d_0$**

**which has non-trivial minima that depend on f:**

$$\frac{\partial \dot{s}_{tot}}{\partial L_0} = K_f \frac{m_0^2}{d_0^5}\left(1+\frac{f'(L_0)}{\delta^5}\right)$$

$$L_{0,opt} = -\frac{b+\delta^5}{a} \quad \text{if } f=aL_0^2+bL_0+c;$$

$$\text{and } L_{0,opt} = -\frac{\ln\left(\delta^5\right)}{a\ln(a)} \quad \text{if } f=\exp(-aL_0)$$

**If the link between $L_0$ and $L_1$ is one of pure proportionality, $L_1=\alpha L_0$:**

$$\frac{\partial \dot{s}_{tot}}{\partial L_0} = K_f \frac{m_0^2}{d_0^5}\left(1+\frac{\alpha}{\delta^5}\right)$$

**and no minimum is possible**

**But if the link between $L_0$ and $L_1$ is dictated by a conservation of the total volume occupied by the channels,**

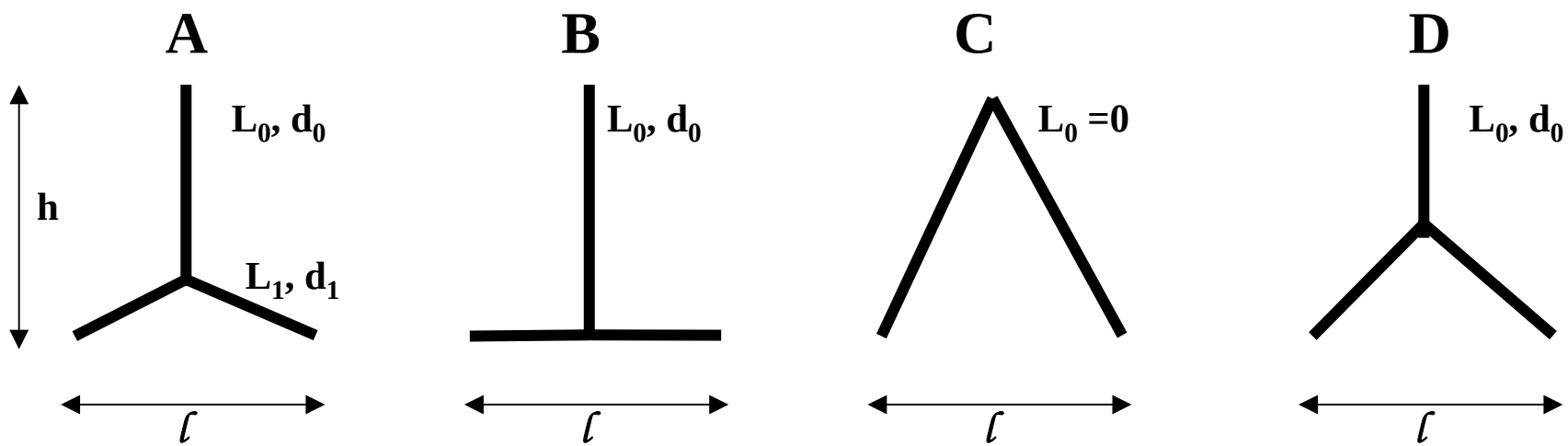
$$L_1 = \frac{V_{tot}}{2d_1} - \frac{L_0 d_0}{2d_1}$$

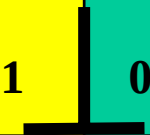
**it turns out that there is a minimum for**

$$\delta_{opt} = \left(\frac{d_1}{d_0}\right)_{opt} = \frac{1}{\sqrt[6]{2}}$$

**In conclusion, there is a set of different minima, each one corresponding to a proper (i.e., mathematically consistant and physically realistic) link between $L_0$ and $L_1$**

**Let us consider an application to a small set of bifurcational geometries: which one is "optimal"?**



| $\delta \Rightarrow$ | **A, 0.891** | **A, 0.794** | **B, 0.891**  | **B, 0.794** | **C, 0.891** | **C, 0.794** | **D, 0.891** | **D, 0.794** |
|---|---|---|---|---|---|---|---|---|
| **$L_0$** | $\sqrt{3}\ell/4$ | | $\sqrt{3}\ell/2$ | | 0 | | $\ell/\sqrt{3}$ | |
| **$L_1$** | $\sqrt{7}\ell/4$ | | $\ell/2$ | | $\ell$ | | $\ell/\sqrt{3}$ | |
| **$s_{tot,adim}$** | **1.022** | **1.483** | **1.311** | **1.659** | **0.891** | **1.587** | **1.09** | **1.493** |
| **$V_{tot,adim}$** | **1.611** | **1.483** | **1.757** | **1.659** | **1.782** | **1.587** | **1.606** | **1.493** |
| **$\Delta p_{tot,adim}$** | **0.9** | **1.09** | **1.22** | **1.366** | **0.707** | **1** | **0.985** | **1.15** |
| **Time through $L_0+L_1$** | **1.611** | **1.483** | **1.757** | **1.659** | **1.782** | **1.587** | **1.606** | **1.494** |

**These results -albeit grossly preliminary- indicate that:**

1) **"minimum $\Delta p$" and "minimum s" generate the same optima**
2) **"minimum volume" consistently indicates different optima**
3) **"minimum delivery time" leads to the same optima as the minimum volume**

(1) **was to be expected: under the present model, $\Delta p \propto s_{tot}$**
(2) **the reason for which minimum V and minimum t lead to the same optimum, remains to be investigated**
(3) **biological scientists generally assume that "minimum V" is the objective function for the optimisation of dendritic structures, but it is more likely that Nature may prefer something like:**

$$\mathcal{L} = \underbrace{\alpha_{L_0, d_0} \dot{s}_{tot}}_{I} + \underbrace{\beta_{L_0, d_0} V_{tot}}_{II}$$

**i.e., an "exergo-economic criterion!**

**(Suggestion) "Natural" structures are generated under the following conditions:**

1) **A weighted sum of the exergy destruction (friction, thermal gradients…) and of the embodied exergy (material & energy to "build" the channels) is minimised;**
2) **External boundary conditions dictate the details**

$$\mathcal{L} = \underbrace{\alpha_{L_0, d_0} \dot{s}_{tot}}_{\text{I}} + \underbrace{\beta_{L_0, d_0} V_{tot}}_{\text{II}}$$

**For instance, for the "constructor" of the bifurcations discussed above:**

1) **If the pumping power required to make up for the entropy dissipation is much smaller than the exergy needed to build the channels, $\alpha << \beta$, and the optimal structure is C1;**

2) **If exergy is abundant, and $\beta << \alpha$, the optimal structure is A2;**

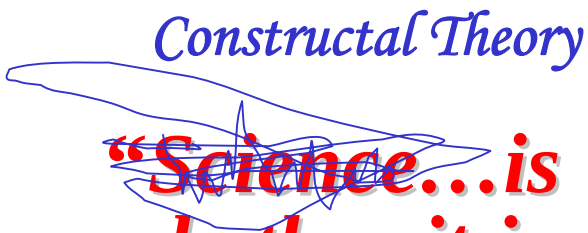
3) **If $\alpha = \beta = 0.5$, the optimal structure is D1**

$$\mathcal{L} = \underbrace{\alpha_{L_0, d_0} \dot{s}_{tot}}_{I} + \underbrace{\beta_{L_0, d_0} V_{tot}}_{II}$$

**Constructal Theory & Exergy Analysis have the same goal: are they using the same tools?**

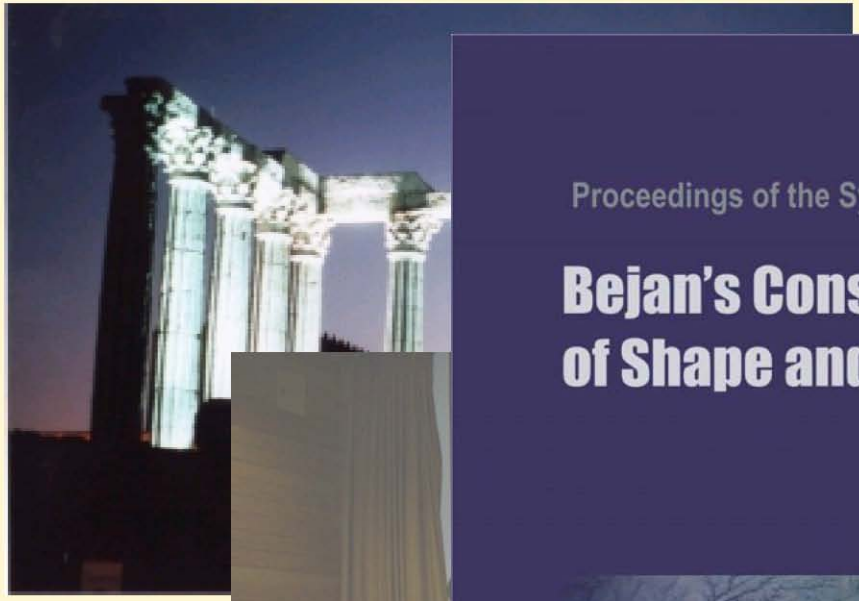
**There is an enormous incentive to investigate this field, for the applications in engineering, physical & biological sciences are of substantial importance (heat transfer, filters, chemical reactors, composite structures, allocation of resources, neuronal science, vascular systems…)**

# Conclusion:



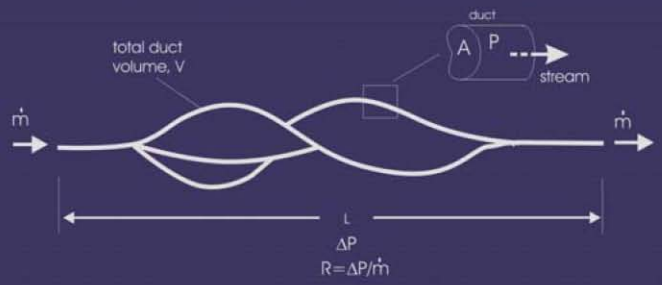

***"Science…is good for the scientist: whether it is good for the rest of mankind, it is arguable"***

***Erwin Chargaff*, 1905-2002**



Proceedings of the Symposium

# Bejan's Constructal Theory of Shape and Structure




Rui N. Rosa
A. Heitor Reis
Antonio F. Miguel
Eds.

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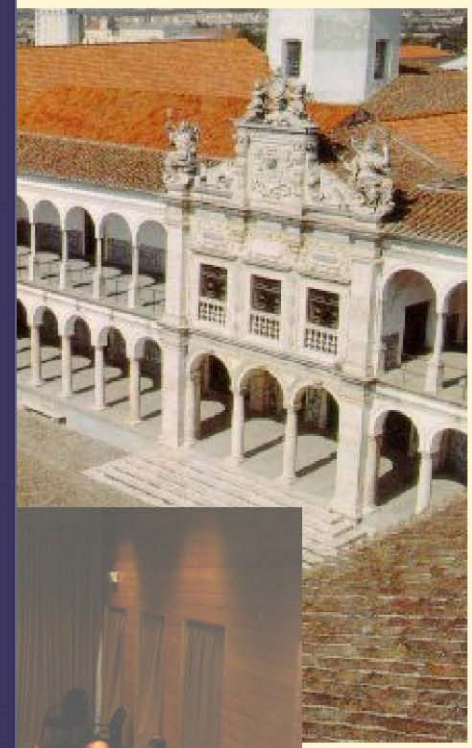
University of Évora



# Particle deposition, and shape in some inanimate/animate systems

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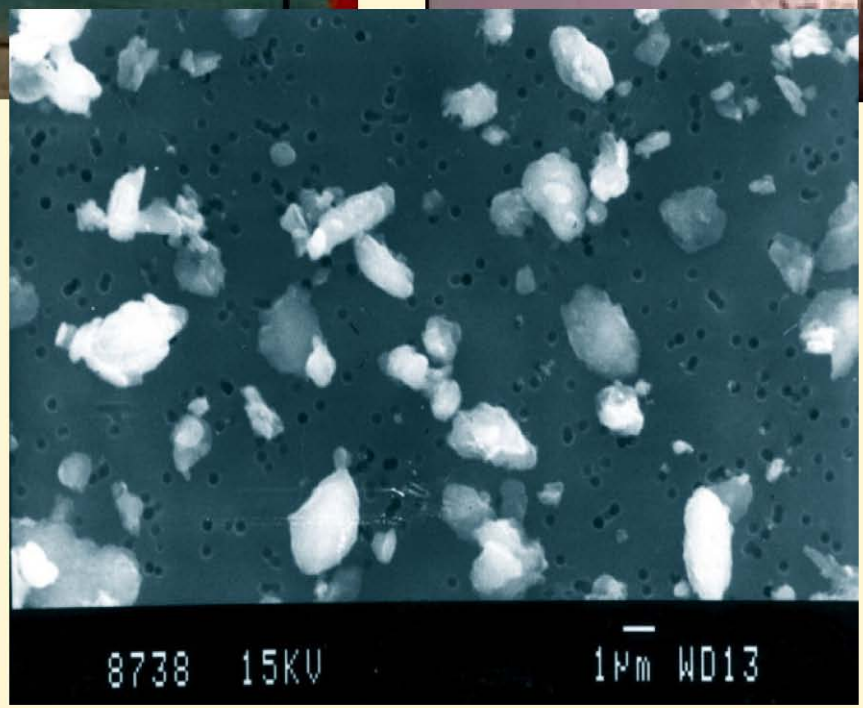
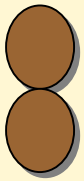
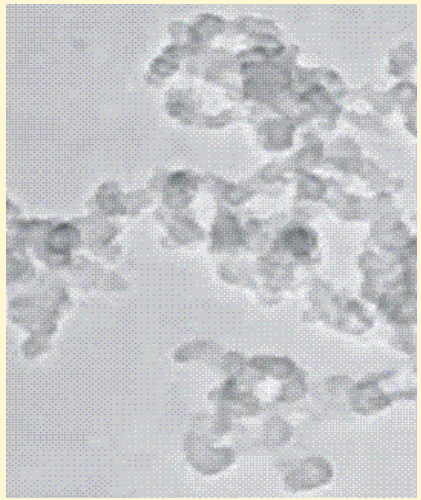

8738 15KV
1μm WD13

# A set of inanimate particles

coagulation = agglomeration

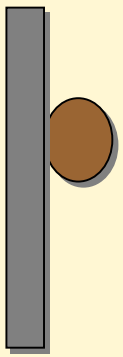
**Katzer et al. 2001**

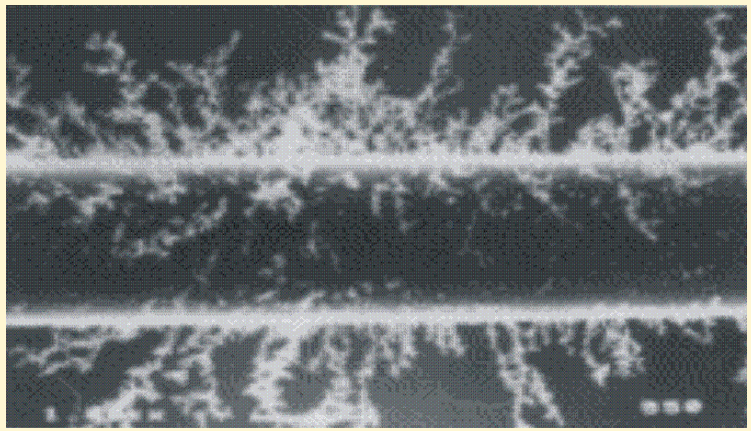




**Smith et al. 2002**

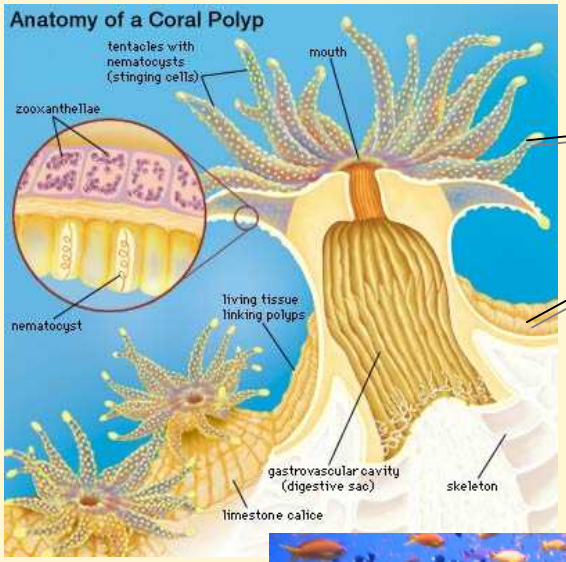
Deposition





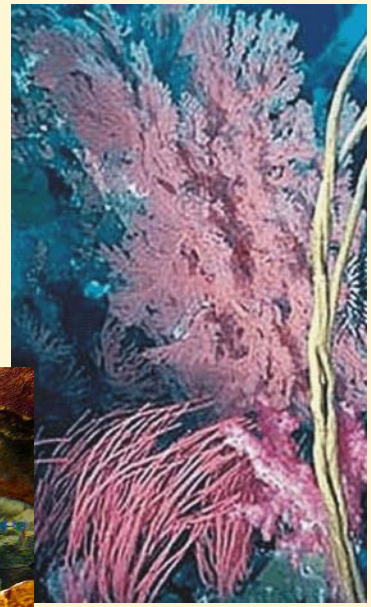
**Kanaoka et al., 2001**

# A set of living organisms




## Coral colony association of polyps

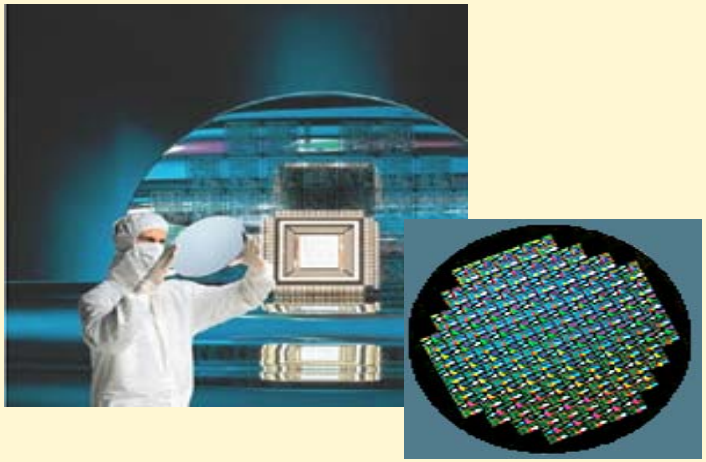
- Tentacles to trap food
- Cells on the lower sides and bottom produce the limestone that builds the colony

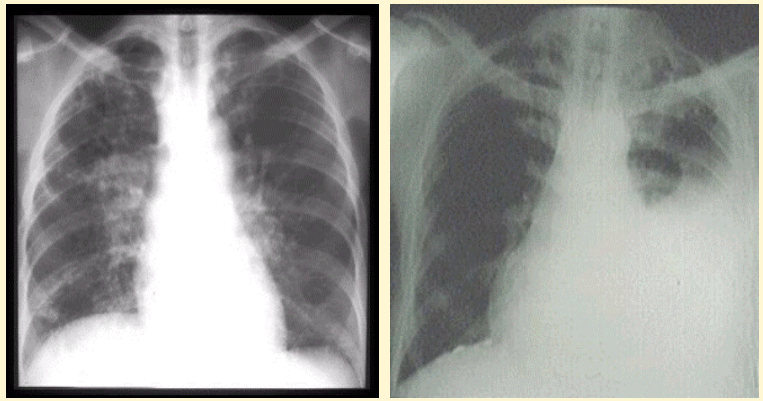


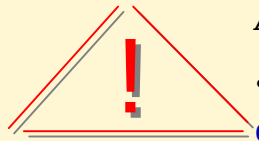
**Kaandorp and Sloot**

**(2001)**

# Why agglomeration/deposition is important ?







***At USA (1996)***

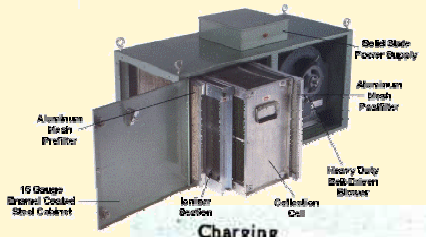
- 134 109 people were diagnosed with lung diseases (7 202 people died)
- medical care for people with chronic respiratory diseases cost 45.3 billion USD

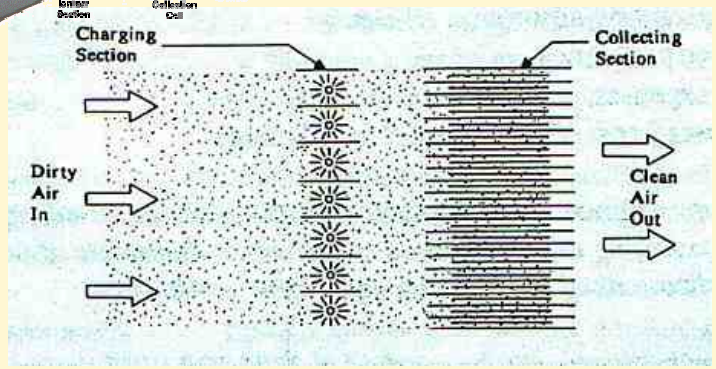
*European Respiratory Journal* (2002)

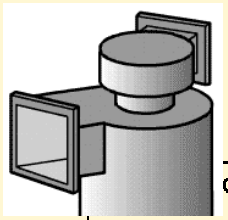
**inhalation therapy** (drug delivery via the respiratory system easier than delivery via ingestion and the transdermal route)

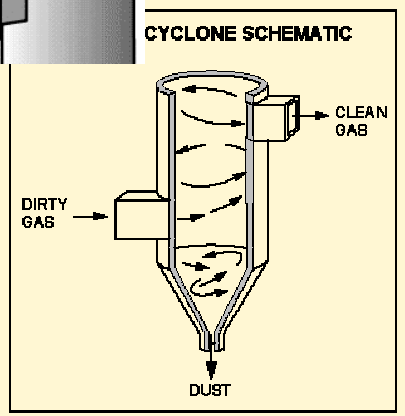
# Air pollution control devices

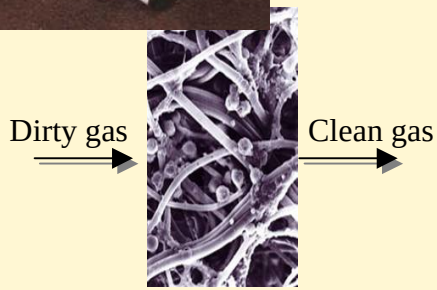
- **Electrostatic precipitators** (expansive, fail to filtrate fine particles and high-resistivity dust) **Dietz (1977), Shapiro (1998)**
- **Space-charged precipitators** (only effective for high density aerosols) **Shapiro & Brenner (1990)**
- **Cyclones** (only effective for coarse particles > 5 μm) **Shapiro & Brenner (1990)**
- **Diffusion batteries** (very efficient for particles < 0.1 μm) **Knutson (1999)**
- **Filters** (simple, highly efficient for both micrometer and submicrometer particles, coast-saving process) **Shapiro & Brenner (1990), Miguel (2003)**







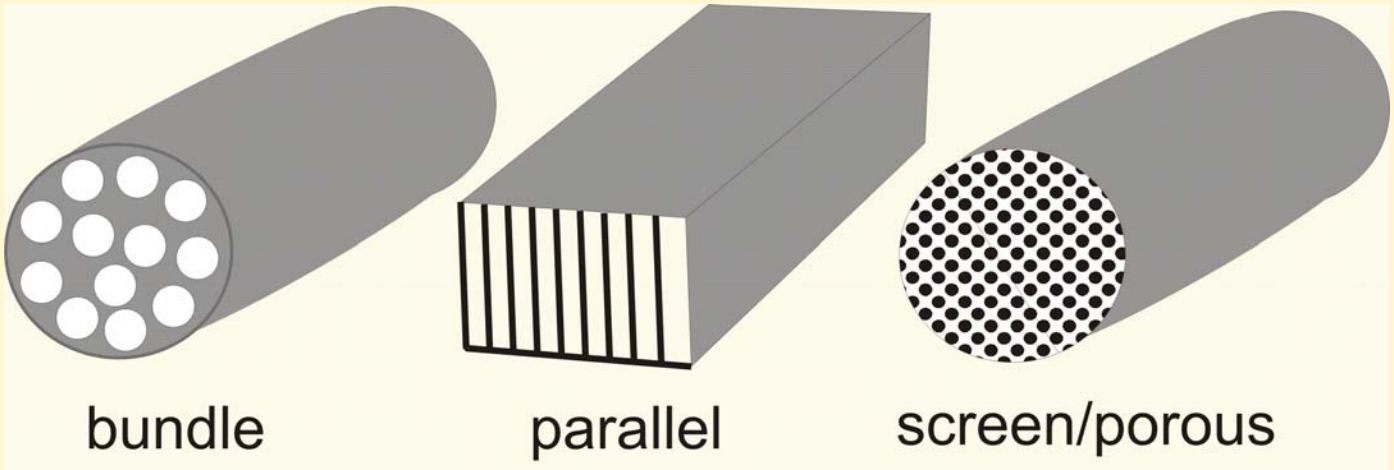


# Outline

## Constructal view

- Particle coagulation (agglomeration)
- Colony association of polyps
- Design of **air pollution control devices**

# Design of air pollution control devices




- Operate at very low Re (laminar flow)
- Very important for removal of submicrometer particles

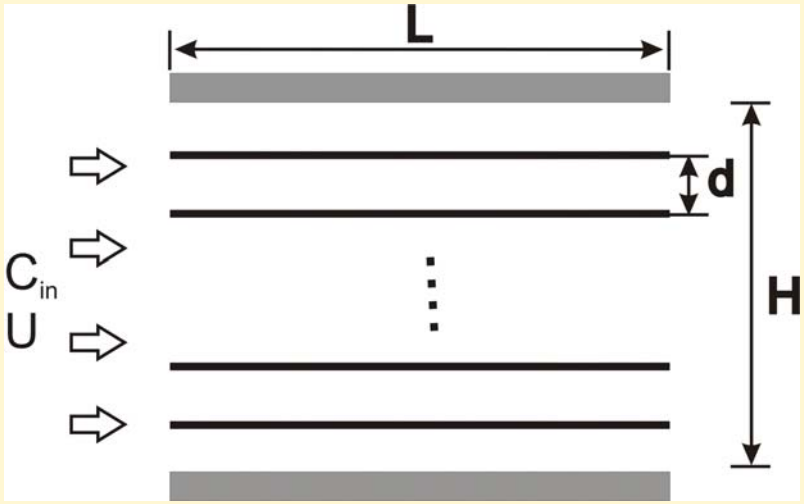
What are the rules to obtain the best design ?

## Constructal idea:

The ultimate purpose is to bring the system into equilibrium trough capturing the all particles in the air.

Global constrain

Due to practical and economical reasons the device should fit into a volume V




$\phi = H/d$

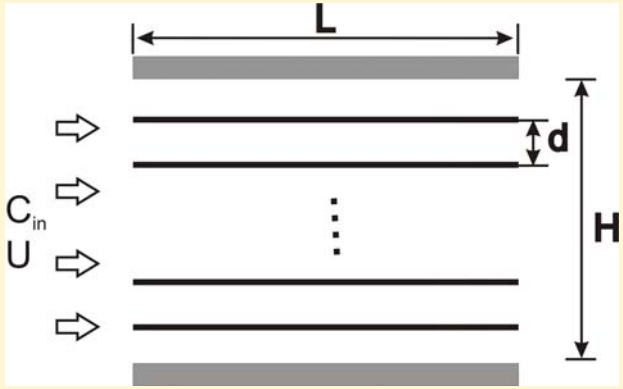
**Similar to optimal geometry of plates in forced convection heat transfer**

**Bejan (2000); Bejan (2004)**

(i) finding of two d-value limits

(ii) identifying the d-value that maximizes the particle deposition

(i) **d** (small) **ϕ** (large)




→ outlet concentration of particles (minimum)

→ steady-state particle transfer density $m_p = \frac{HWU}{HLW}(C_{in} - C_o)$

→ fully developed (Hagen-Poiseuille) flow $U = \frac{d^2}{12\mu}\frac{\Delta p}{L}$

$$m_p = \frac{d^2}{12\mu}\frac{\Delta p}{L^2}(C_{in} - C_o)$$

**d** (large) **ϕ** (samll)

→ steady-state particle transfer density for the boundary layers

$$m_p = \frac{2\phi\lambda LW}{HLW}(C_{in} - C_o)$$

$$Sh = 0.664\,Re_L^{1/2}\,Sc^{1/3}$$

Sherwood number (λL/D) --- Nu
Schmidt number (υ/D) ---Pr

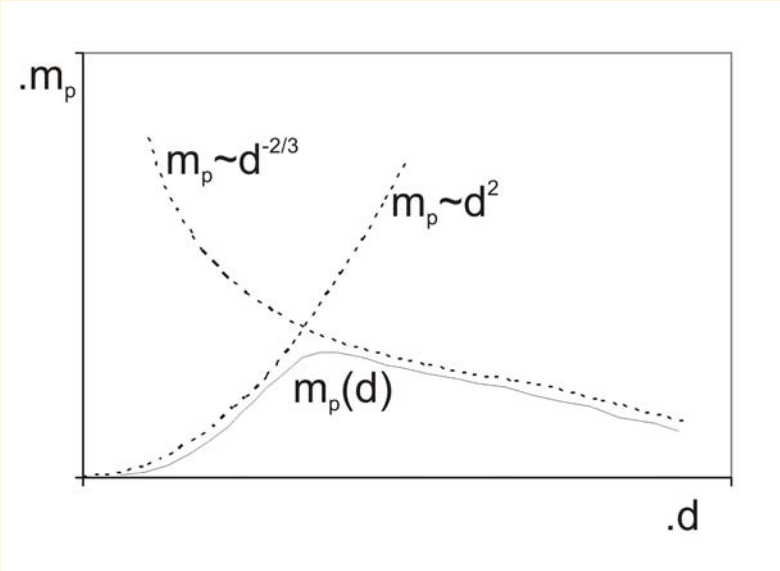
$$m_p = 1.238\frac{\phi DSc^{1/3}}{HL}\left(\frac{\rho LU_o}{\mu}\right)^{1/2}(C_{in} - C_o)$$

→ free-stream velocity $U_o$ Bejan (2000, 2004)

$$U_o^{1.5} = \frac{\Delta pH}{1.328L^{1.5}(\rho\mu)^{0.5}}$$

$$m_p = 1.208Dd^{-2/3}\left(\frac{\rho Sc\Delta p}{\mu^2 L^2}\right)^{1/3}(C_{in} - C_o)$$

# (ii) optimal number of plates **method of intersecting asymptotes**

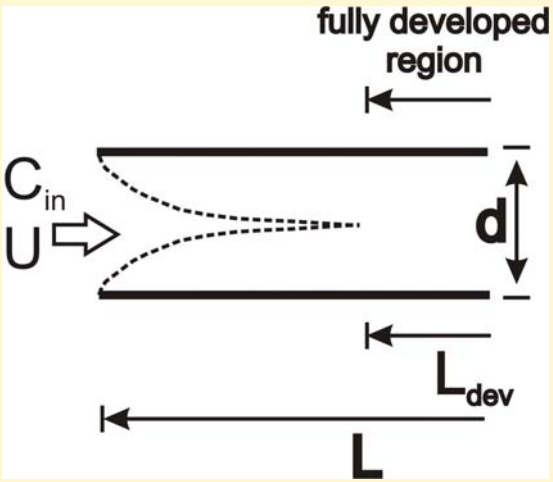



$$\frac{d_{opt}}{L} \cong 2.73 Be_m^{-1/4}$$

$$Be_m = \frac{L^2 \Delta p}{\mu D}$$

Bhattacharjee & Grosshandler (1988)

## Best elementary construct



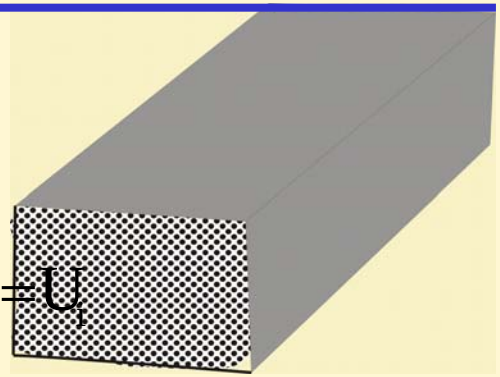

**$L_{dev} > L$** flow fluid developed particles interact with plate

**$L_{dev} < L$** air in the core duct not interact with plate

Maximum particle transfer **$L_{dev} = L_{opt}$**

$$\left(\frac{d}{L}\right)_{opt} = 1.86 Sh^{1/4} Be_m^{-1/4}$$

# Device with a porous structure




(i) finding of two extremes

$\varepsilon \sim 0$

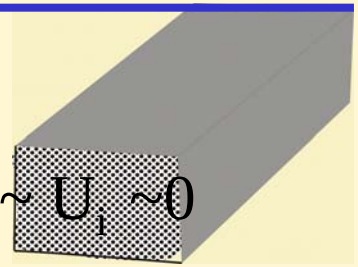
→ outlet concentration of particles (minimum)

→ steady-state particle transfer density $m_p = \frac{U}{L}(C_{in} - C_o)$

→ Darcy flow $U = \frac{K}{\mu}\frac{\Delta p}{L}$ Carman-Kozeny equation $K = \varsigma_K \frac{\varepsilon^3}{(1-\varepsilon)^2} d^2$

$$m_p = \frac{\varsigma_K}{\mu} \frac{\varepsilon^3}{(1-\varepsilon)^2} \frac{d^2}{L^2} \Delta p (C_{in} - C_o)$$

$\varepsilon \sim 1$




→ steady-state particle transfer density to N collectors

$$m_p = N\varsigma_m D \frac{d}{V}(C_{in} - C_o)$$

→ $\varepsilon$ and N

$$\varepsilon = 1 - \varsigma_\varepsilon \frac{Nd^3}{V}$$

$$\frac{\pi}{6} \qquad \frac{\pi}{3(2)^{1/2}}$$

$$m_p = \varsigma_{m\varepsilon}(1-\varepsilon)\frac{D}{d^2}(C_{in} - C_o)$$

# (ii) identifying the ε-value that maximizes the particle deposition

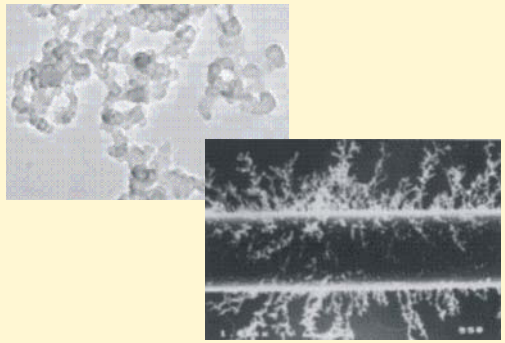
particles transferred from air stream to V = particles transferred from air stream to collectors of porous material

$$\frac{\varsigma_K}{\mu}\frac{\varepsilon^3}{(1-\varepsilon)^2}\frac{d^2}{L^2}\Delta p(C_{in}-C_o) = \varsigma_{m\varepsilon}(1-\varepsilon)\frac{D}{d^2}(C_{in}-C_o)$$

$$\varepsilon_{opt} = \left(1+\varsigma\left(\frac{d}{L}\right)^{4/3} Be_m^{1/3}\right)^{-1}$$

# Constructal view of aerosol agglomeration/deposition process

What determines the shape of in these processes ?

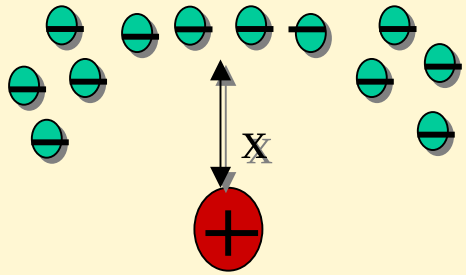


**Constructal law** → architecture optimized
→ accumulation of particles maximized

aerosol particles >100 nm carry an electrostatic charge

**Vincent (1986); Kerasev et al. (2001)**

aerosols travel under the influence of Coulomb forces




t=0

t>0

Electric field from a point charge

$E=kq/r^2$

Coulomb Force

$F=qE=kqq/r^2$

Aerosol migrates Stokes flow velocity U=dr/dt

$$F = 3\pi \frac{\mu d}{c_c} U$$

$$t_x = \frac{\pi}{c_c k} x^3 \frac{qq}{\mu d}$$ ⟵ "flying" time

The flow of particles that lands on originates a spherical annulus of radius x and thickness $\Delta x$

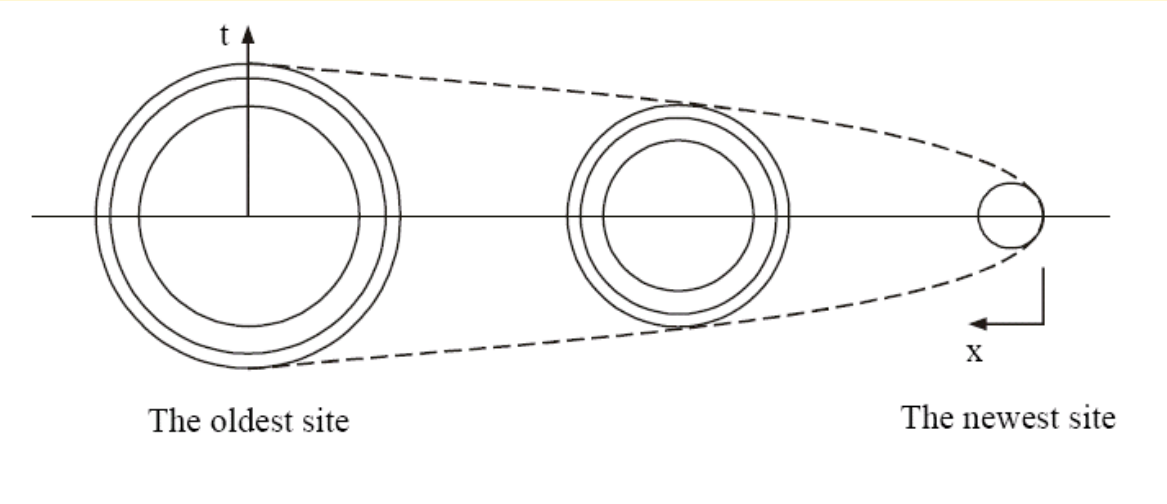
$$\Delta N = n\, 4\pi x^2 \Delta x$$

$$\Delta N/\Delta t \sim d(D^3)/dt \longrightarrow D = \left( 2kc_c n \frac{\mu d}{qq} t \right)^{1/3}$$

- **Cluster diameter grows fast early, and slow late**
- **Mass accumulated (~$D^3$) increases linear with t**

# Constructal question

There is any another configuration (shape) that maximizes the mass accumulated ?




Needle body of revolution with radius $R=fx^{1/3}$

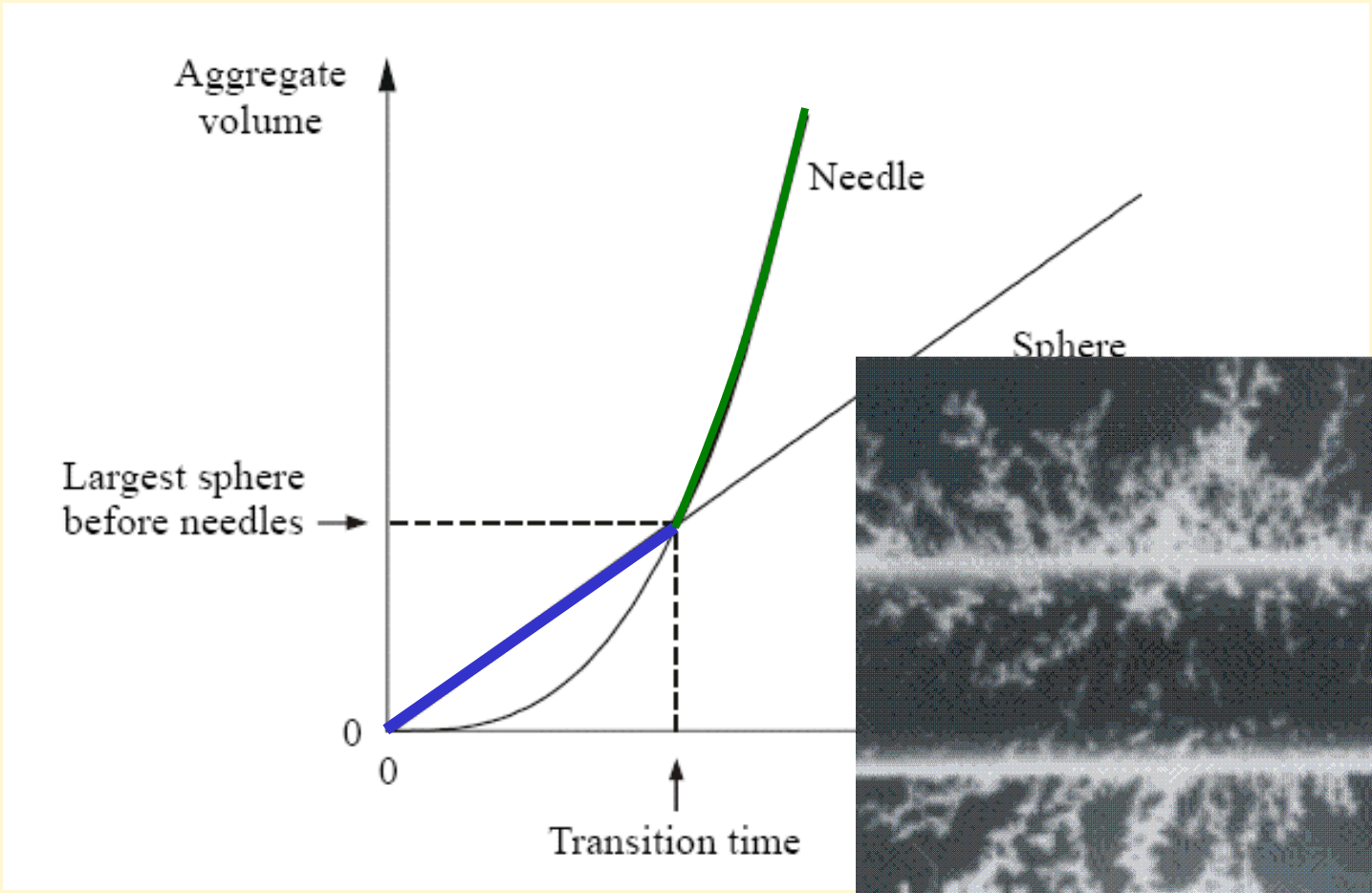
x instantaneous needle length (Ut)

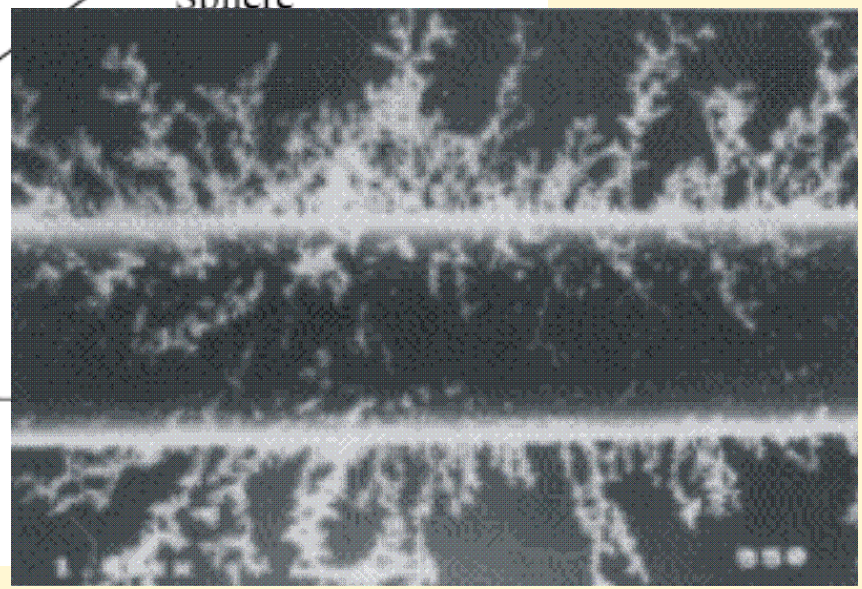
$$f=\left(\frac{2kc_c n\mu d}{UqQ}\right)^{1/3}$$

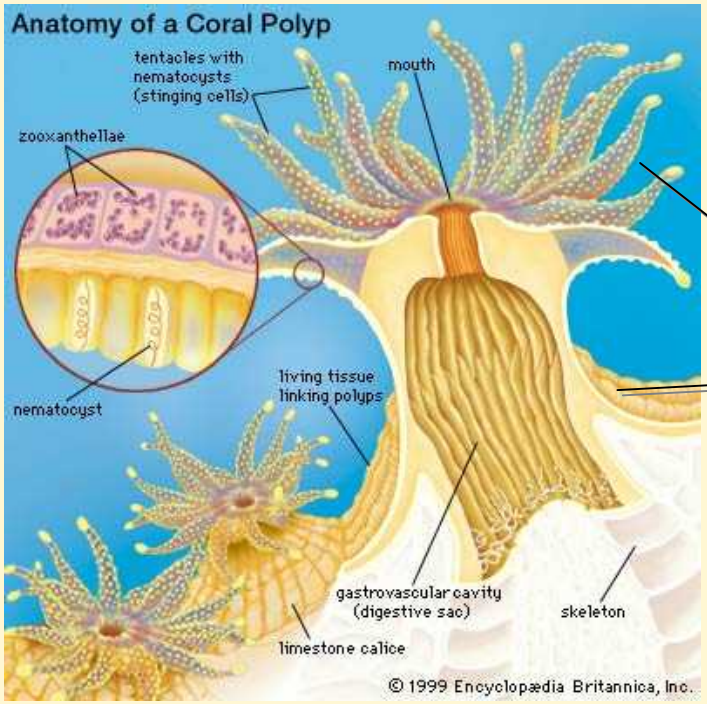
$$V_{sphere} = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 = \frac{4}{3}\pi f^3 x$$

$$V_{needle} = \int_0^x \pi R^2 dx = \frac{3\pi}{5} f^2 x^{5/3}$$

$$x = Ut$$






# Constructal view of coral colony association of polyps

Tentacles to trap food

Cells on the lower sides and bottom produce the limestone that builds the colony

Porites spp. (stony coral)

| | **rounded and compact** | **dendritic** |
|---|---|---|
| | cm/year | cm/year |
| growth rate | 1.2±0.5 | 0.2 to 4.8 |
| | Lough and Barnes (1997) | Harriott (1999) |

# Constructal view of coral growing process

**Why rounded and compact forms? Why branches?**
**Why are the branches necessary?**

Food particles very small — convective-dispersive transport

Growth process starts at birth (t=0) $L_c = U_c t$

➡ **Sheltered growth site** $Pe\left(=\frac{Ul}{D^*}\right)<1$

food particles near colony $C_c \quad (<C_{bulk})$

food "wave"

$$L_p \approx (D^* t)^{0.5}$$

Food particles velocity

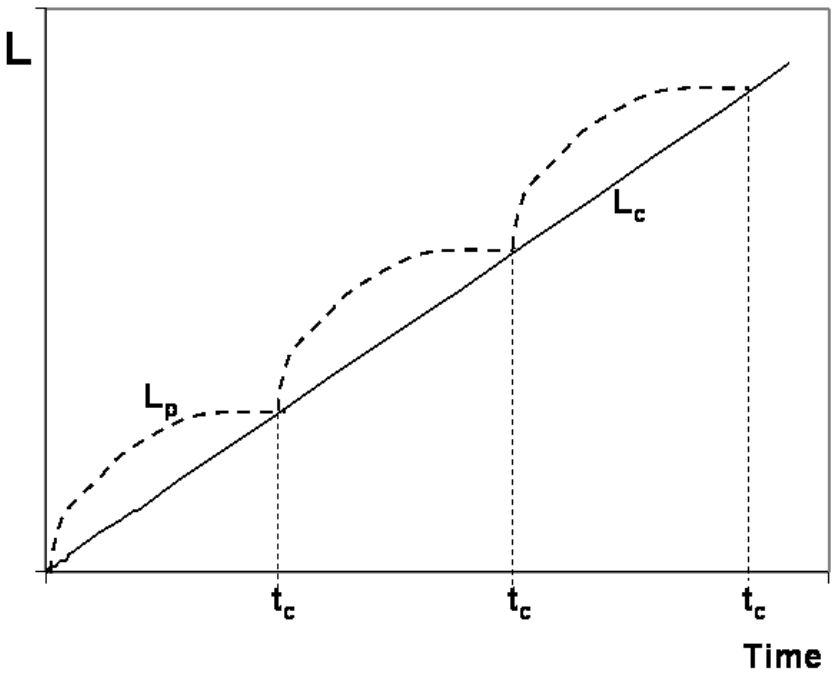
$$U_p = \frac{D^*}{t^{0.5}}$$

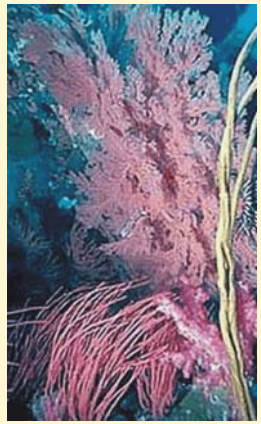
fast early and slow late

# How can the access to nutrients by the colony of coral be optimized ?

$$U_c \sim \text{const} \qquad U_p = \frac{D^*}{t^{0.5}}$$

fast early and slow late



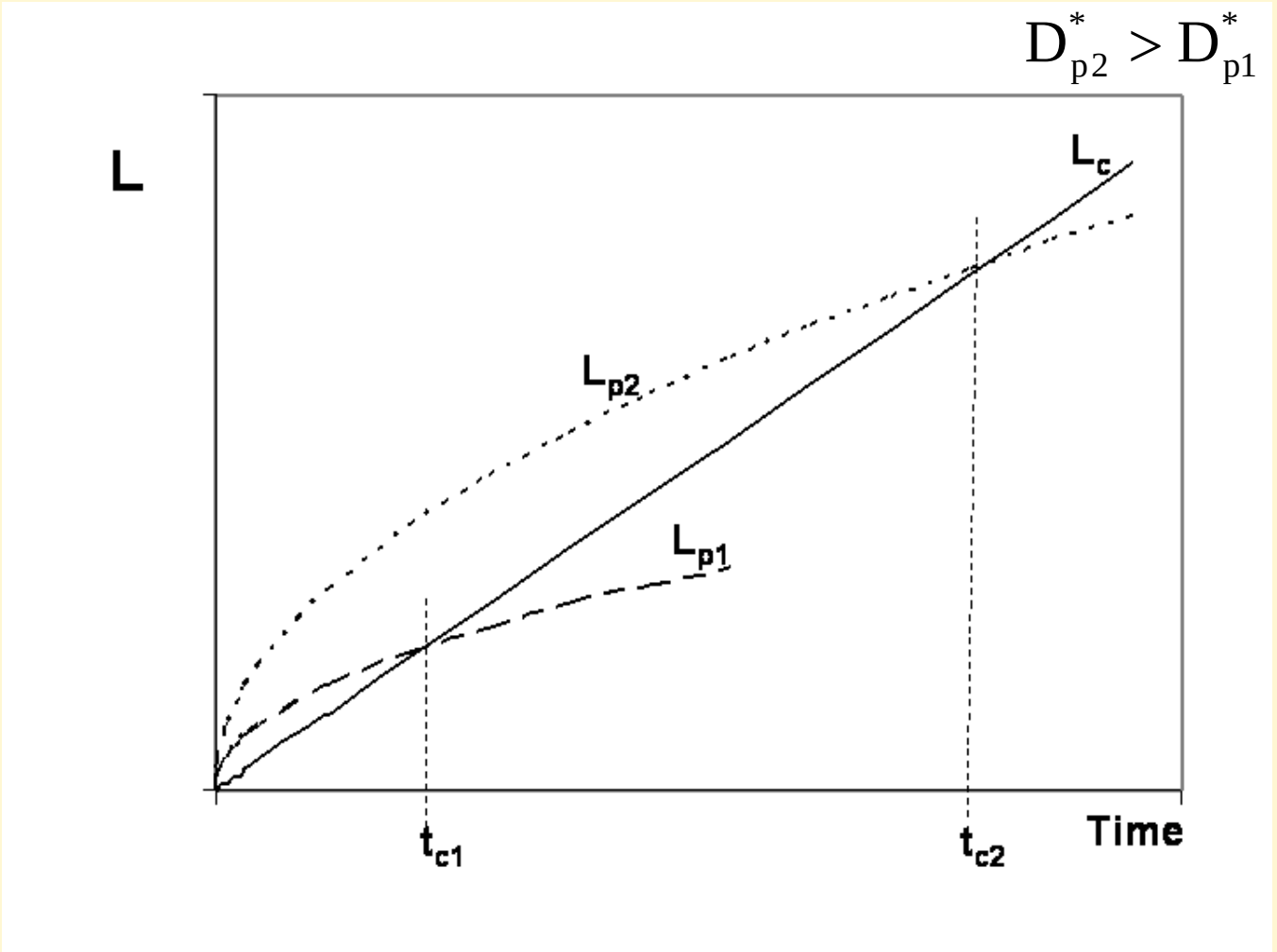



# Does the nutrient size influence the form of coral colony ?

$$D^* = \frac{c_{cn} k_B T}{6\pi\mu r_p}$$

$$U_p = \frac{D^*}{t^{0.5}}$$

$U_c \sim$ const



## Colony more exposed to water current

$$Pe\left(=\frac{Ul}{D*}\right)>1$$

$U_c$ 1.2±0.5 cm/year Lough and Barnes (1997)

0.2 to 4.8 cm/year Harriott (1999)

$U >> U_c$

$t_c$

# What is the constructal view of stony coral growth?

Branches generation allows a faster growth of the coral colony because it provides internal paths such that the entire substrate volume approaches internal equilibrium faster (depletion of nutrients).

→ Bacteria colony & plant roots

Miguel (2003)

# Final remarks

## Constructal Theory

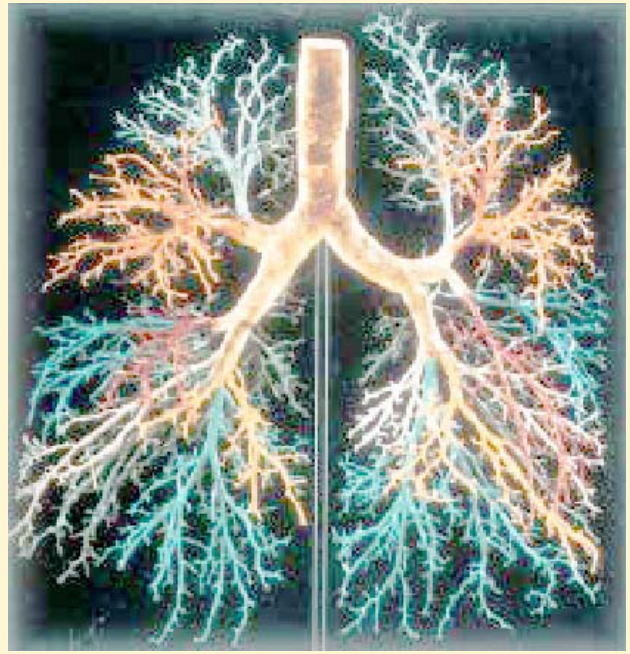
- **design optimization of air-cleaning devices**

- **cluster of particles grows fast early, and slow late**
- **at small times spherical agglomeration; at long times needle (dendrite) more effective**

- **in stony coral branches generation provides the best internal path to reach the food (*i.e., internal paths such that the entire substrate volume approaches internal equilibrium faster*).**

# Constructal theory of flow architectures of the lungs

(Reis, Miguel and Aydin, 2004)



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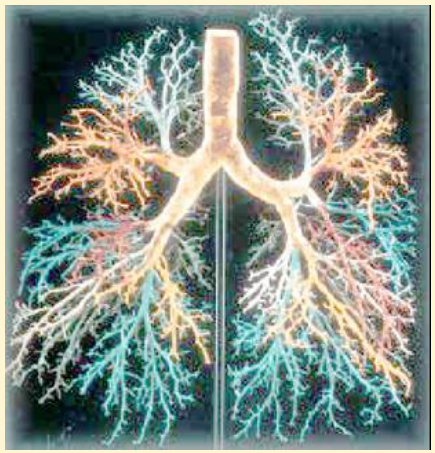
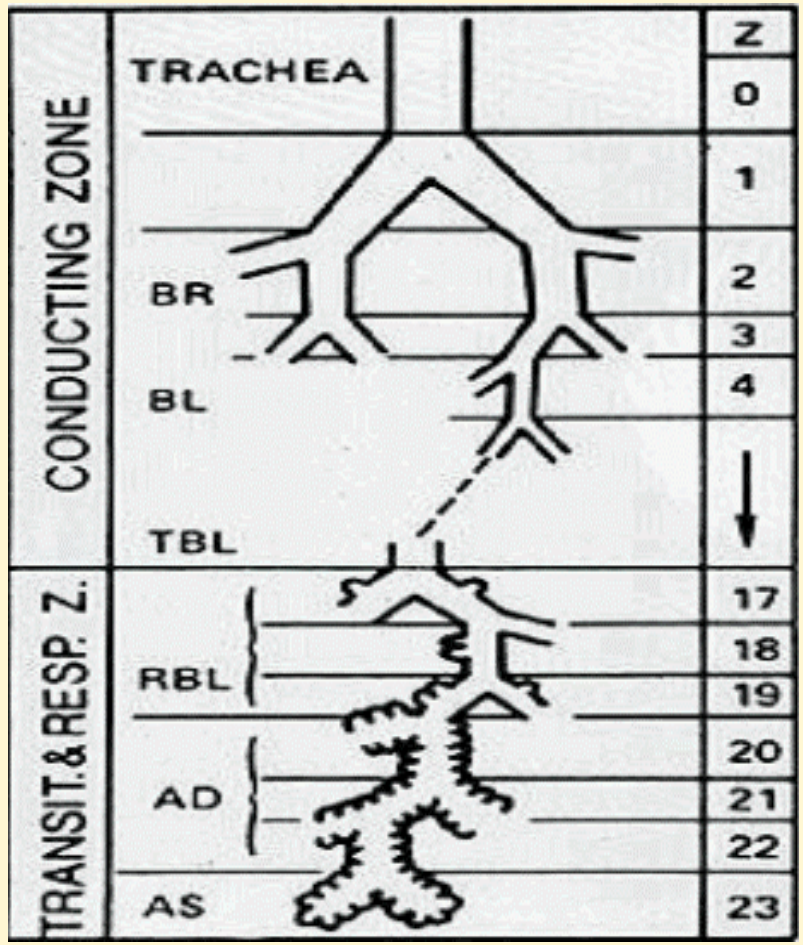
# Outline

- A fluid tree with purpose
- Bronchial tree resistance and alveolar resistance
- Optimization of the respiratory tree based on the Constructal Principle
- Constructal laws of the lung airways
- Conclusions

# The respiratory tree

- Starts at the trachea;
- Channels bifurcate 23 times before reaching the alveolar sac.






*Has this special flow architecture been developed by chance or does it represent the optimum structure for the lung's purpose, which is the oxygenation of the blood?*

## The purpose of the respiratory tree

- Oxygenation of blood;
- Removal of carbon dioxide.

## The trade-off

- High alveolar surface promotes better oxygenation, but requires increased access to the external air (higher flow resistance).
- Lower level of channel branching reduces flow resistance, but reduces also the number of alveoli and therefore decreases the area allocated for blood oxygenation.

# The asymptotic leeways

I) A duct system that ends with an alveolar volume from which the oxygen diffuses onto the tissues, where it meets the blood, and in which the carbon dioxide diffuses after being released from the blood;

$t_{Flow} = \pi \eta L^2/(d^2 \Delta P) \sim 1$ s

II) A unique volume open to the external air, in which the oxygen reaches the blood in the tissues, and removes the carbon dioxide rejected from the blood, only by diffusion through the internal air.

$t_{Diff} = L^2/D \sim 10^4$ s

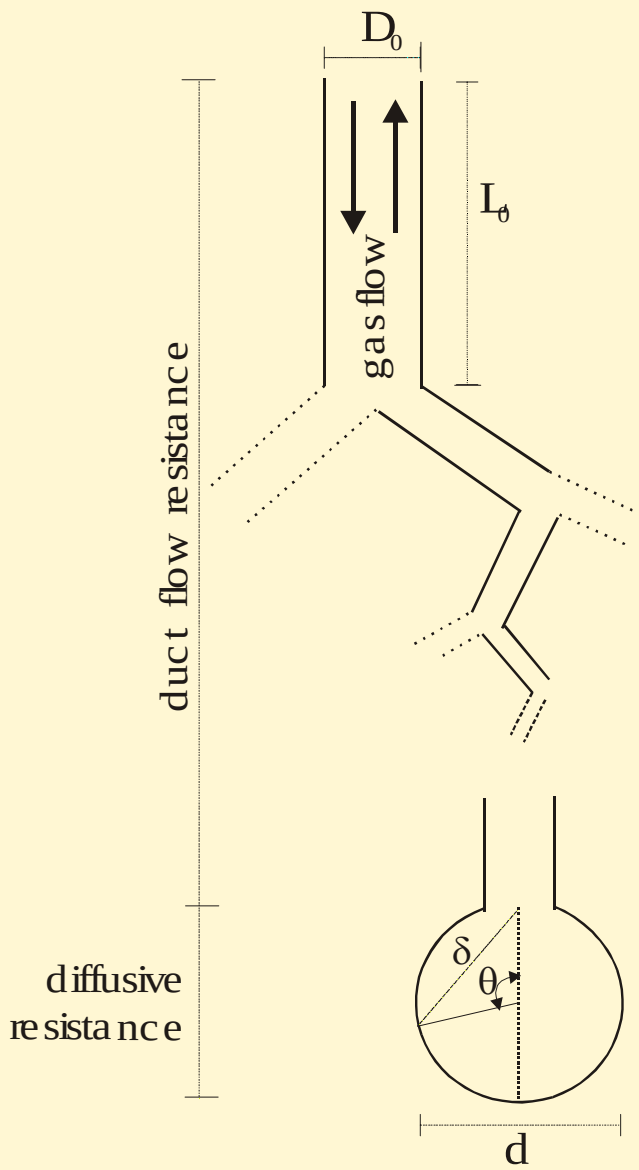
# Bronchial tree resistance

## Assumptions

- Airflow within the bronchial tree is assumed to be laminar (Re<1000), isothermal and incompressible

- The difference in chemical potential drives oxygen into the lungs and cabon dioxide out of the lungs $\Delta\mu = \rho^{-1}\Delta P + \Delta\varepsilon$

- The bronchial tree is composed of cylindrical channels with Hagen-Poiseuille flow,




Airflow rate: $$\dot{m}_n = \frac{\pi \rho D_n^4}{128 \nu L_n} \Delta\mu_{cn}$$

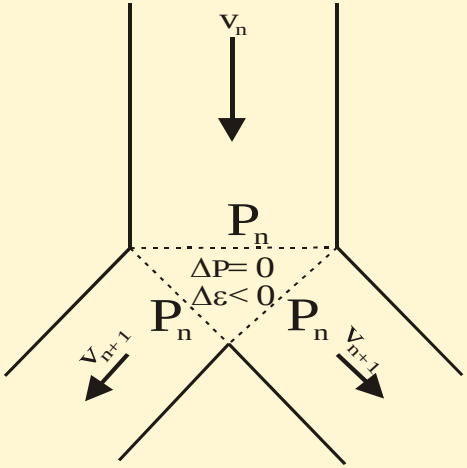
Minimum flow resistance at a bifurcation

Constructal rules :

$$D_n/D_{n-1}=2^{-1/3} \qquad L_n/L_{n-1}=2^{-1/3}$$

Resistance posed by the $n^{th}$ bronchial tube

$$r_{cn} = \frac{\rho \Delta\mu_{cn}}{\dot{m}_n} = 2^n \frac{128 \nu L_0}{\pi \rho D_0^4}$$




$$\dot{m}_n = \frac{\Delta\mu_{bn}}{r_{bn}} = -\frac{\Delta\varepsilon_{bn}}{r_{bn}}$$

Resistance due to bifurcation

$$r_{bn} = \frac{\dot{m}_0}{8\pi\rho^2 D_0^4} 2^{n/3}$$

Resistance of the $n^{th}$ level

($2^n$ bronchial tubes)

$$r_n = \frac{128\nu L_0}{\pi\rho D_0^4}\left(1 + \frac{\dot{m}_0 2^{-2n/3}}{1024\rho\nu L_0}\right)$$

overall convective resistance

$$R_b = \sum_{n=0}^{N-1} r_n = \frac{128\nu L_0}{\pi\rho D_0^4}\left[N + \frac{\dot{m}_0\left(1-2^{-2N/3}\right)}{379\pi\rho\nu L_0}\right]$$

## Diffusive Resistance

$$\dot{m}_{ox} = \frac{1}{2}\left((\phi_{ox})_0 - \phi_{ox}\right)\dot{m}_b = \frac{|\Delta\mu_b|}{(R_{ox})_b}$$

$\phi$ - concentration

$$\dot{m}_{ox} = 2^N \frac{2\pi d \rho D_{ox} (\Delta\mu_{ox})_a}{R_{ox} T}$$

$$d = L - \sum_{i=1}^{N} L_i \quad \Rightarrow \quad d = 4.85 \times 2^{-(N+1)/3} L_0$$

resistance of the $N^{th}$ level of bifurcation

$$(R_{ox})_N = \frac{128 \nu L_0}{\pi \rho D_0^4} + 0.13 (R_g)_{ox} T \frac{2^{-2N/3}}{\pi L_0 D_{ox}}$$

Global resistance of the constructal respiratory tree ($kg^2J^{-1}s^{-1}$)

$$R_{ox} \cong \frac{256\nu L_0}{\pi D_0^4 \left((\phi_{ox})_0 - \phi_{ox}\right)\rho}(N+1) + \frac{0.13\times 2^{-2N/3}\left(R_g\right)_{ox} T}{\pi L_0 D \phi_{ox} \rho}$$

Air, oxygen and carbon dioxide properties were taken at 36º C

$\phi_{ox}$ is evaluated from the alveolar air equation : $((\phi_{ox})_0-\phi_{ox})Q-S=0$,

Q is the tidal airflow and S is the rate of oxygen consumption.

$(\phi_{ox})_{air}=0.2095$; $(\phi_{cd})_{air}\sim 0.315\times 10^{-3}$; Q~6 $dm^3/min$ and S~0.3 $dm^3/min$.

trachea length $L_0$ ~ 15 cm; trachea diameter, $D_0$ ~1.5 cm.

Constructal law (principle) the flow architectures evolve in time in order to maximize the flow access under the constraints posed to the flow

$$N_{opt} = 2.164 \ln \left[ \frac{2.35 \times 10^{-4} D_0^4 \left(R_g\right)_{ox} T}{L_0^2 \nu D_{ox}} \left( \frac{(\phi_{ox})_0}{\phi_{ox}} - 1 \right) \right]$$

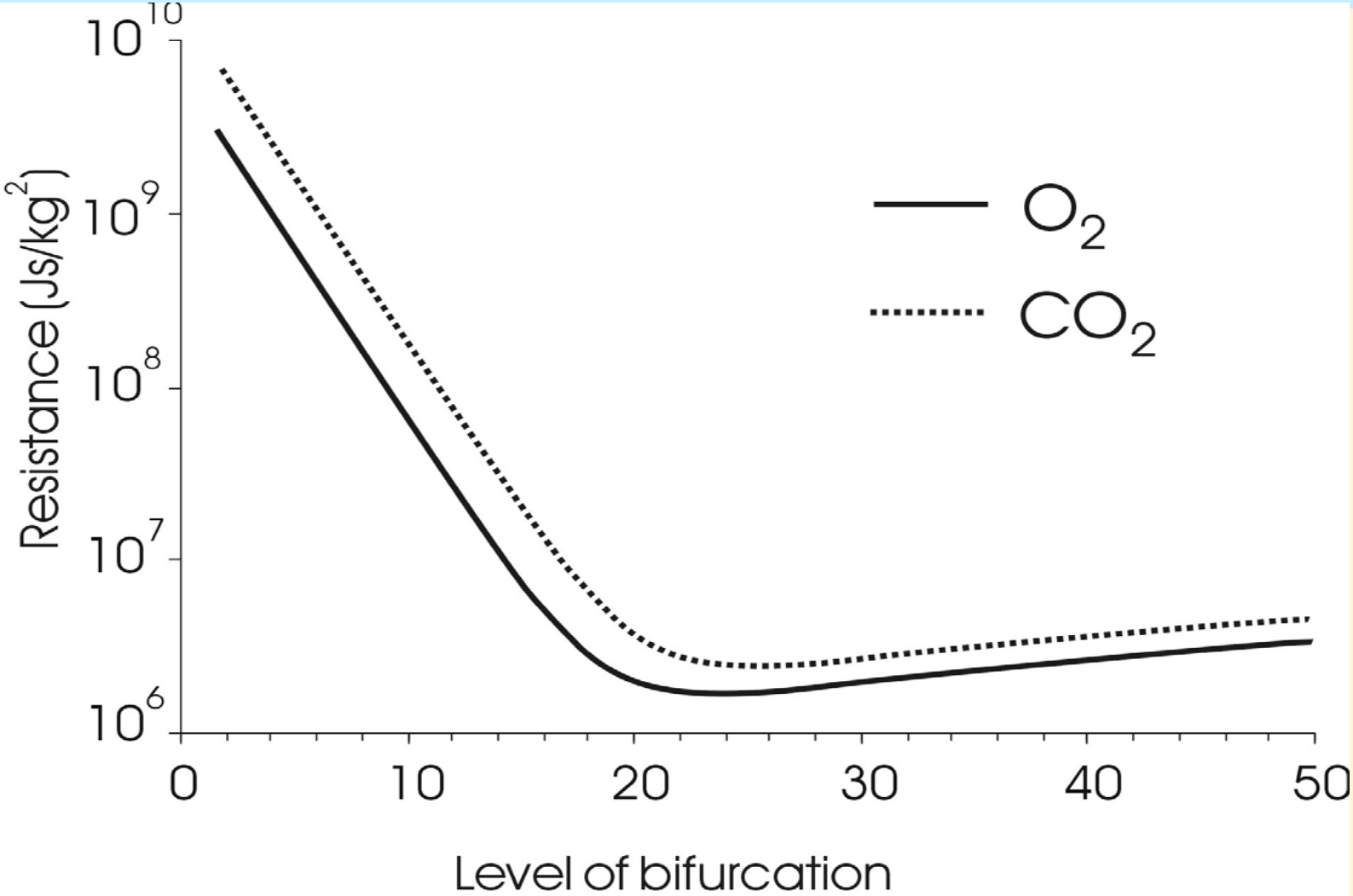
Minimization of the global resistance to oxygen access with respect to level of bifurcation

$N_{opt} = 23$ (23.4)

Minimization of the global resistance to carbon dioxide removal with respect to level of bifurcation

$N_{opt} = 23$ (23.2)

Total resistance to oxygen and carbon dioxide transport between the entrance of the trachea and the alveolar surface is plotted as function of the level of bifurcation (N).



# Constructal laws of the human respiratory tree

(I)

If the number $N_{opt}=23$ is common to mankind then a constructal rule emerges:

*"the ratio between the square of the trachea diameter and its length is constant and a length characteristic of mankind:"*

$$\lambda=\frac{D_0^2}{L_0}=\text{const.}=1.6\times10^{-3}\,\text{m}$$

V – Global volume of the respiratory tree; L – average length

A – Area allocated to gas ($O_2$ and $CO_2$) exchange

$$\frac{D_0^2}{L_0} = 8.63 \frac{AL}{V} \left( \frac{\nu D_{ox} \phi_{ox}}{(R_g)_{ox} T((\phi_{ox})_0 - \phi_{ox})} \right)^{1/2}$$

(II)

The non-dimensional number AL/V, determines the characteristic length $\lambda = D_0^2/L_0$, which determines the number of bifurcations of the respiratory tree by:

*"The alveolar area required for gas exchange, A, the volume allocated to the respiratory system, V, and the length of the respiratory tree, L, which are constraints posed to the respiratory process determine univocally the structure of the lungs, namely the bifurcation level of the bronchial tree."*

# Global volume and average length of the respiratory tree, and area allocated to gas ($O_2$ and $CO_2$) exchange

Average length of the respiratory tree: $L=4.85L_0=0.\ 68m$ ;
Observed ~1m

Alveolar diameter: $d=6V/A=2.67\times10^{-3}m$ ; Observed ~ $10^{-3}m$

Alveolar surface area as $A=2^{23}\pi d^2=187.7m^2$ ; Observed 100 -150$m^2$

Total alveolar volume $V=2^{23}(\pi/6)d^3=83.5dm^3$ ; Observed 8 -10$m^3$

# CONCLUSIONS

- The best oxygen access to the tissues where it reaches the blood is performed by a flow structure composed of ducts with 23 levels of bifurcation

- The same structure has been shown being optimized for carbon dioxide removal.

- The optimized number of bifurcation levels matches the 23 levels that the physiology literature indicates for the bronchial tree.

- Theory also predicts the dimension of the alveolar sac, the total alveolar surface area, the total alveolar volume, and the total length of the airways. These values agree, at least in an order of magnitude sense with the values found in the physiology literature

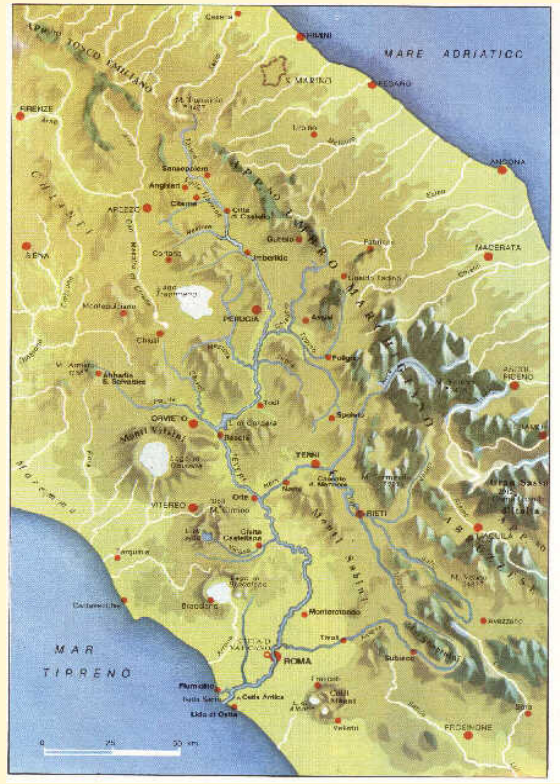
• It was shown that the length $\lambda$ (defined as the ratio between the square of the first airway diameter and its length) is constant for every individual of the same species and related to the characteristics of the space allocated for the respiratory process.

• The length $\lambda$ is univocally determined by a non-dimensional number, AL/V, which involves the characteristics of the space allocated to the respiratory system, namely the total alveolar area, A, the total volume V, and the total length of the airways, L.

• In general, we conclude, that for every species whose respiratory tree is optimized the same rule must hold, and exhibit the respective characteristic length, $\lambda$.

•The application of the Constructal Principle to the generation of the optimal configuration of the respiratory tree was based on the view that Nature has optimized the living flow structures, in time.

# Fluid trees – from Constructal theory to actual river basins

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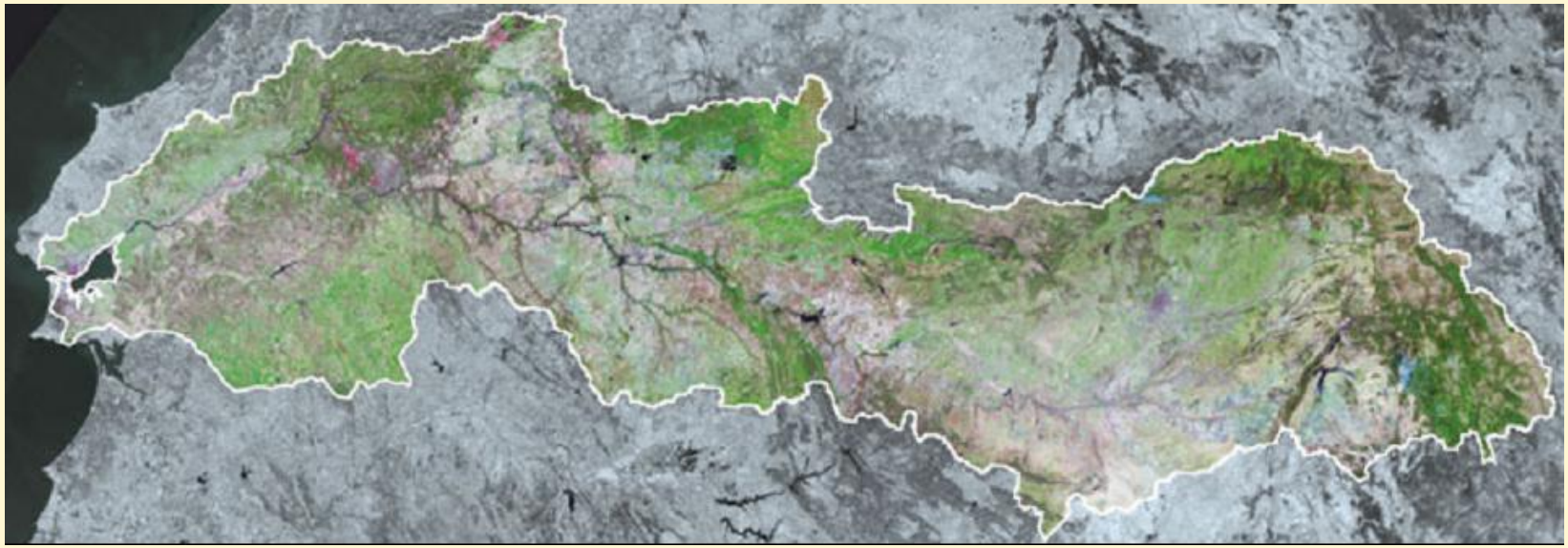
# Outline

- Natural flow architectures
- Scaling laws of river basins
- River networks as constructal fluid trees
- A constructal model of river basin development
- Conclusions

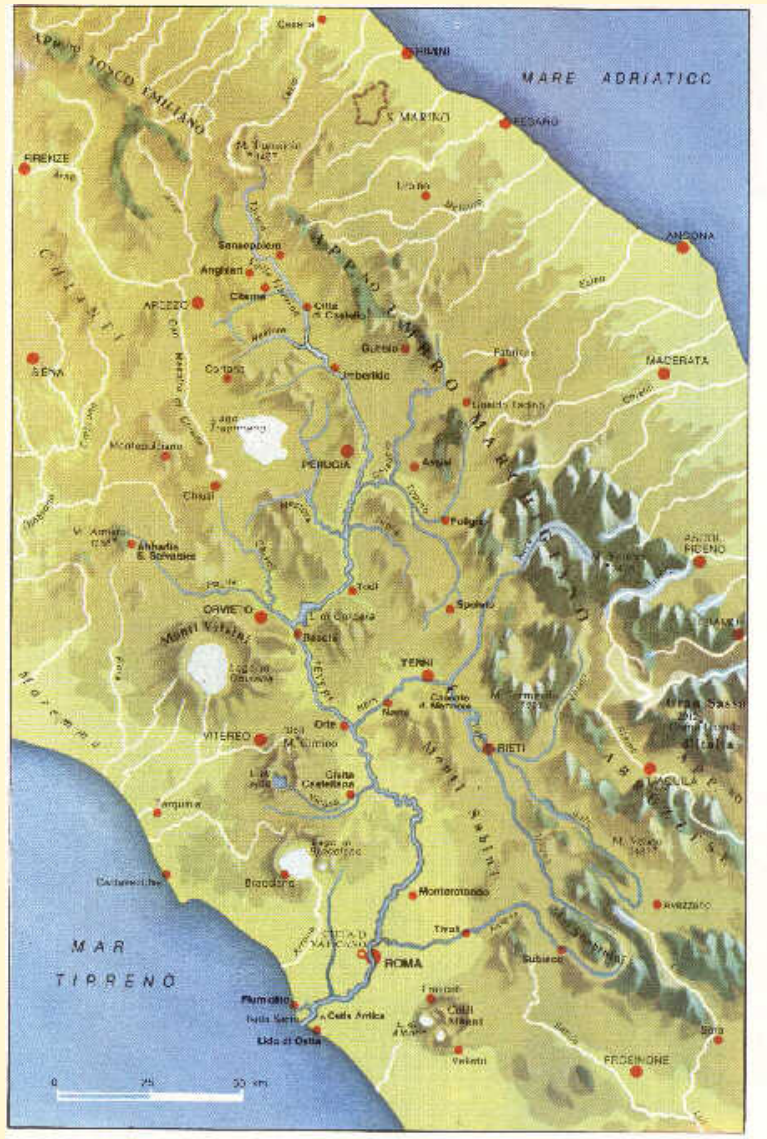
# Tagus river basin (Tejo, in Portuguese)



Length (km): 1 100
Drainage Area ($km^2$): 88 700
Discharge ($m^3/s$): 600

# Tevere river basin

Length (km): 405
Drainage Area ($km^2$): 17375
Discharge ($m^3/s$): 250



# River networks are self-similar structures over a range of scales

Horton's law of stream lengths: $L_i / L_{i-1} = R_L$

$1.5 < R_L < 3.5$

Horton's law of stream numbers: $n_{i-1} / n_i = R_B$

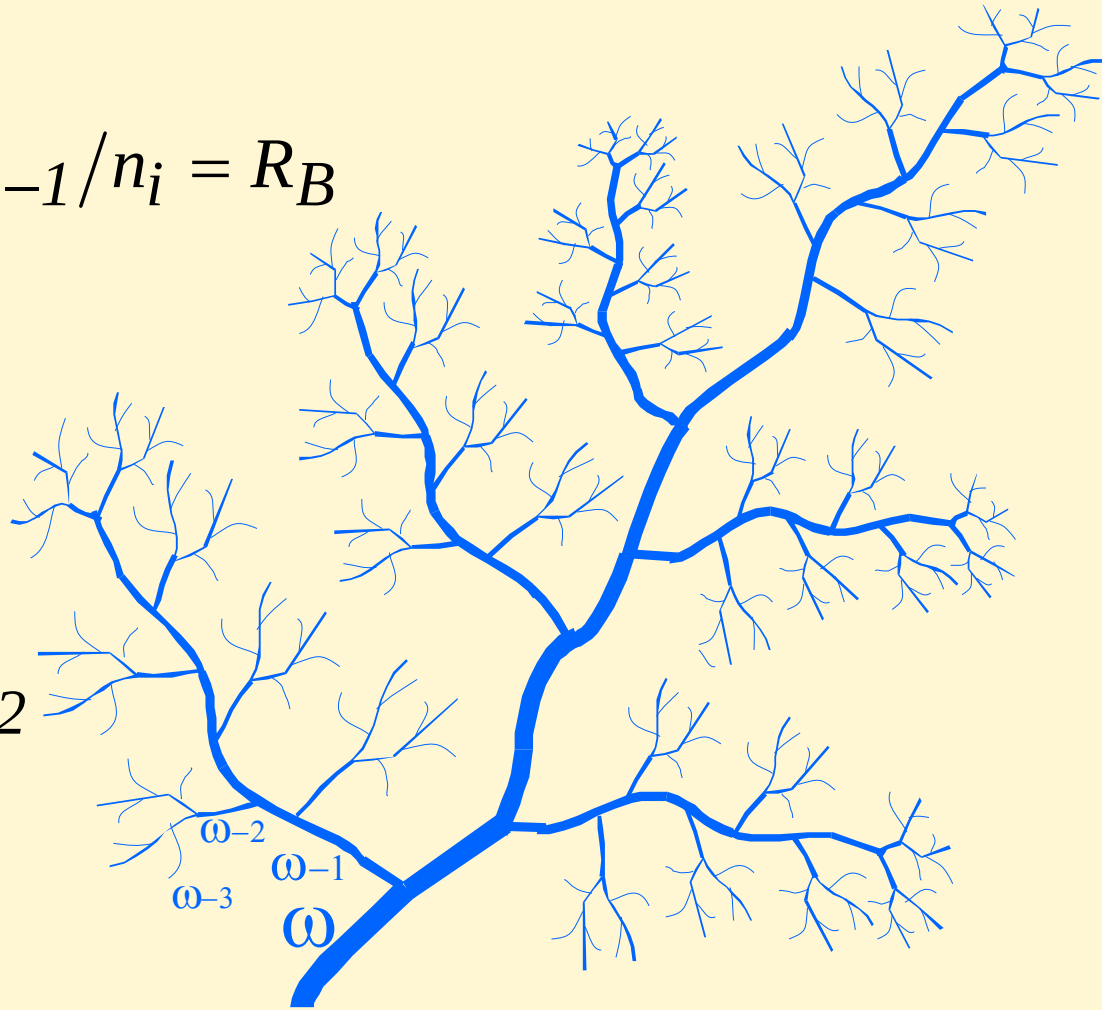
$3 < R_B < 5$

Hack's law $L_\omega = \alpha (A_\omega)^b$

$b \sim 0.56 - 0.5$

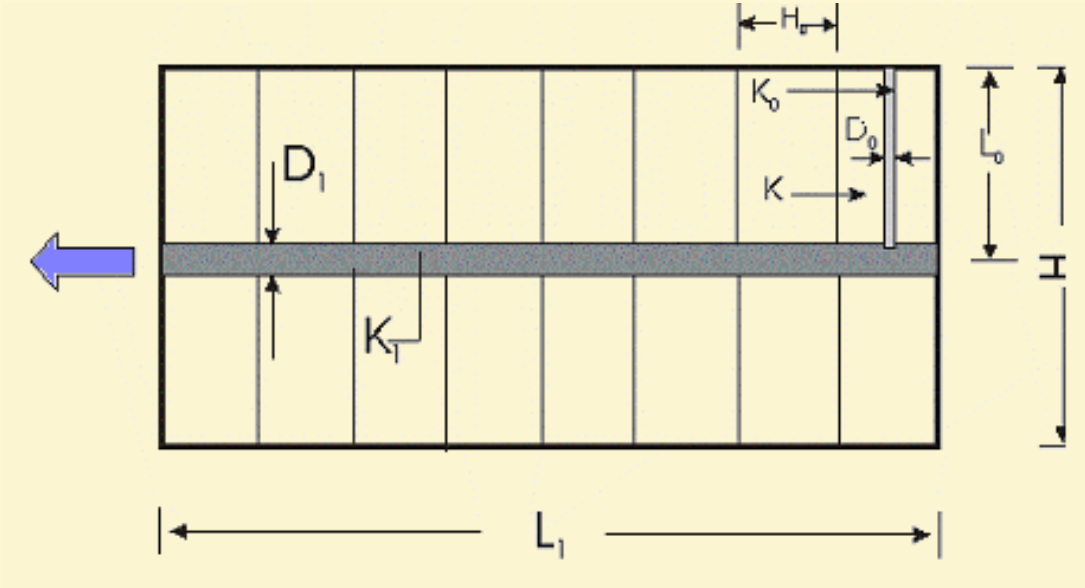
Melton's law: $F_S = 0.694 (D_\omega)^2$

$D_\omega = L_T / A \; ; \; F_s = N_\omega / A$



# CONSTRUCTAL THEORY (Bejan)

## River basins as area-to-point flows




First construct made of elemental areas, $A_0 = H_0 L_0$.

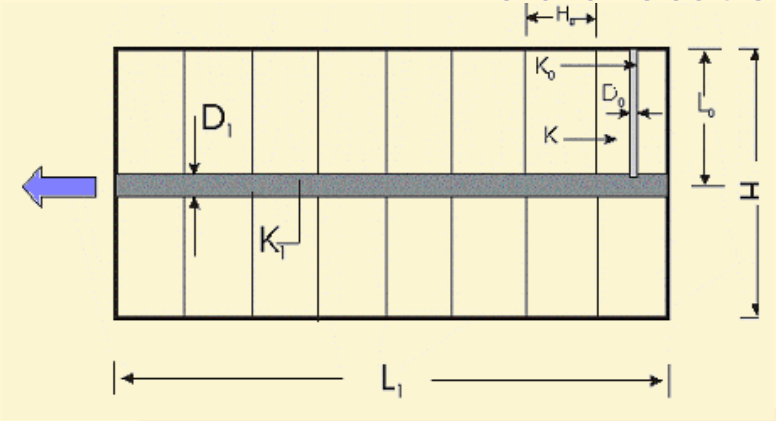
A new channel of higher permeability collects flow from the elemental areas.

# The optimised geometry of area-to-point flow (channels with Hagen-Poiseuille flow, Bejan)

$$\hat{K} = K / A_0 \quad (\tilde{H}_i, \tilde{L}_i) = (H_i, L_i) / (A_0)^{1/2} \quad \Phi_i = D_i / H_i$$

| | $\tilde{H}_i$ | $\tilde{L}_i$ | $n_i$ |
|---|---|---|---|
| 0 | $\frac{2^{5/6} 3^{1/6} \hat{K}^{1/6}}{\Phi_0^{1/2}}$ | $\frac{\Phi_0^{1/2}}{2^{5/6} 3^{1/6} \hat{K}^{1/6}}$ | - |
| 1 | $\frac{2^{1/6} \Phi_0^{1/2}}{3^{1/6} \hat{K}^{1/6}}$ | $\frac{\Phi_1^{3/2}}{2^{3/2} \hat{K}^{1/2}}$ | $\frac{\Phi_1^{3/2} \Phi_0^{1/2}}{2^{4/3} 3^{1/6} \hat{K}^{2/3}}$ |
| 2 | $\frac{\Phi_1^{3/2}}{2^{1/2} \hat{K}^{1/2}}$ | $\frac{3^{1/6} (\Phi_2 \Phi_1)^{3/2}}{2^{5/3} \Phi_0^{1/2} \hat{K}^{5/6}}$ | $\frac{3^{1/3} (\Phi_2 \Phi)^{3/2}}{2^{5/6} \Phi_0 \hat{K}^{2/3}}$ |
| 3 | $\frac{3^{1/6} (\Phi_2 \Phi_1)^{3/2}}{2^{2/3} \Phi_0^{1/2} \hat{K}^{5/6}}$ | $\frac{3^{1/3} (\Phi_3 \Phi_2 \Phi_1)^{3/2}}{2^{4/3} \Phi_0 \hat{K}^{7/6}}$ | $\frac{2^{1/6} 3^{1/3} (\Phi_3 \Phi_2)^{3/2}}{\Phi_0 \hat{K}^{2/3}}$ |
| 4 | $\frac{3^{2/3} (\Phi_3 \Phi_2 \Phi_1)^{3/2}}{2^{1/3} \Phi_0 \hat{K}^{7/6}}$ | $\frac{3^{1/2} (\Phi_4 \Phi_3 \Phi_2 \Phi_1)^{3/2}}{2^{1/2} \Phi_0^{3/2} \hat{K}^{9/6}}$ | $\frac{2^{7/6} 3^{2/3} (\Phi_4 \Phi_3)^{3/2}}{\Phi_0 \hat{K}^{2/3}}$ |

# Void-allocation (channel) optimisation




$$\Phi_i = D_i / H_i \qquad \hat{K} = K / A_0$$

$$\Phi_1 = \Phi_0 \qquad \Phi_2 = (6/7)\Phi_0$$

$$\Phi_3 = (60/77)\Phi_0 \qquad \Phi_4 = (8/11)\Phi_0$$

| | $\tilde{L}_i$ | $n_i$ |
|---|---|---|
| 0 | $0.467\left(\Phi_0 \hat{K}^{-1/3}\right)^{1/2}$ | - |
| 1 | $0.357\left(\Phi_0 \hat{K}^{-1/3}\right)^{3/2}$ | $0.331\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 2 | $0.300\left(\Phi_0 \hat{K}^{-1/3}\right)^{5/2}$ | $0.809\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 3 | $0.312\left(\Phi_0 \hat{K}^{-1/3}\right)^{7/2}$ | $0.883\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 4 | $0.414\left(\Phi_0 \hat{K}^{-1/3}\right)^{9/2}$ | $1.990\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |

Assumption:

*Channel hierarchy is understood in the Hortonian sense, i.e. all streams of order i are tributaries of streams of order i+1.*

| | $\tilde{L}_i$ | $n_i$ |
|---|---|---|
| 0 | $0.467\left(\Phi_0\hat{K}^{-1/3}\right)^{1/2}$ | - |
| 1 | $0.357\left(\Phi_0\hat{K}^{-1/3}\right)^{3/2}$ | $0.331\left(\Phi_0\hat{K}^{-1/3}\right)^{2}$ |
| 2 | $0.300\left(\Phi_0\hat{K}^{-1/3}\right)^{5/2}$ | $0.809\left(\Phi_0\hat{K}^{-1/3}\right)^{2}$ |
| 3 | $0.312\left(\Phi_0\hat{K}^{-1/3}\right)^{7/2}$ | $0.883\left(\Phi_0\hat{K}^{-1/3}\right)^{2}$ |
| 4 | $0.414\left(\Phi_0\hat{K}^{-1/3}\right)^{9/2}$ | $1.990\left(\Phi_0\hat{K}^{-1/3}\right)^{2}$ |

Horton's law of stream lengths

$$\tilde{L}_{i-1}/\tilde{L}_i \sim \Phi_0\hat{K}^{-1/3} \quad \sim \text{constant}$$

| $\tilde{L}_1/\tilde{L}_0$ | $\tilde{L}_2/\tilde{L}_1$ | $\tilde{L}_3/\tilde{L}_2$ | $\tilde{L}_4/\tilde{L}_3$ |
|---|---|---|---|
| $0.758\Phi_0\hat{K}^{-\frac{1}{3}}$ | $0.847\Phi_0\hat{K}^{-\frac{1}{3}}$ | $1.038\Phi_0\hat{K}^{-\frac{1}{3}}$ | $1.327\Phi_0\hat{K}^{-\frac{1}{3}}$ |

Number of streams of order *i* : $N_i = n_i \times n_{i-1} \times n_{i-2} \times \ldots \times n_1$

The ratio of the number of streams of order *i-1* to the number of streams of order *i* is $N_i / N_{i+1} = n_i$

| | $\tilde{L}_i$ | $n_i$ |
|---|---|---|
| 0 | $0.467\left(\Phi_0 \hat{K}^{-1/3}\right)^{1/2}$ | - |
| 1 | $0.357\left(\Phi_0 \hat{K}^{-1/3}\right)^{3/2}$ | $0.331\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 2 | $0.300\left(\Phi_0 \hat{K}^{-1/3}\right)^{5/2}$ | $0.809\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 3 | $0.312\left(\Phi_0 \hat{K}^{-1/3}\right)^{7/2}$ | $0.883\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |
| 4 | $0.414\left(\Phi_0 \hat{K}^{-1/3}\right)^{9/2}$ | $1.990\left(\Phi_0 \hat{K}^{-1/3}\right)^{2}$ |

Horton's law of stream numbers

$$N_i / N_{i+1} \sim \left(\Phi_0 \hat{K}^{-1/3}\right)^2 \sim \text{constant}$$

# Relationship between $R_L$ and $R_B$

Horton's law of stream lengths:

$$1.5 < R_L < 3.5 \; ; \; R_L \sim 2$$

$$L_i / L_{i-1} = R_L$$

Horton's law of stream numbers:

$$3 < R_B < 5 \; ; \; R_B \sim 4$$

$$n_{i-1} / n_i = R_B$$

$$\tilde{L}_{i-1} / \tilde{L}_i \sim \Phi_0 \hat{K}^{-1/3}$$

$$N_i / N_{i+1} \sim \left( \Phi_0 \hat{K}^{-1/3} \right)^2$$

$$R_B \sim (R_L)^2$$

## Hack's law

$$L_\omega = \alpha (A_\omega)^b$$

$$b \sim 0.56 - 0.5$$

$$A_i = H_i L_i$$

| | $\tilde{H}_i$ | $\tilde{L}_i$ | $n_i$ |
|---|---|---|---|
| 0 | $\frac{2^{5/6}3^{1/6}\hat{K}^{1/6}}{\Phi_0^{1/2}}$ | $\frac{\Phi_0^{1/2}}{2^{5/6}3^{1/6}\hat{K}^{1/6}}$ | - |
| 1 | $\frac{2^{1/6}\Phi_0^{1/2}}{3^{1/6}\hat{K}^{1/6}}$ | $\frac{\Phi_1^{3/2}}{2^{3/2}\hat{K}^{1/2}}$ | $\frac{\Phi_1^{3/2}\Phi_0^{1/2}}{2^{4/3}3^{1/6}\hat{K}^{2/3}}$ |
| 2 | $\frac{\Phi_1^{3/2}}{2^{1/2}\hat{K}^{1/2}}$ | $\frac{3^{1/6}(\Phi_2\Phi_1)^{3/2}}{2^{5/3}\Phi_0^{1/2}\hat{K}^{5/6}}$ | $\frac{3^{1/3}(\Phi_2\Phi)^{3/2}}{2^{5/6}\Phi_0\hat{K}^{2/3}}$ |
| 3 | $\frac{3^{1/6}(\Phi_2\Phi_1)^{3/2}}{2^{2/3}\Phi_0^{1/2}\hat{K}^{5/6}}$ | $\frac{3^{1/3}(\Phi_3\Phi_2\Phi_1)^{3/2}}{2^{4/3}\Phi_0\hat{K}^{7/6}}$ | $\frac{2^{1/6}3^{1/3}(\Phi_3\Phi_2)^{3/2}}{\Phi_0\hat{K}^{2/3}}$ |
| 4 | $\frac{3^{2/3}(\Phi_3\Phi_2\Phi_1)^{3/2}}{2^{1/3}\Phi_0\hat{K}^{7/6}}$ | $\frac{3^{1/2}(\Phi_4\Phi_3\Phi_2\Phi_1)^{3/2}}{2^{1/2}\Phi_0^{3/2}\hat{K}^{9/6}}$ | $\frac{2^{7/6}3^{2/3}(\Phi_4\Phi_3)^{3/2}}{\Phi_0\hat{K}^{2/3}}$ |

Constructal Hack's exponent $\beta$ for river basins up to order 4.

$$\tilde{L}_1 \sim A_1^{0.750} \qquad \tilde{L}_2 \sim A_2^{0.625} \qquad \tilde{L}_3 \sim A_3^{0.583} \qquad \tilde{L}_4 \sim A_4^{0.563}$$

constructal rule for the exponent $b$

$$\beta_\omega = \frac{2\omega + 1}{4\omega}$$

*Muller reported that b ~ 0.6 for river basins less than 8000 mi², b ~ 0.5 for basins between 8000 and 100,000 mi² and b ~ 0.47 for basins larger than 100,000 mi²*

Melton's law: $F_s = 0.694(D_\omega)^2$

$D_\omega = L_T/A \; ; \; F_s = N_\omega/A$

$$D_\omega = \sum_{i=1}^{\omega} n_i \tilde{L}_i \Big/ \tilde{H}_\omega \tilde{L}_\omega$$

$$F_s = \sum_{i=1}^{\omega} N_i \Big/ \tilde{H}_\omega \tilde{L}\omega$$

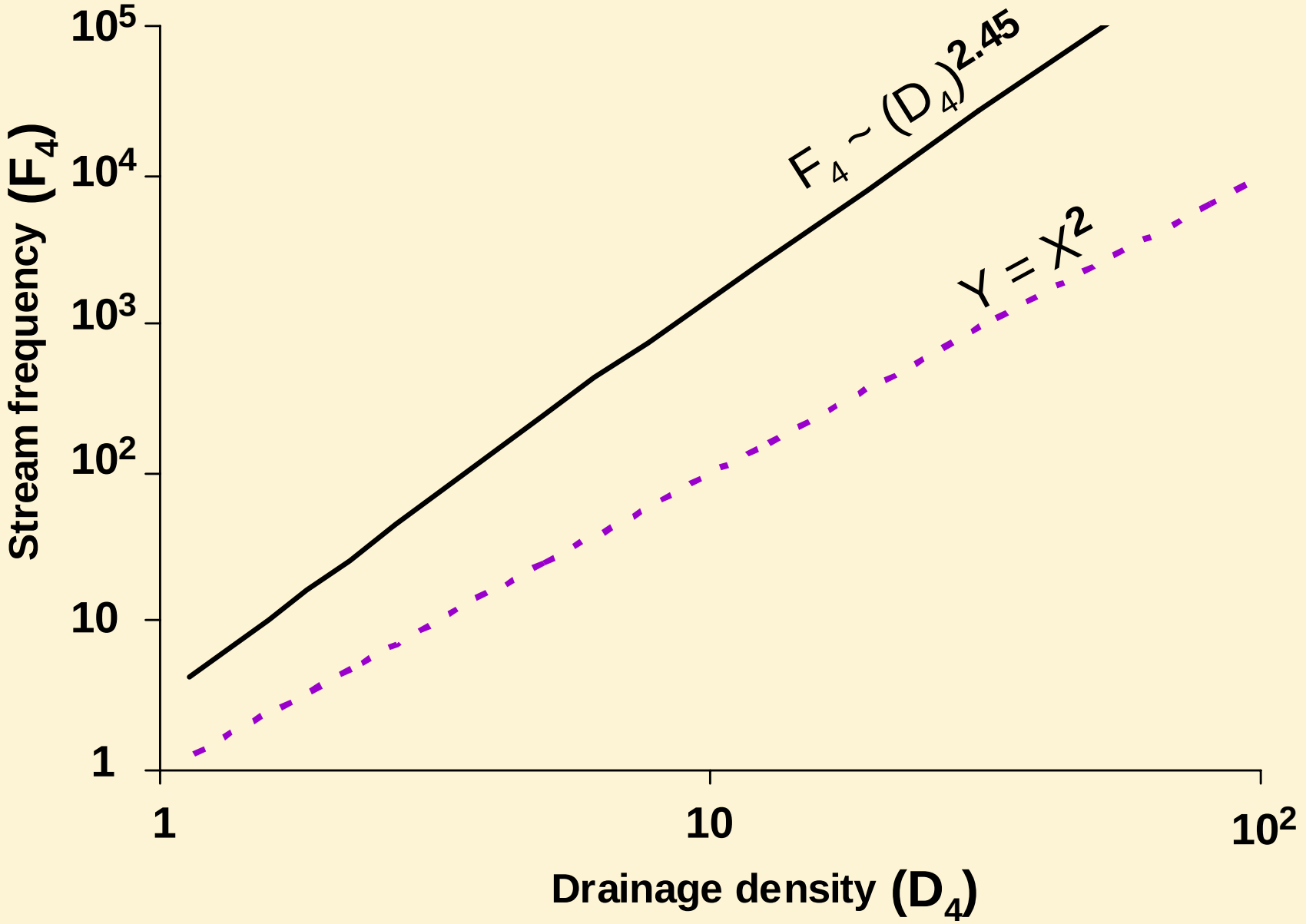
River network with streams up to order 4

$$D_4 = 0.182\left(\Phi_0 \hat{K}^{-1/3}\right) + 0.135\left(\Phi_0 \hat{K}^{-1/3}\right)^{-0.5} +$$

$$+ 0.345\left(\Phi_0 \hat{K}^{-1/3}\right)^{-1.5} + 0.443\left(\Phi_0 \hat{K}^{-1/3}\right)^{-2.5}$$

$$F_4 = 1 + 0.381\left(\Phi_0 \hat{K}^{-1/3}\right)^{-2} + 1.155\left(\Phi_0 \hat{K}^{-1/3}\right)^{-4} +$$

$$+ 1.424\left(\Phi_0 \hat{K}^{-1/3}\right)^{-6}$$


$10^5$
$10^4$
$10^3$
$10^2$
10
1
Stream frequency ($F_4$)
$F_4 \sim (D_4)^{2.45}$
$Y = X^2$
1
10
$10^2$
Drainage density ($D_4$)

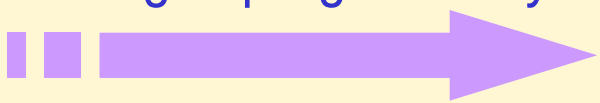
# A constructal model of river basin development
## (Errera and Bejan)

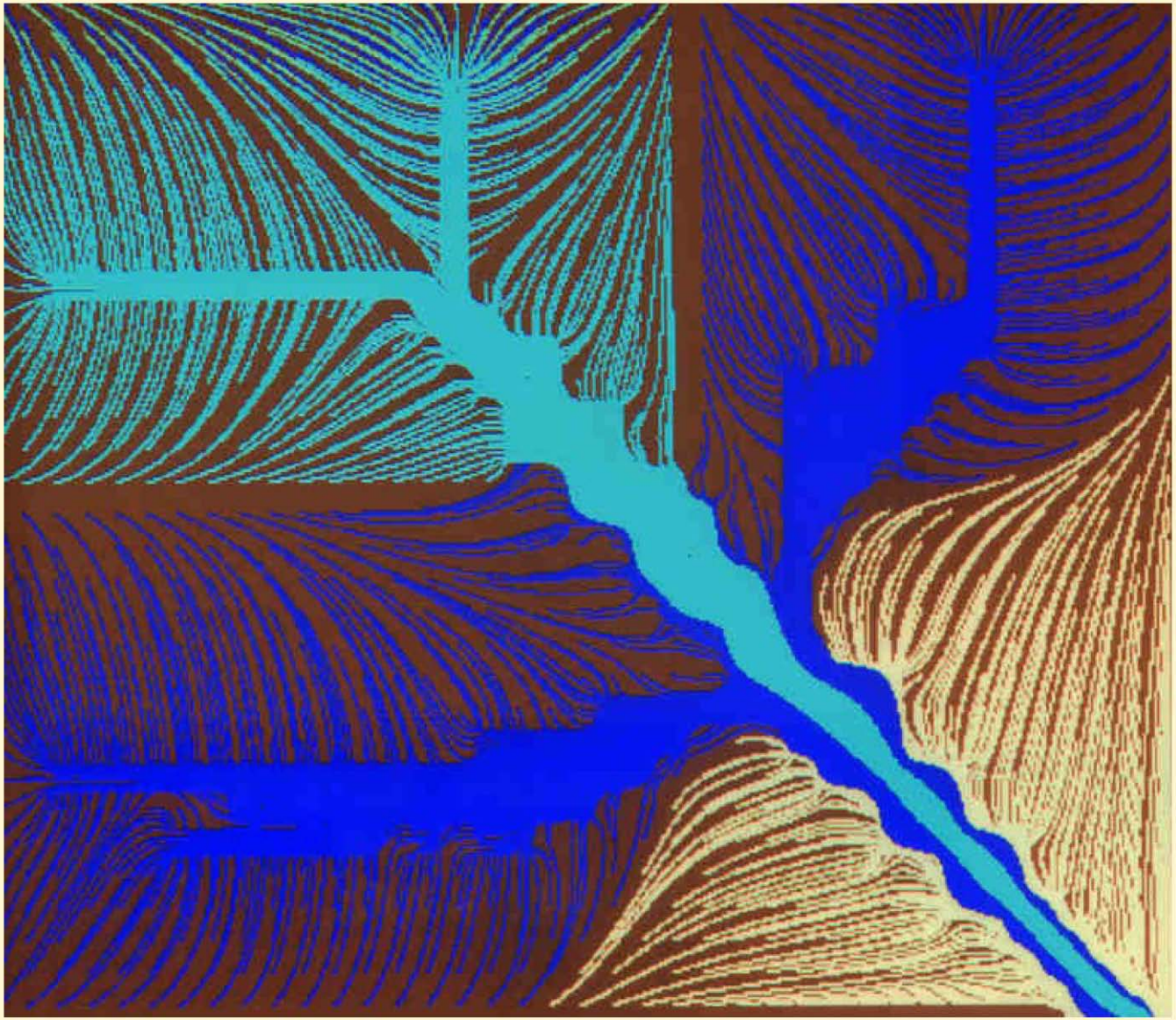
Objective: providing minimal resistance to flow

Changes in the river channel are possible because finite blocks can be dislodged and entrained in the stream

Rule: every squared block of area $L^2$ and height W, is dislodged whenever the pressure difference $\Delta P$ across the block surpasses the critical force needed to dislodge it, i.e. $\Delta PLW > \tau L^2$,

Flow resistance decreases with block removal. Further increase in the flow rate may create the conditions for the removal a second block and for the repetition of the process. A macroscopic dendrite-like structure emerges progressively while flow resistance decreases.





# Conclusions

The scaling laws of geometric features of river basins can be anticipated based on Constructal Theory, which views the pathways by which drainage networks develop in a basin not as the result of chance but as flow architectures that originate naturally as the result of minimization of the overall resistance to flow (Constructal Law).

The ratios of constructal lengths of consecutive streams match Horton's law for the same ratio.

The ratios of constructal lengths of consecutive streams match Horton's law for the same ratio.

Agreement is also found with the number of consecutive streams that match Horton's law of ratios of consecutive stream numbers

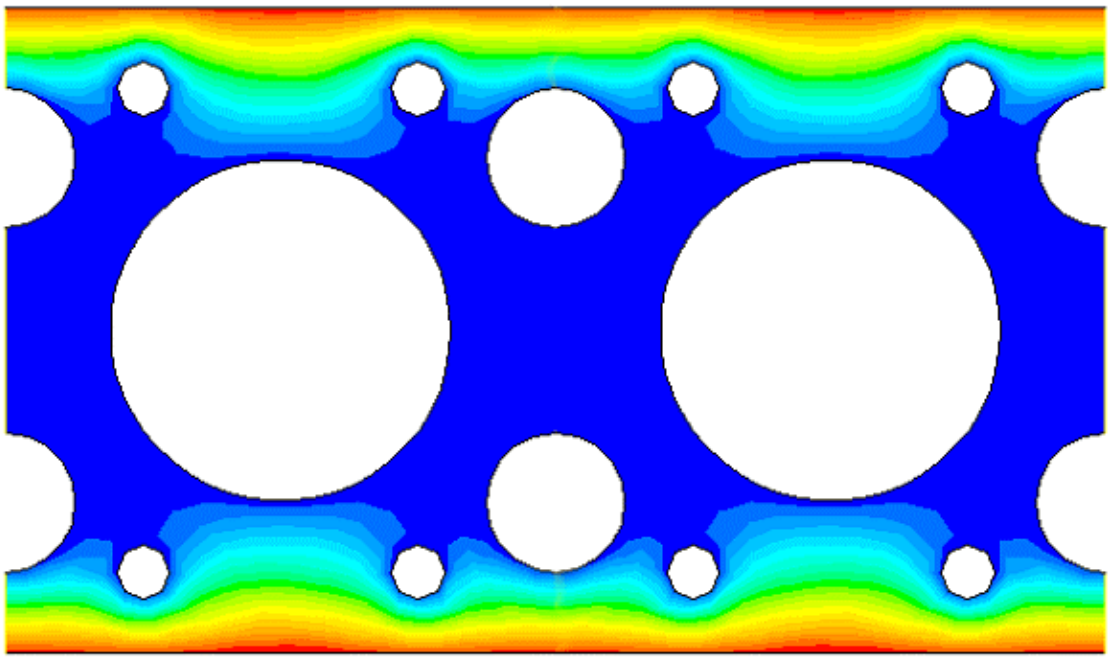
Hack's law is also correctly anticipated by Constructal Theory, which provides Hack's exponent accurately.

Melton's law is verified approximately by Constructal Theory, which indicates 2.45 instead of 2 for the Melton's exponent.

It was also shown that a constructal model of erosion can generate dendrite like patterns of low resistance channels that reproduce the typical shape of a river basin

As has been demonstrated with many other examples either from engineering or from animate structures, the development of flow architectures is governed by the Constructal Law.

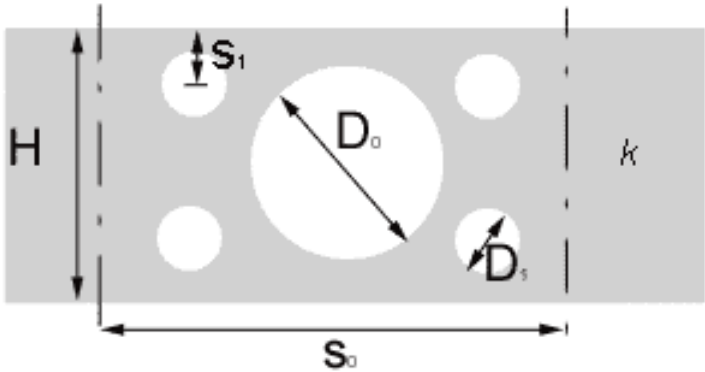
# Optimal geometry for a rectangular slab with internal convection cooling



# Initial Assumptions

- The slab thickness is prescribed
- The geometry is made dimensionless w.r.t. the slab thickness
- Some characteristic length ratios between relevant structures are also prescribed
- Additional geometrical constraints are introduced to make the model as real as possible and as close as possible to the sections of internally cooled blades
- The boundary conditions are realistic and derived from real blade cooling cases

# Slab configuration




Used relations:

$$\phi_0 = \frac{\frac{\pi}{4} * D_o^{\,2}}{S_0^2}$$

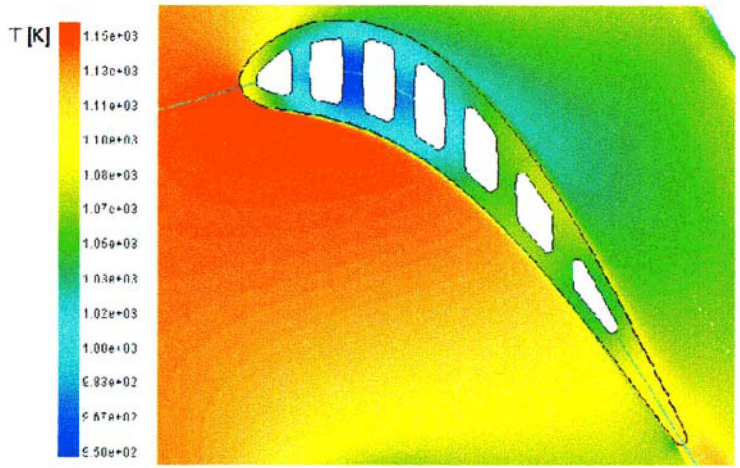
$$\phi_1 = \frac{\frac{\pi}{4} D_0^2 + 2 * \frac{\pi}{4} D_1^2}{S_0^2}$$

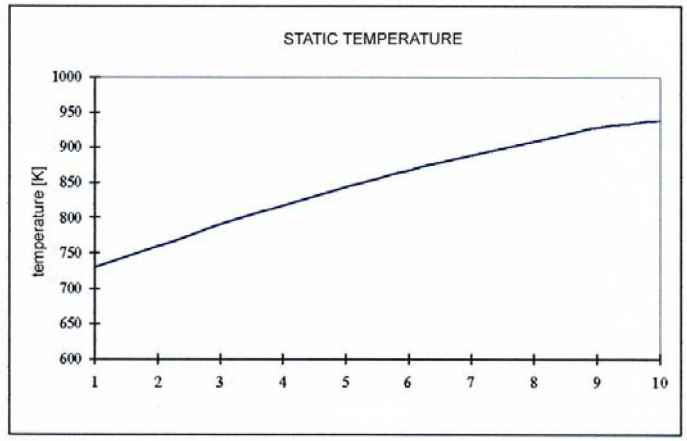
Corrected relations:

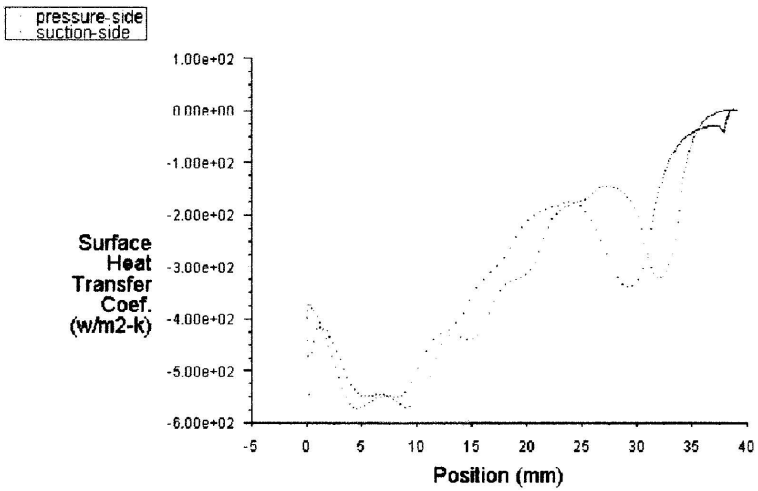
$$\phi_0 = \frac{\frac{\pi}{4} * D_o^{\,2}}{S_0 H}$$

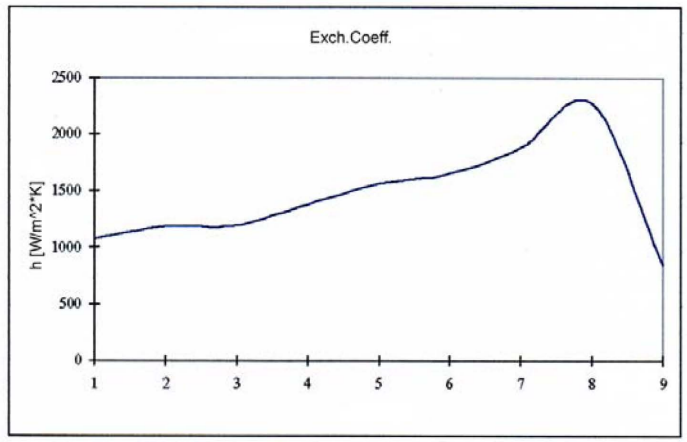
$$\phi_1 = \frac{\frac{\pi}{4} D_0^2 + 2 * \frac{\pi}{4} D_1^2}{S_0 H}$$

# Values of surface heat transfer coefficients



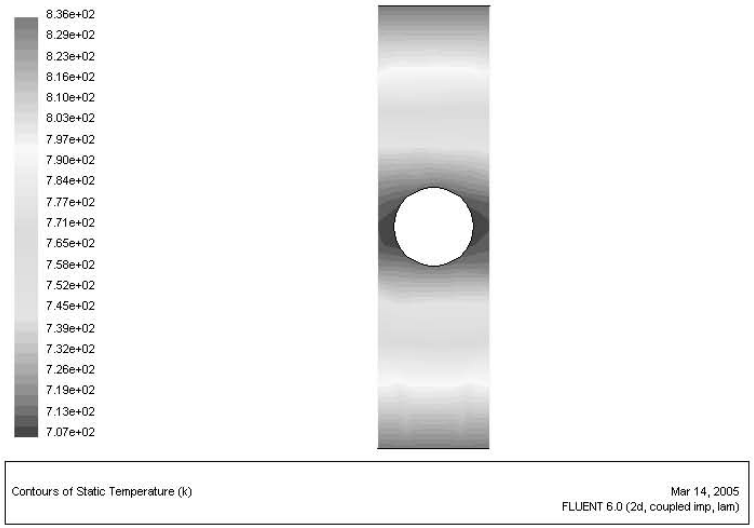



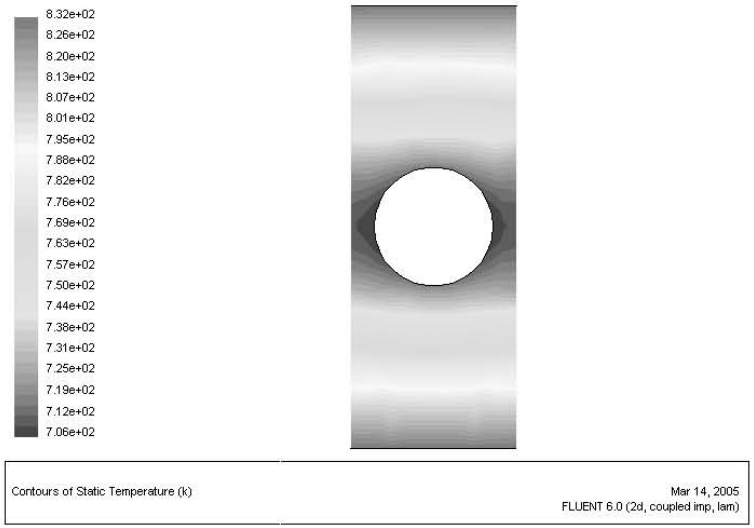



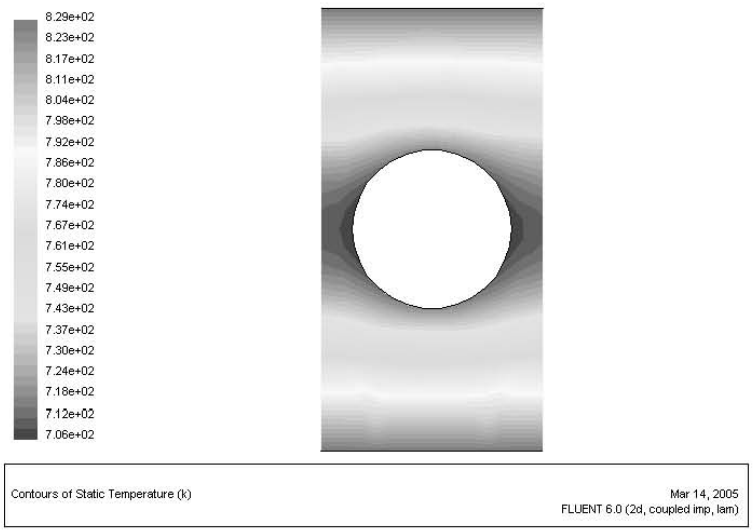
# Dimensions

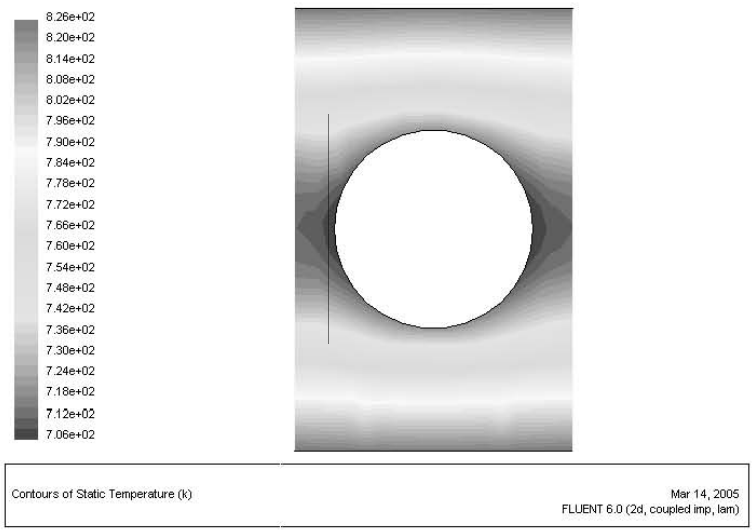
| fi1 value | fi2 value | fi3 value | Width S0 | Diameter H1 | Diameter H2 | Diameter H3 | H ext | Hint | T ext | Tint |
|---|---|---|---|---|---|---|---|---|---|---|
| 0,300 | 0,400 | 0,730 | 6,400 | 3,955 | 1,615 | 0,626 | 300,000 | 1500,000 | 900,000 | 700,000 |
| 0,300 | 0,400 | 0,730 | 12,810 | 7,916 | 3,233 | 1,252 | 300,000 | 1500,000 | 900,000 | 700,000 |
| 0,300 | 0,400 | 0,730 | 19,210 | 11,871 | 4,848 | 1,878 | 300,000 | 1500,000 | 900,000 | 700,000 |
| 0,300 | 0,400 | 0,730 | 25,620 | 15,833 | 6,466 | 2,504 | 300,000 | 1500,000 | 900,000 | 700,000 |

# First level holes

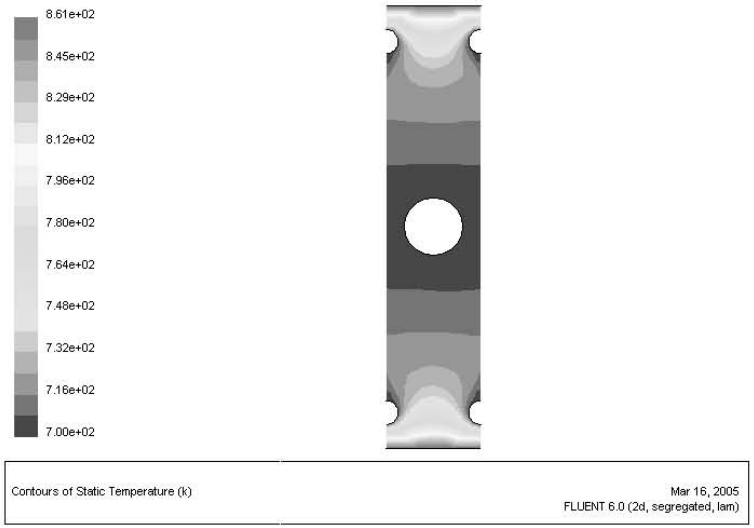


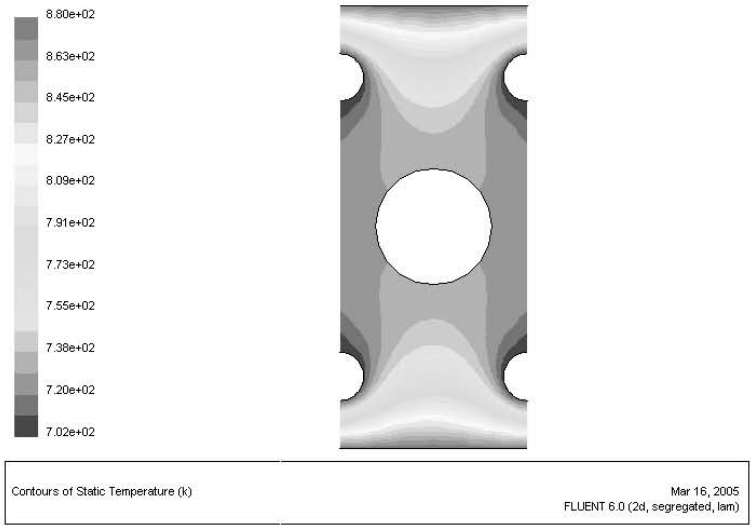



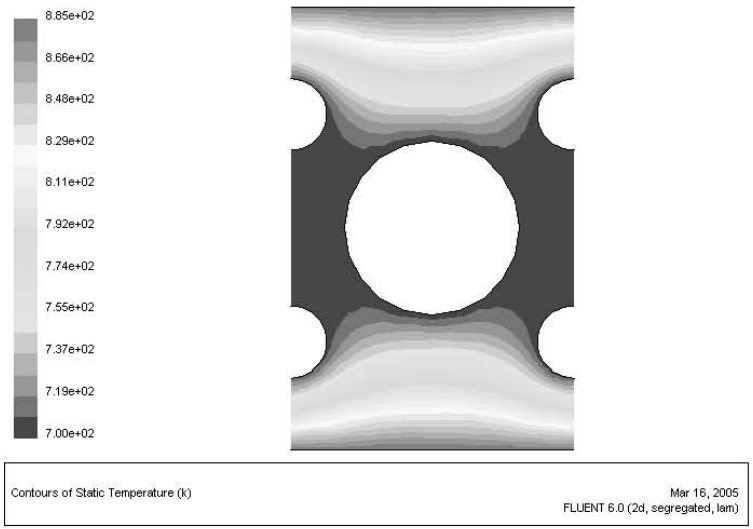



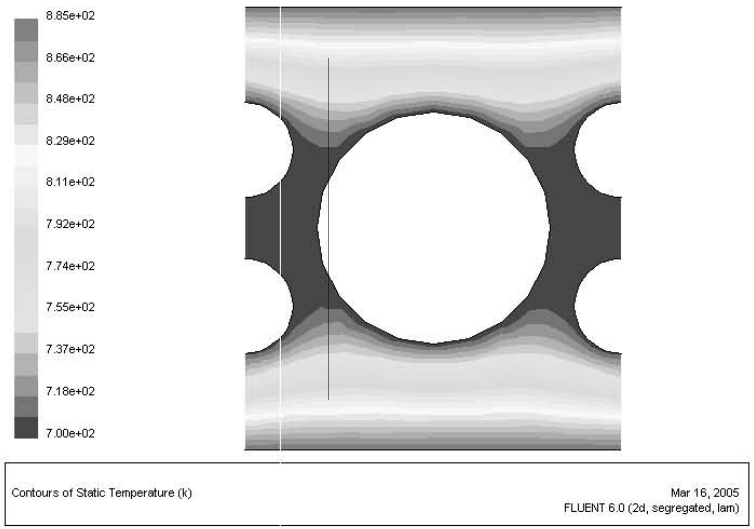



# Second level holes

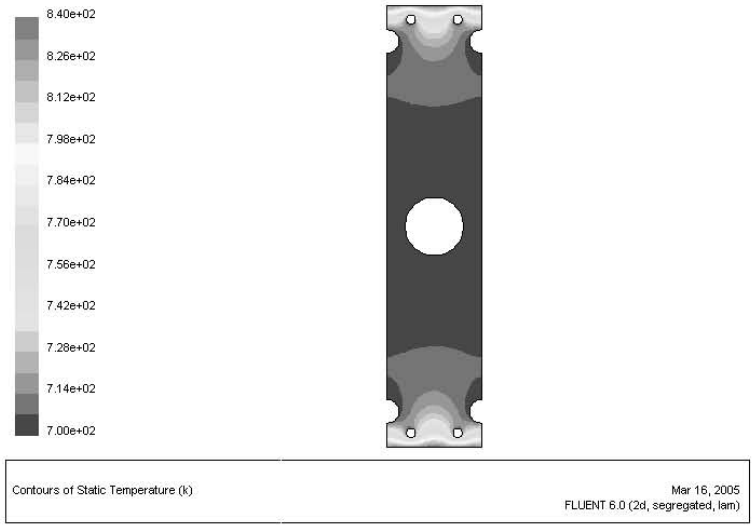


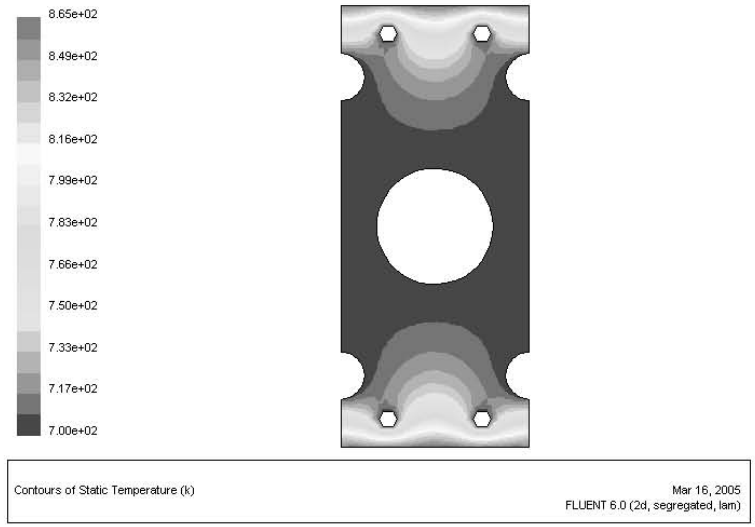



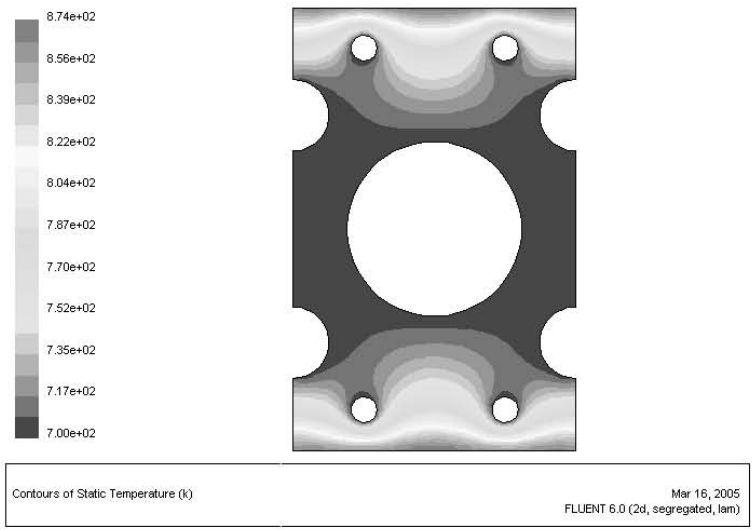



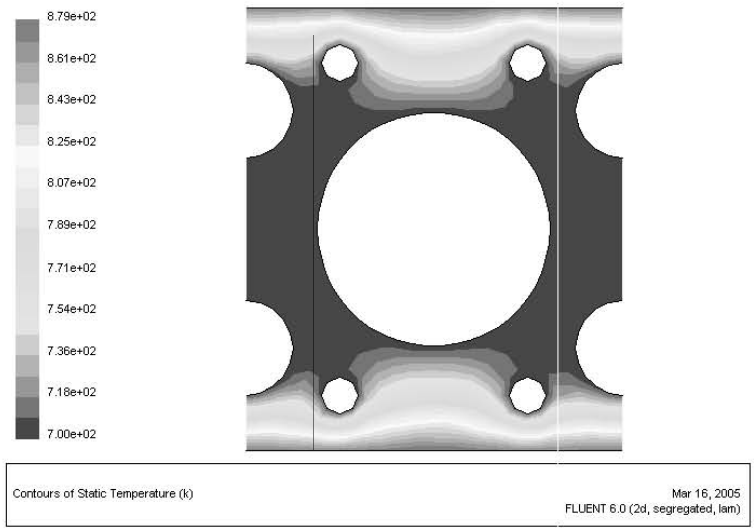



# Third level holes

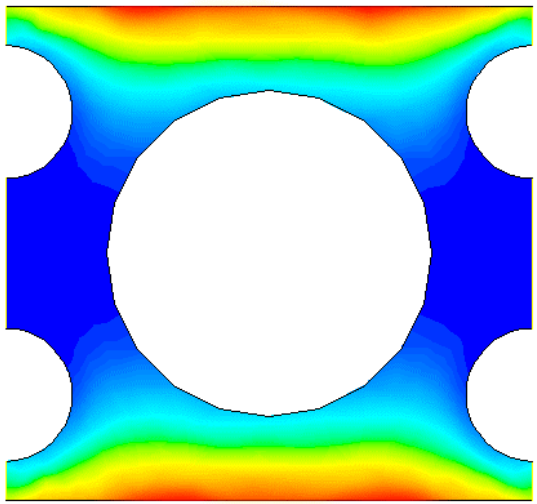


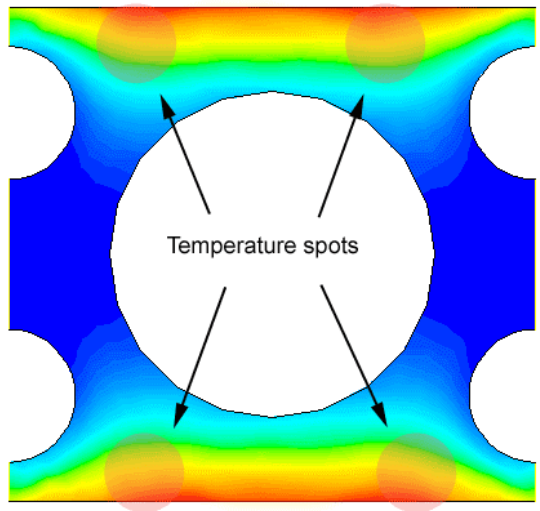



# Position of high-temperature spots





# The position of the hots spots is determined by:

- The relative ratios of the heat transfer coefficients of different tubes
- The distance of the smallest tubes from the slab surface

# Next steps

- 3d case
- Entry lenght analysis
- Different heat transfer values for different holes diameters

Constructal Workshop, 17-18 March 2005, Rome

# Performance Improvement of Tubular Solid Oxide Fuel Cell Stack through Variation of its Configuration Design

Michele Calì, Chiara Ciano, Vittorio Verda
Politecnico di Torino – Dipartimento di Energetica

# SOFC

Some advantages of Solid Oxide Fuel Cell

- high efficiency,
- low NOx production,
- possible direct use of methane by operating an internal reforming,
- possibility of using SOFC in combination with bottoming cycles

This research aims at studying the configuration of the system integrating cells and internal reformers, by changing the cells geometry and disposition.

# From a single cell to a bundle

A model accounting for thermal and electrochemical phenomena in a single cell

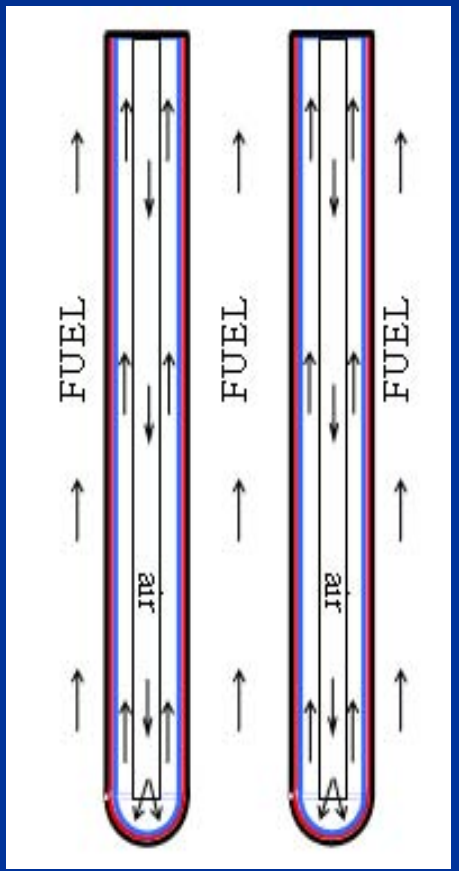
- ✓to calculate the performances of the cell for varyed boundary conditions
- ✓to evaluate the effects produced by varying geometrical data, particularly the cell length.

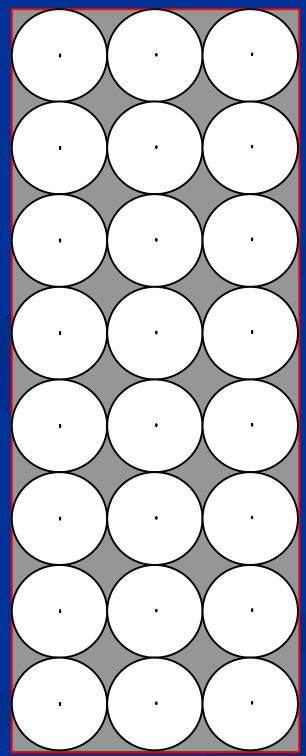
A network approach to compute a bundle

- ✓accounting for the electrical connections among the cells and the energy transfers inside the bundle and with the extern
- ✓to show how the system evolve varying the shape of the bundle and the number and length of the cells.

# System configuration

Three-in-parallel by eigth-in-series cell bundles



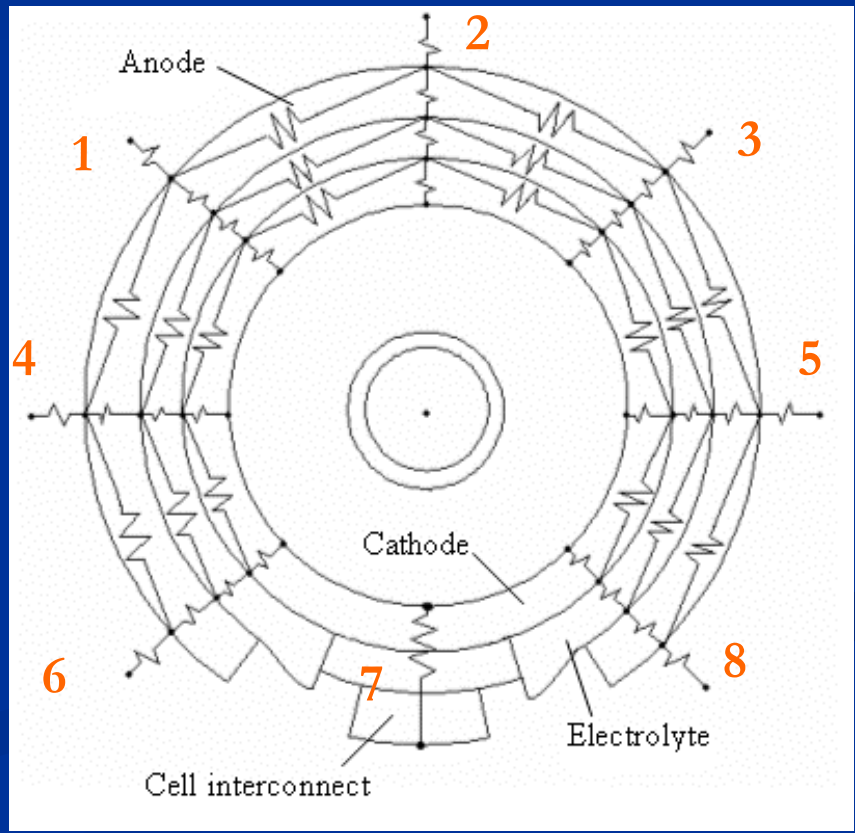
# Electrochemical model

Each cell is represented as divided into resistances connected in series and in parallel.

The fuel feeding the cell flows for each layer of nodes in branches 1, 3, 6 and 8.

Branches 2 and 7 are the electrical connections.

By branches 4 and 5 the cell results electrically isolated from those beside it.



$\Delta V_{cell} = \Delta V_N - \eta_\Omega - \eta_{act} - \eta_{conc}$

# Electrochemical model

The model accounts for ohmic, activation and concentration resistances.

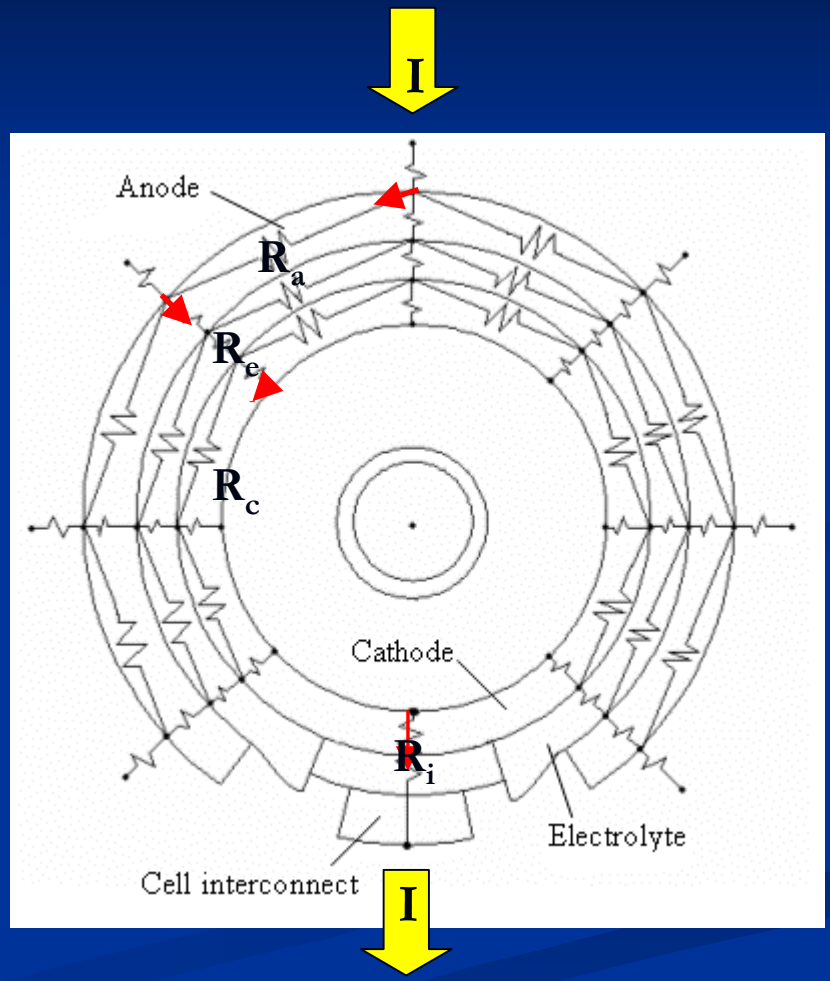
$$\Delta V_{cell} = \Delta V_N - \eta_\Omega - \eta_{act} - \eta_{conc}$$

$$\eta_{ohm} = R \cdot I$$

$$\eta_{act} = \frac{2RT}{n_e F} \cdot \sinh^{-1}\left(\frac{i}{i_e}\right)$$

$$\eta_{concA} = \frac{-RT}{2F} \cdot \ln\left(1 - \frac{i}{i_{Al}}\right) + \frac{RT}{2F} \cdot \ln\left(1 + \frac{i}{i_{Al}} \cdot \frac{p_{H_2}}{p_{H_2O}}\right)$$

$$\eta_{concC} = \frac{-RT}{4F} \cdot \ln\left(1 - \frac{i}{i_{Cl}}\right)$$



$\Delta V_{cell} = \Delta V_N - \eta_\Omega - \eta_{act} - \eta_{conc}$

# Thermal model

Thermal flows are generated inside the cell both by **voltage losses** and the **electrochemical reaction** that takes place at the anode-electrolyte interface.

This reaction, consisting in the oxidation of hydrogen and carbon monoxide, is the cause of the electromotive force E:

$$E = \frac{-\Delta G}{F} = \frac{-\Delta G^\circ}{F} + \frac{RT}{2F} \cdot \ln\left( \frac{p_{H_2} \cdot p_{O_2}{}^{0.5}}{p_{H_2O}} \right)$$

$\Delta V_{cell} = \Delta V_N - \eta_\Omega - \eta_{act} - \eta_{conc}$

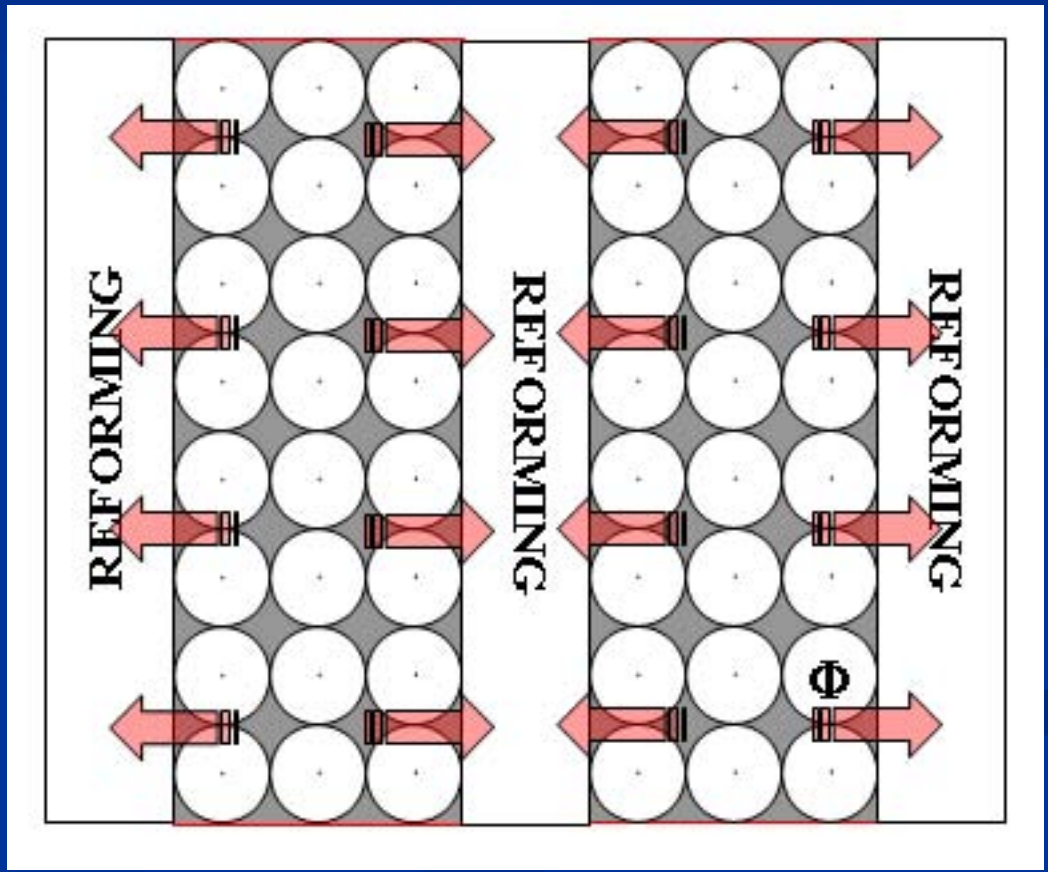
# Thermal model

Heat is partially supplied to the reformers, where it is required for methane to produce hydrogen and carbon monoxide.

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

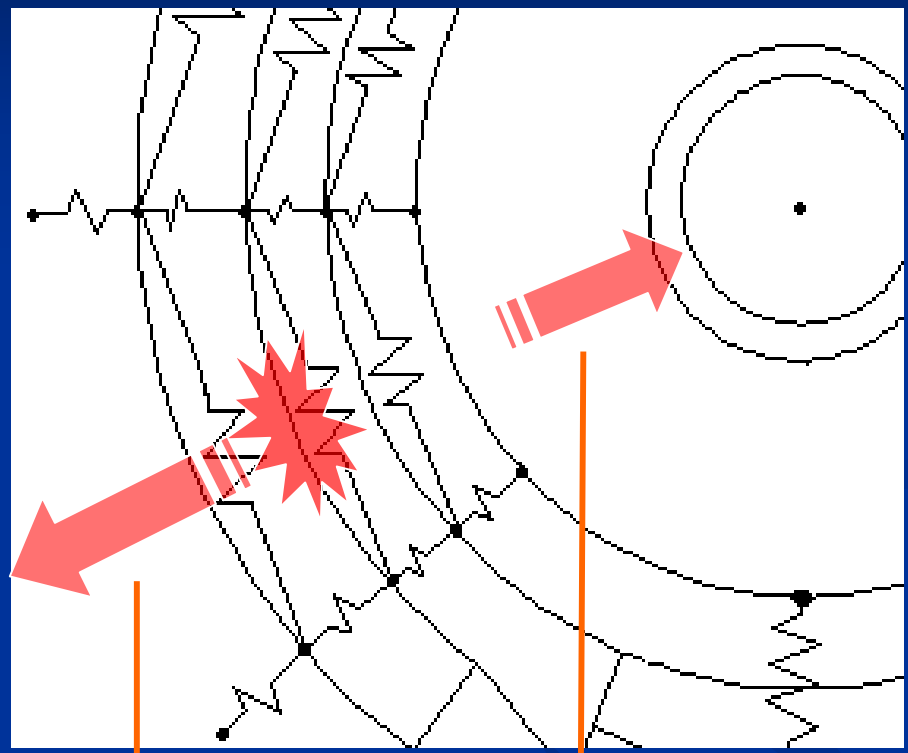
$$CO + H_2O \rightarrow H_2 + CO_2$$

In actual design, reformers are located between the bundles.



# Thermal model

A part of the thermal flow released in the elctrochemical reaction is recuperated by heating the air flux flowing in the annular section.



To reformer

To inlet air

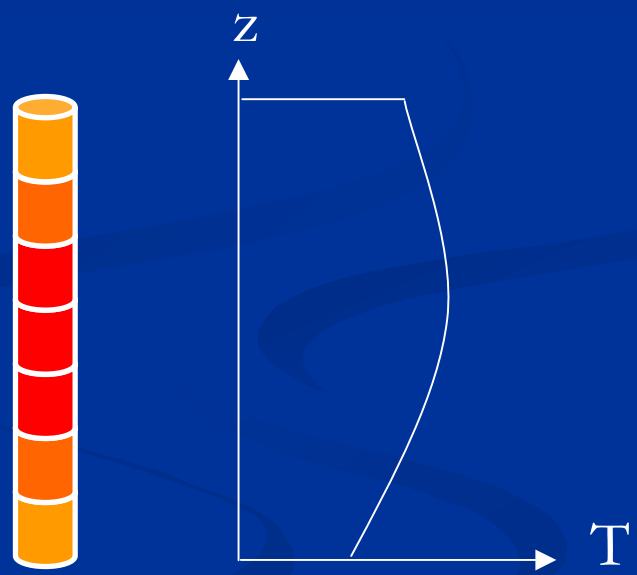
# Resistivity

Electronic and ionic resistivities depend on the local temperature.

$$\rho_A = 0.00298 \cdot \exp\left(\frac{-1392}{T}\right)$$

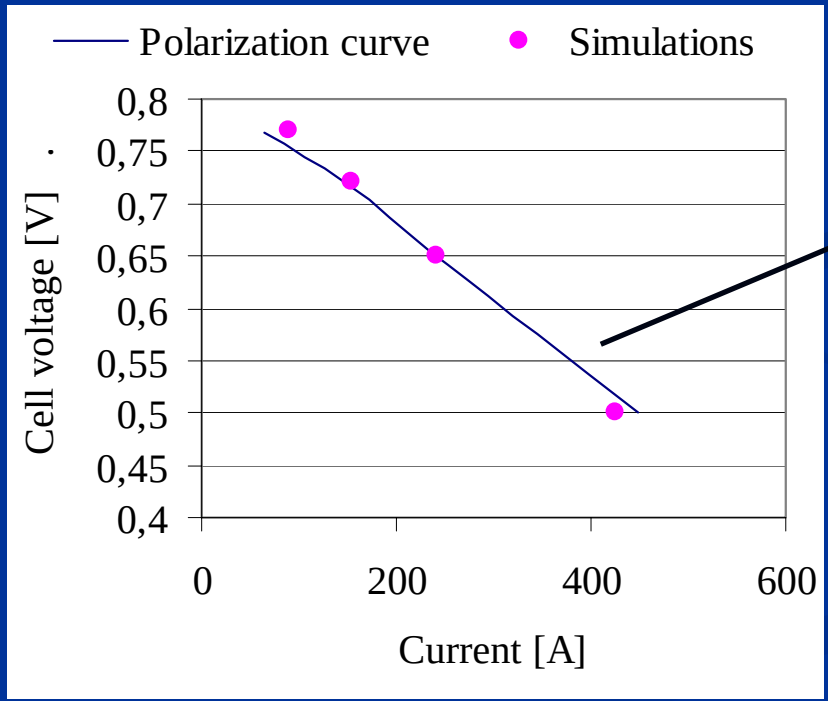
$$\rho_E = 10 \cdot \exp\left[10092 \cdot \left(\frac{1}{T} - \frac{1}{1273.15}\right)\right]$$

$$\rho_C = 0.008114 \cdot \exp\left(\frac{500}{T}\right)$$



# Cell simulation

Single cell simulation
(Operating temperature ~ 900 °C)




DOE, FC Handbook (2002)

Boundary conditions:

- DV bundle = Design DV cell (0.72 V) · Number of cells in series
- Fuel temperature (550 °C)
- Air temperature (830 °C)
- Heat flow for internal reforming (30% of the requirement)

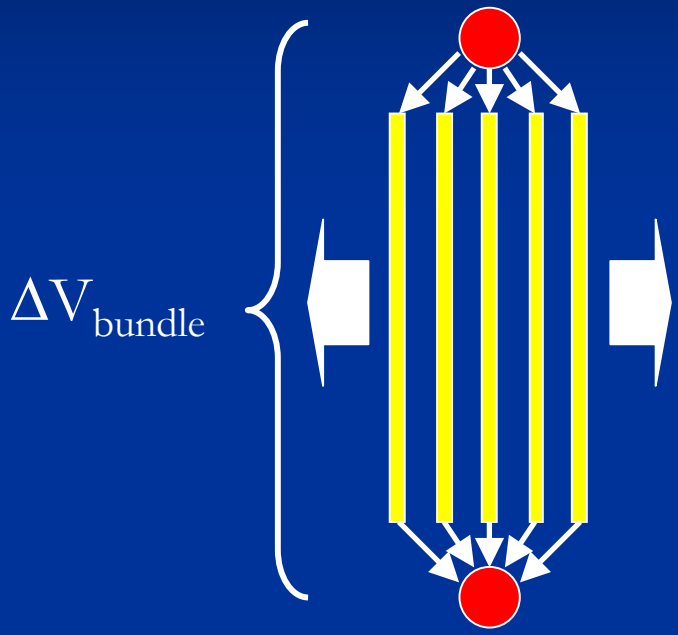
Present design parameters:

- Bundle shape
- Cell length

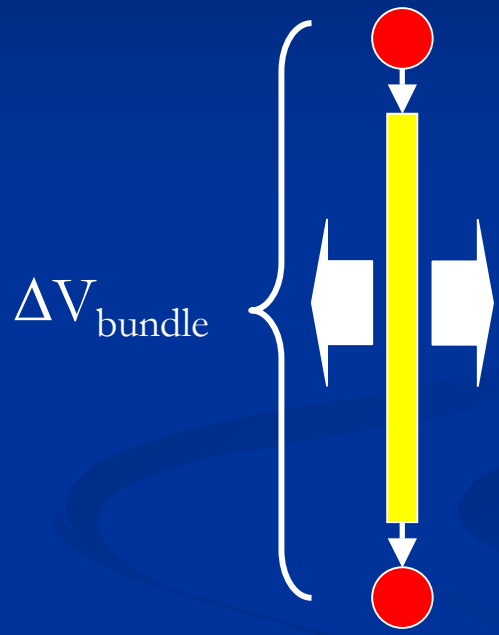
Constraints:

- Total active area
- Anode, cathode and electrolyte thickness

# From constructal theory



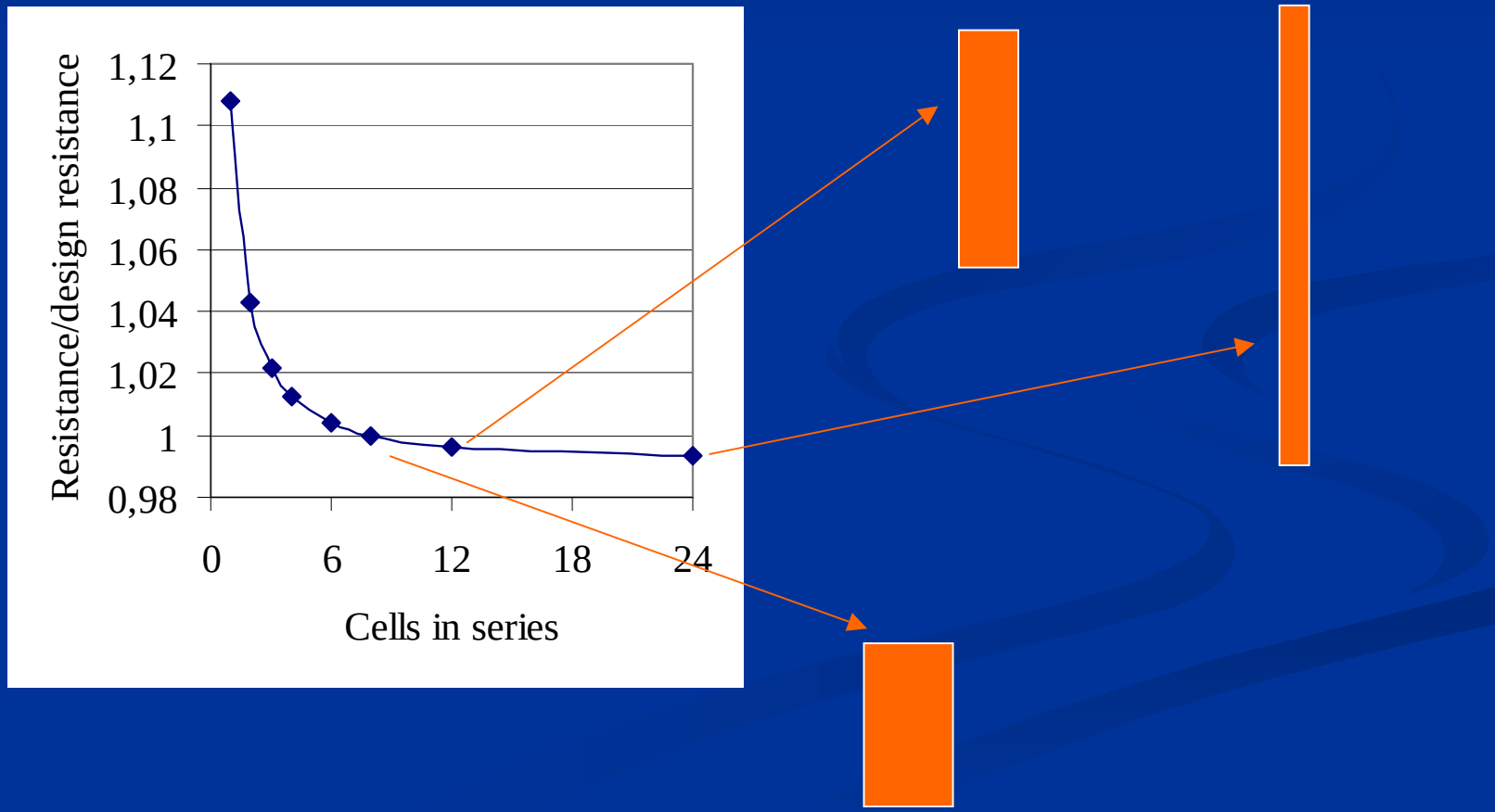

Actual design




Optimal shape

# Electronic/ionic resistance

Overall resistance decreases as the number of cells in series increases.



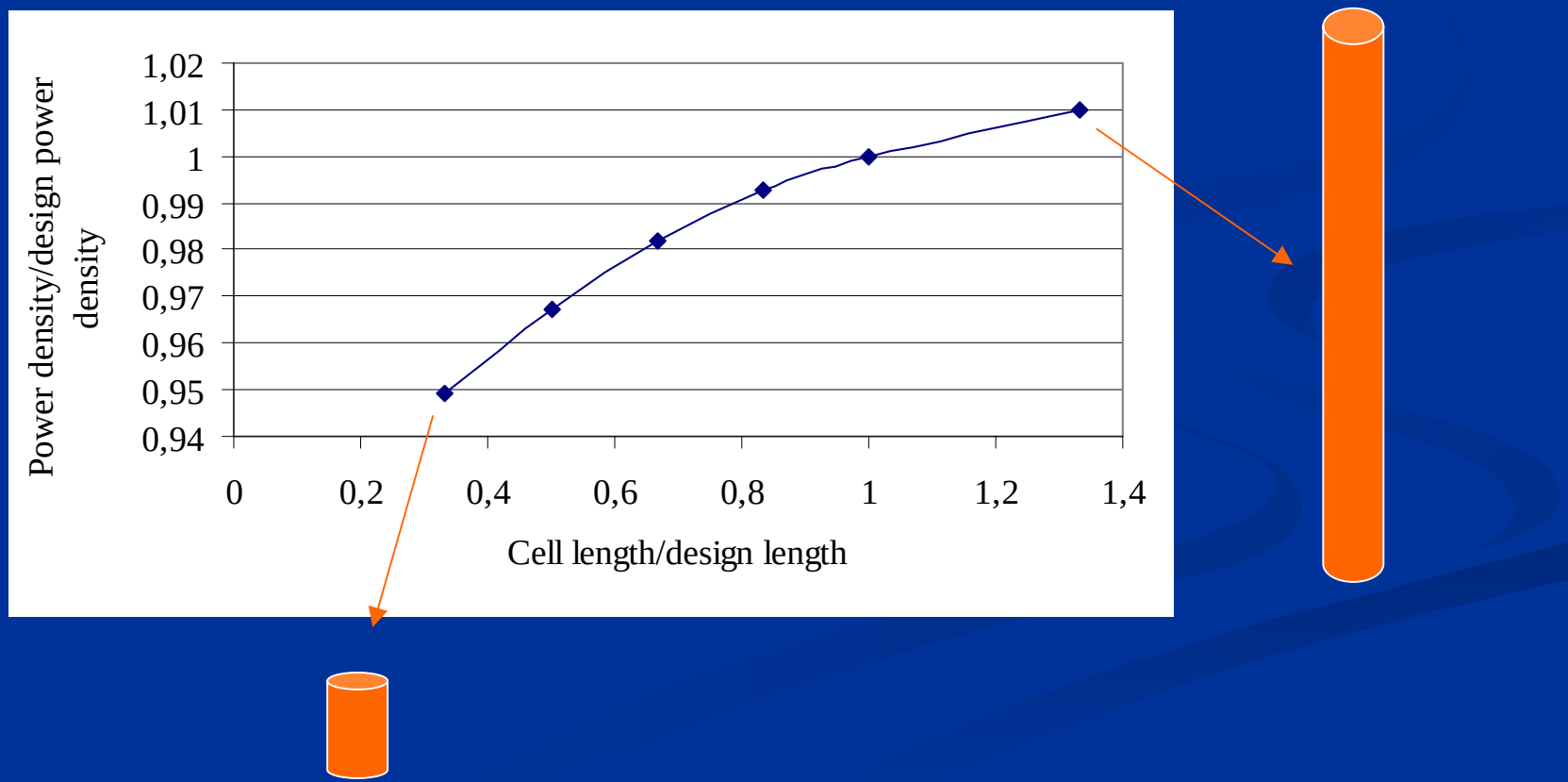
# Present and future work

Geometrical parameters investigated/under investigation:

- Cell length ✓
- Cell length and diameter
- Cell shape

# Present work

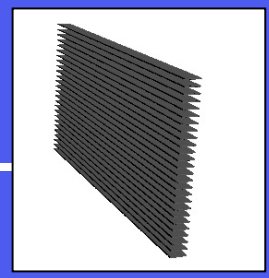
The voltage losses decreases as the cell length increases (design voltage)

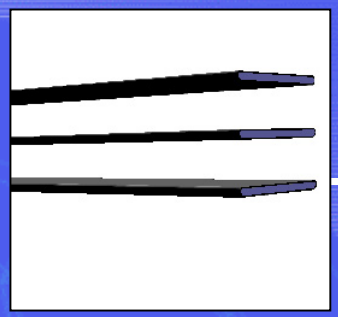


# Numerical simulations of the fluid & heat flow in disc-shaped compact heat echangers with dendritic flow structure

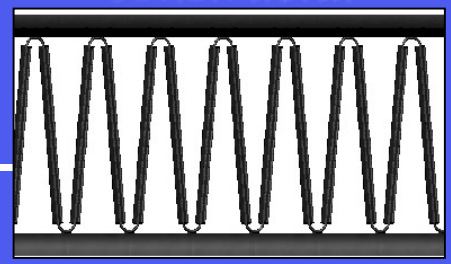
# Compact heat exchangers: rectangular box actual geometries multi-level refinement

Global geometry

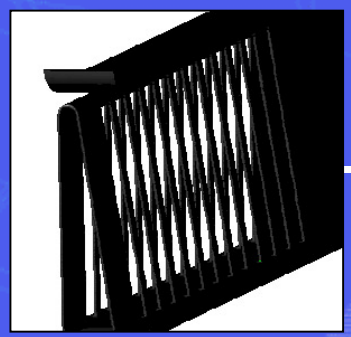




Tubes stage



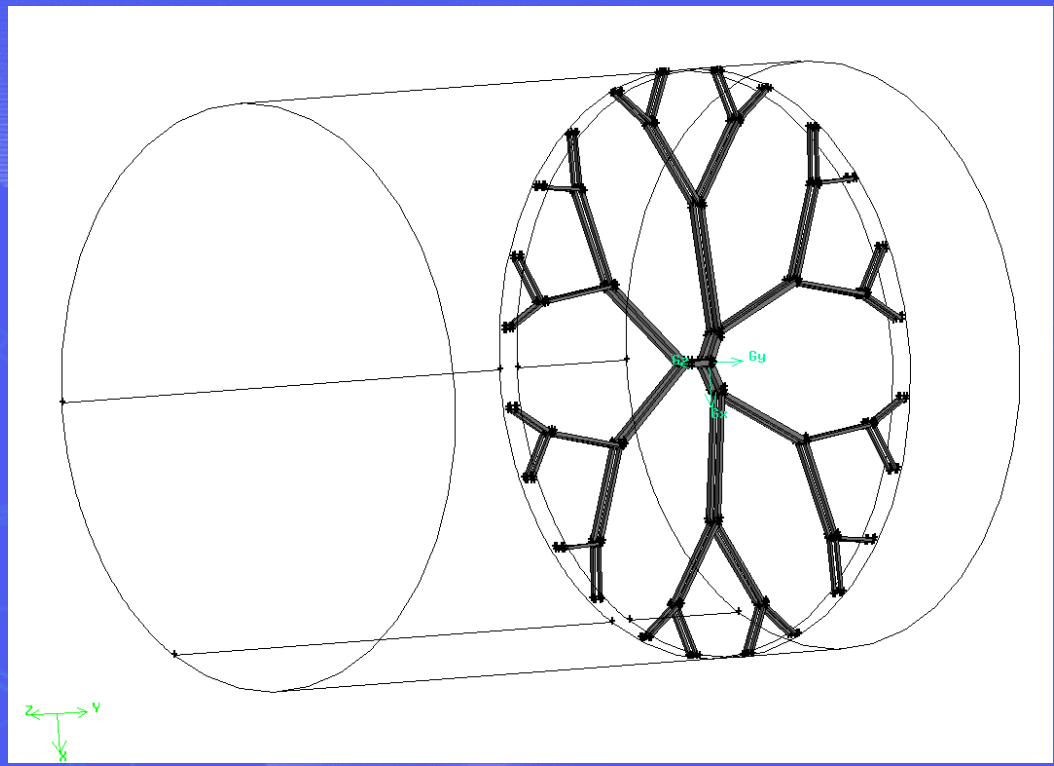
Fin stage



Louver stage

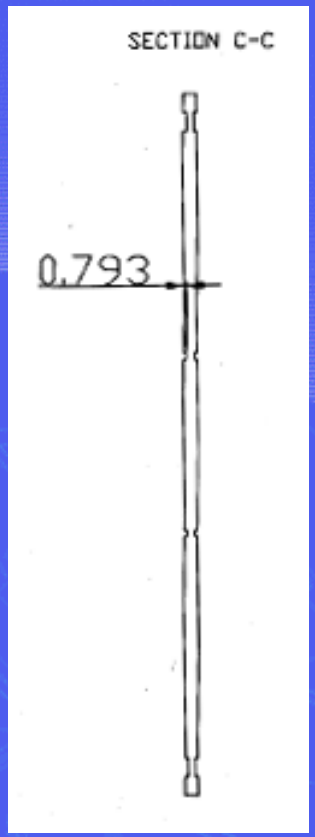
# Constructal compact heat exchanger

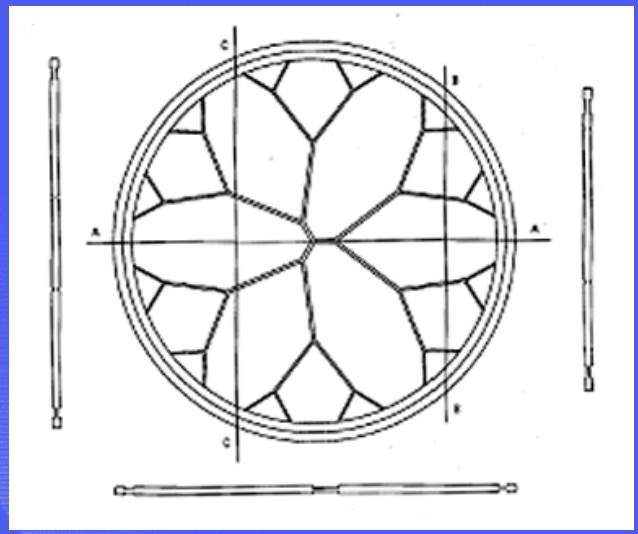


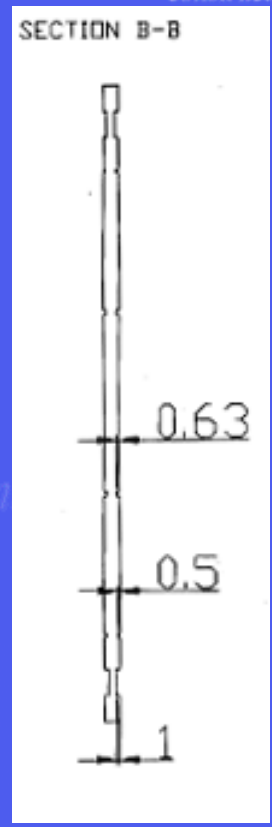


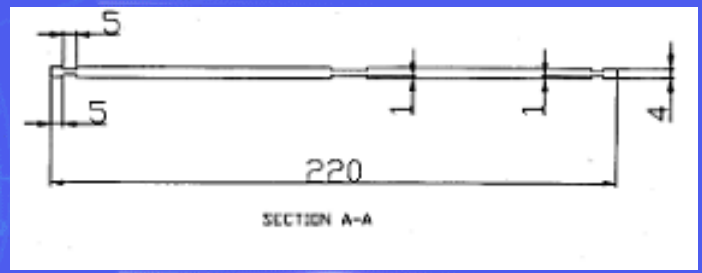

*A.Bejan*

# four levels disc dimensions (mm) 1/2

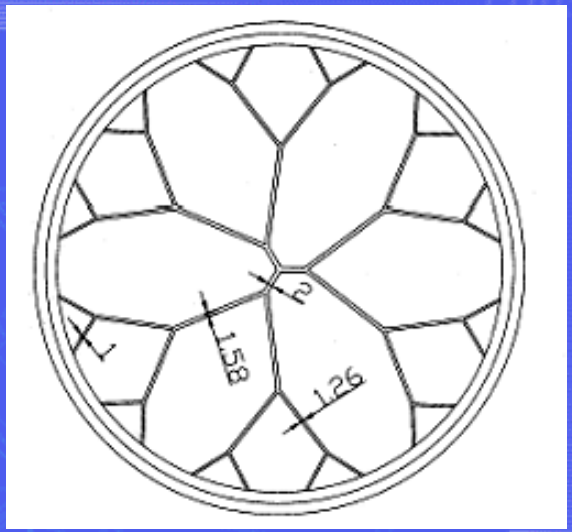


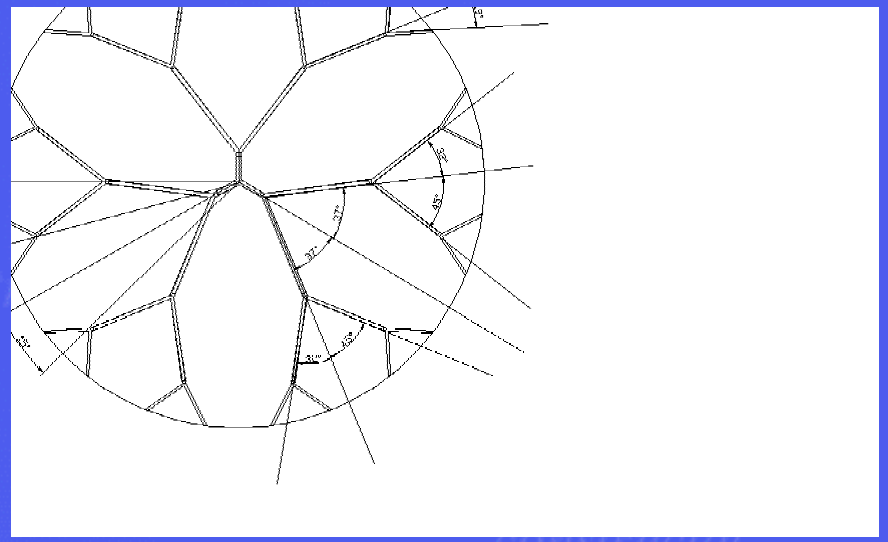



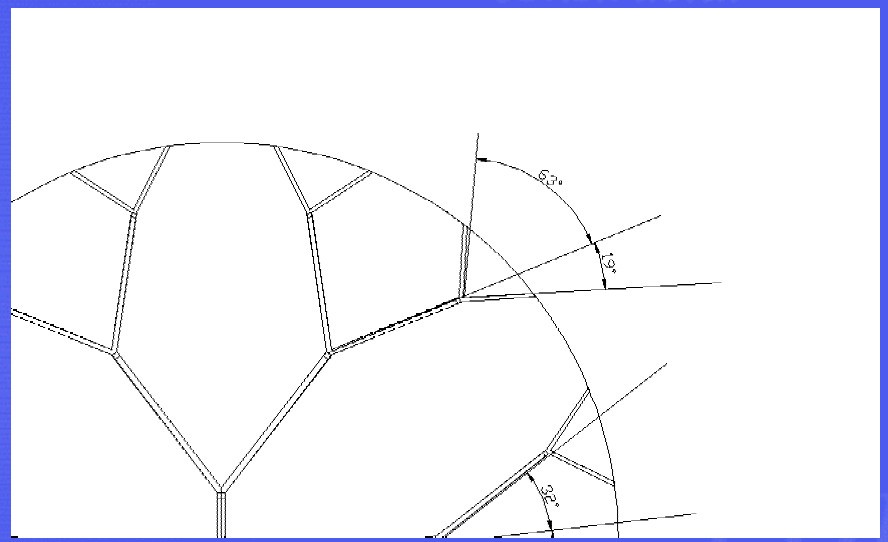


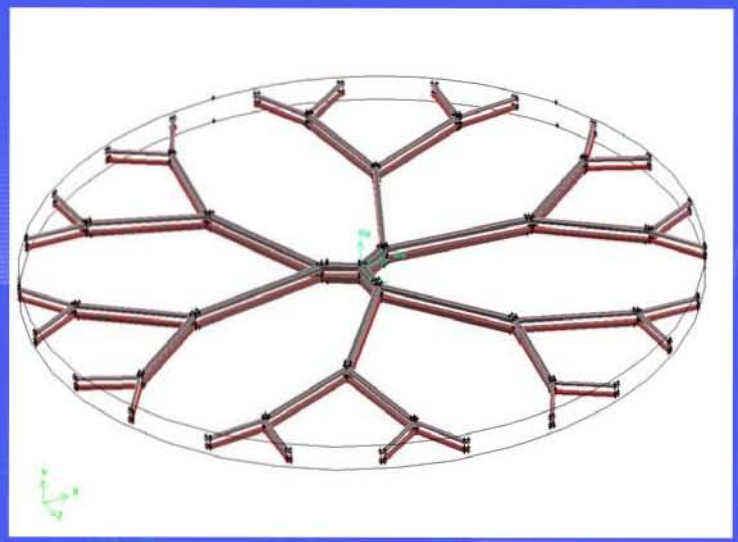
# Disc dimensions 2/2

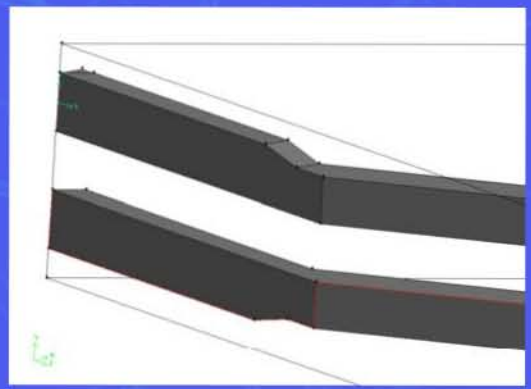


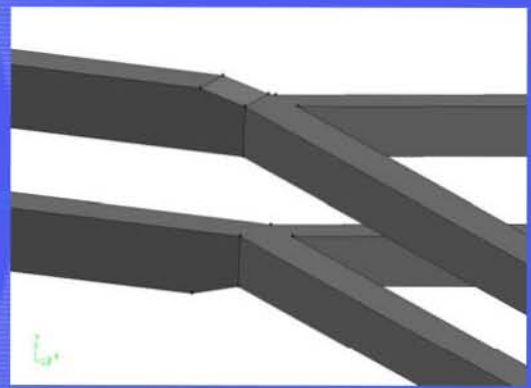



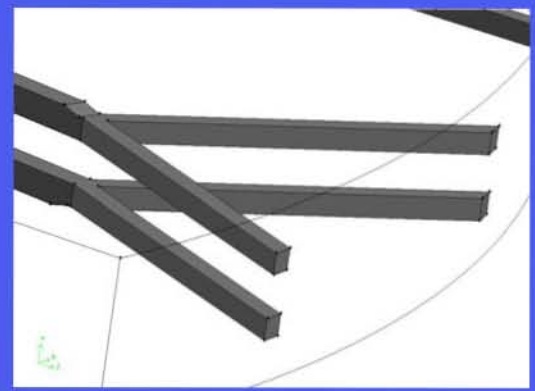


# Disc-shaped constructal compact heat exchangers model





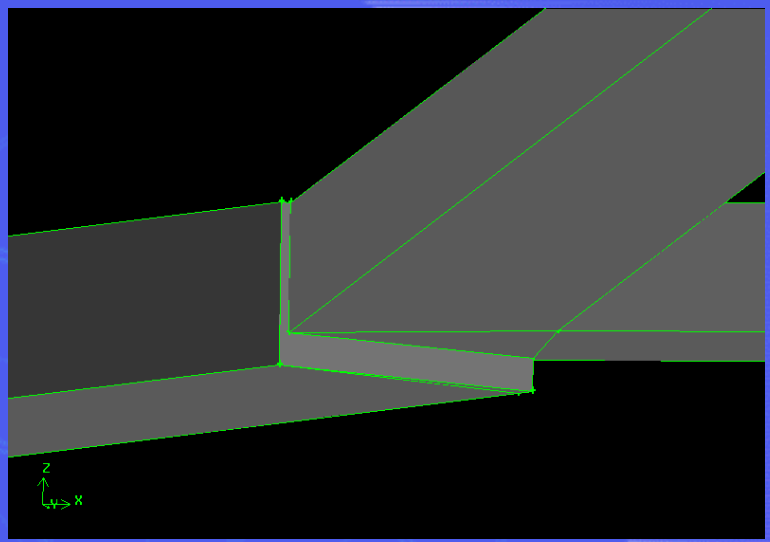




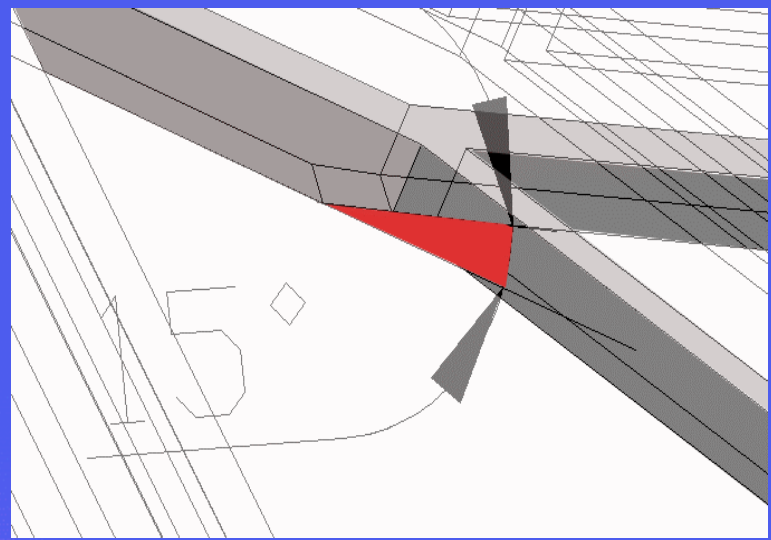
# Model improvement and CAD simplifications

constructal

Discontinuities simplifications



Angles smoothed at the junctions (15°)



# Implications of the modification introduced

- Increased pressure drop for square sections

$$\lambda_{rect}=K_1\lambda$$

($K_1=0.9$)

- Reduced pressure drops for smoothed junctions

$$\zeta=\zeta'(1-F_0/F_1)$$

# Boundary and Initial conditions

Fluid: WATER

Outflow

Pressure inlet=p0+2500Pa

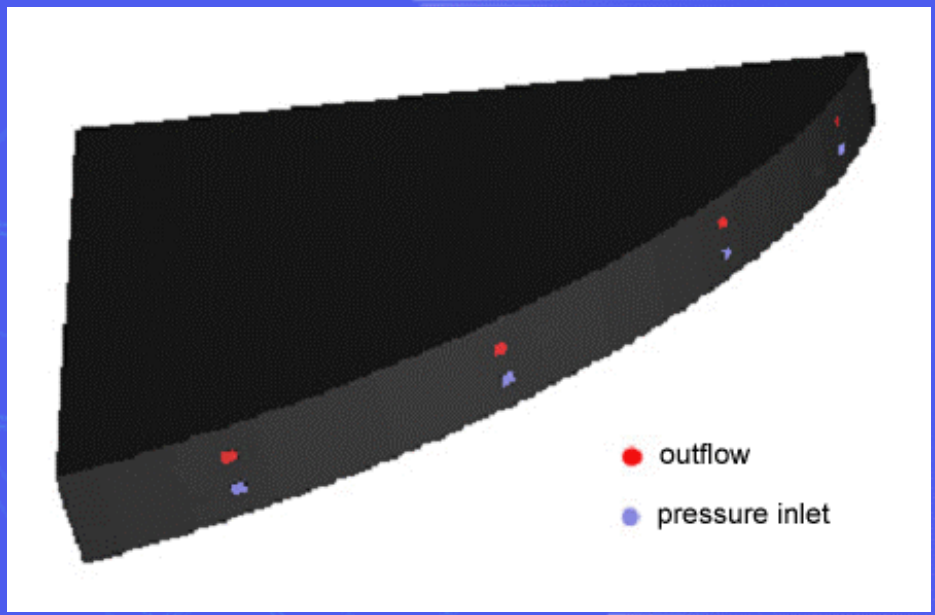
Pressure outlet=p0

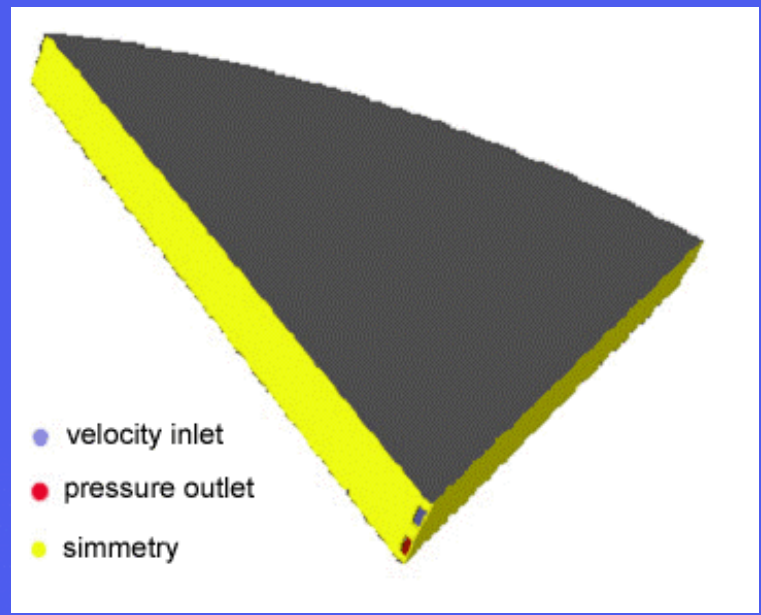
Disc material: ALUMINIUM

Inlet water Temperature=300°K

Inlet hot water temperature 370 °K

Velocity inlet=1m/s

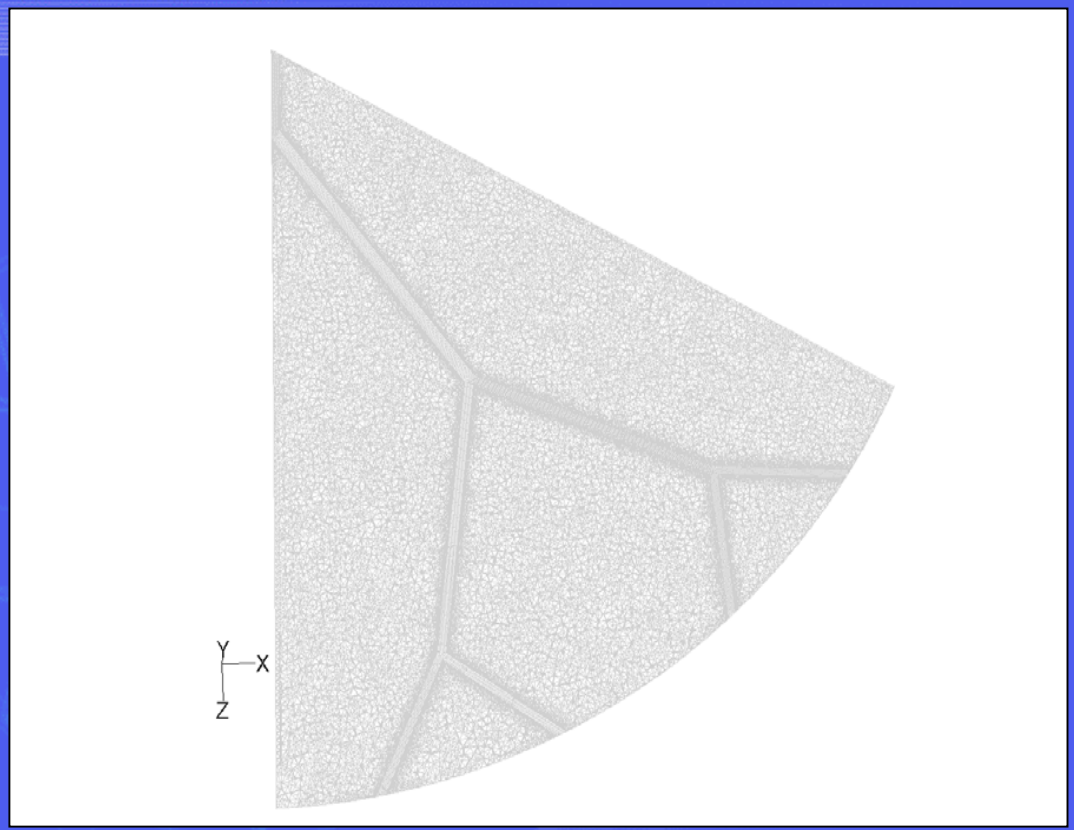


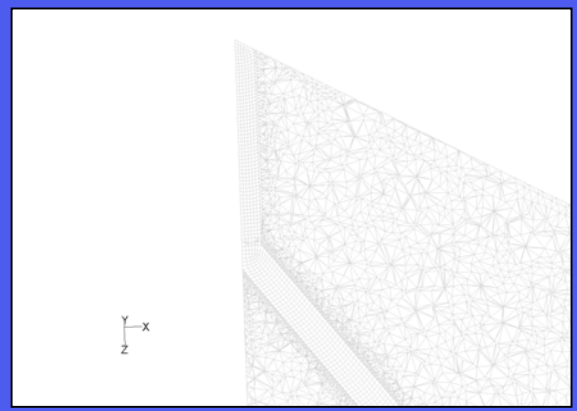



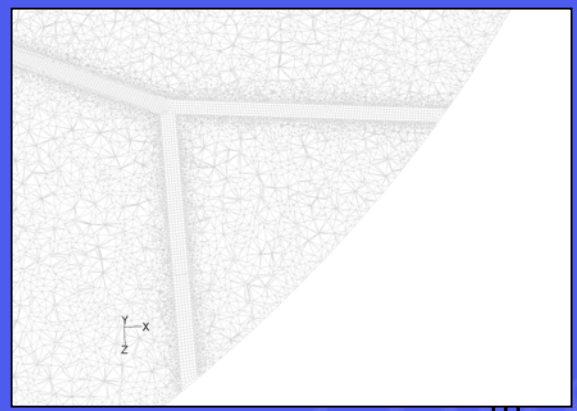
# Grid Description

**Non conformal hybrid mesh:**
**Fluid cells: Hexahedra (62900+62890) – solid cells: tetrahedra**

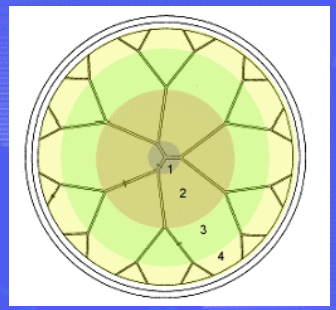
| Level | Cells | Faces | Nodes | Partitions |
|---|---|---|---|---|
| 0 | 1539373 | 3326935 | 450871 | 1 |



# Values of Reynolds numbers at each level




| | |
|---|---|
| Level 0 | 2548 |
| Level 1 | 2013 |
| Level 2 | 1605 |
| Level 3 | 1274 |

# Numerical model details

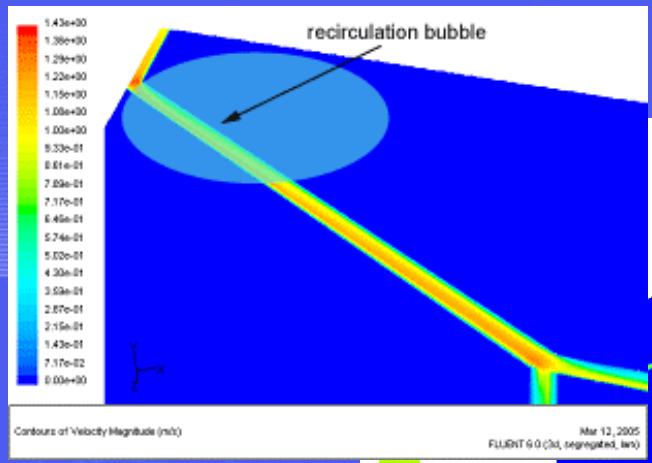
Solver: segregated

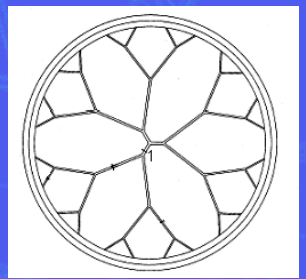
Time: steady

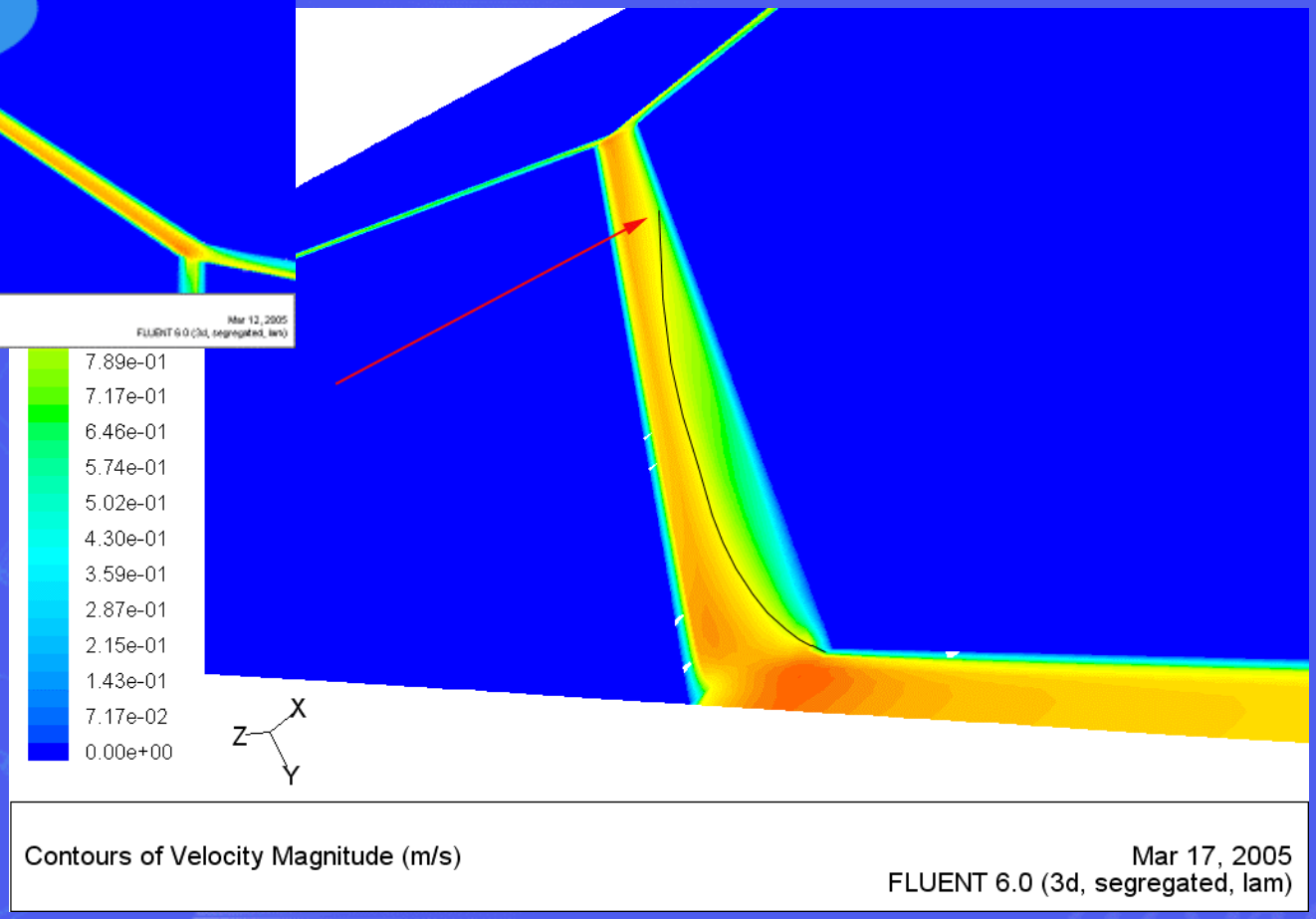
Viscous model: laminar

# Velocity profiles - level 0 – In->out



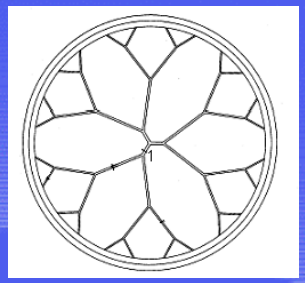


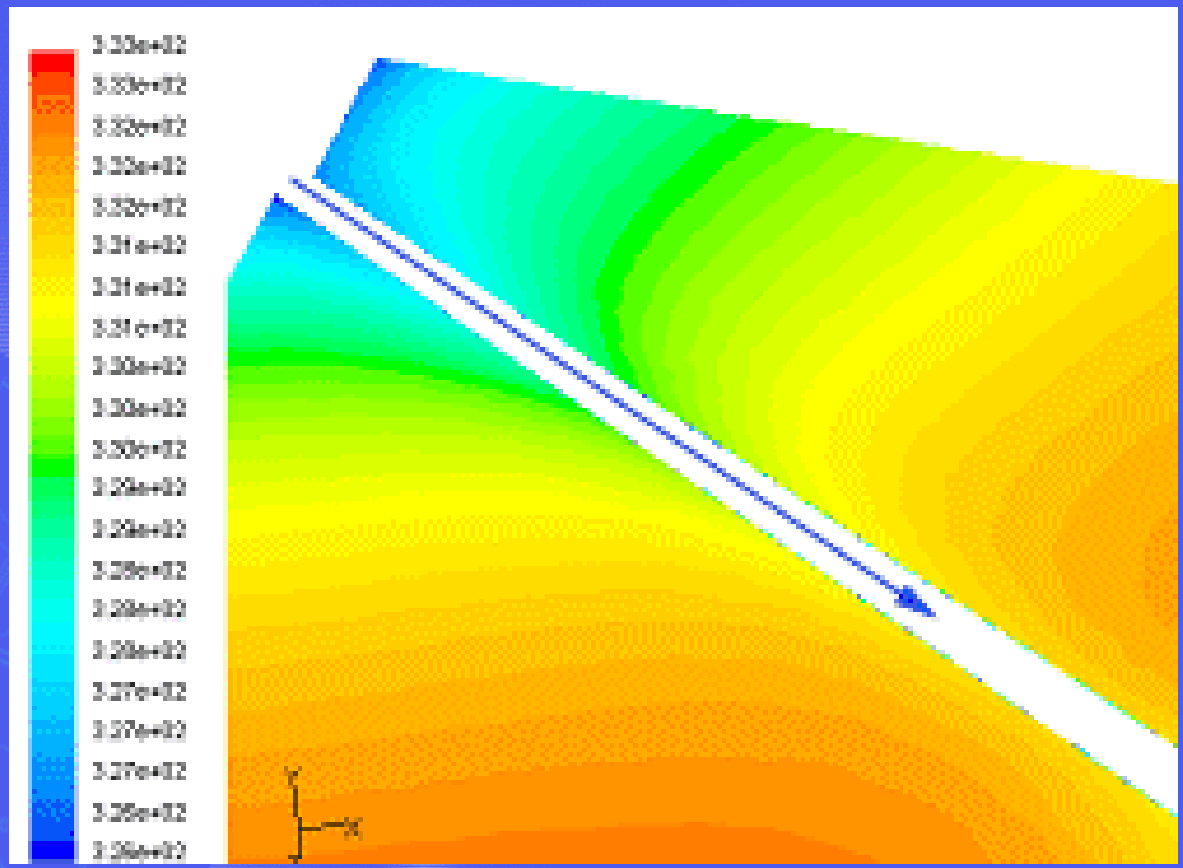





# Temperature profiles – level 0 – In->out

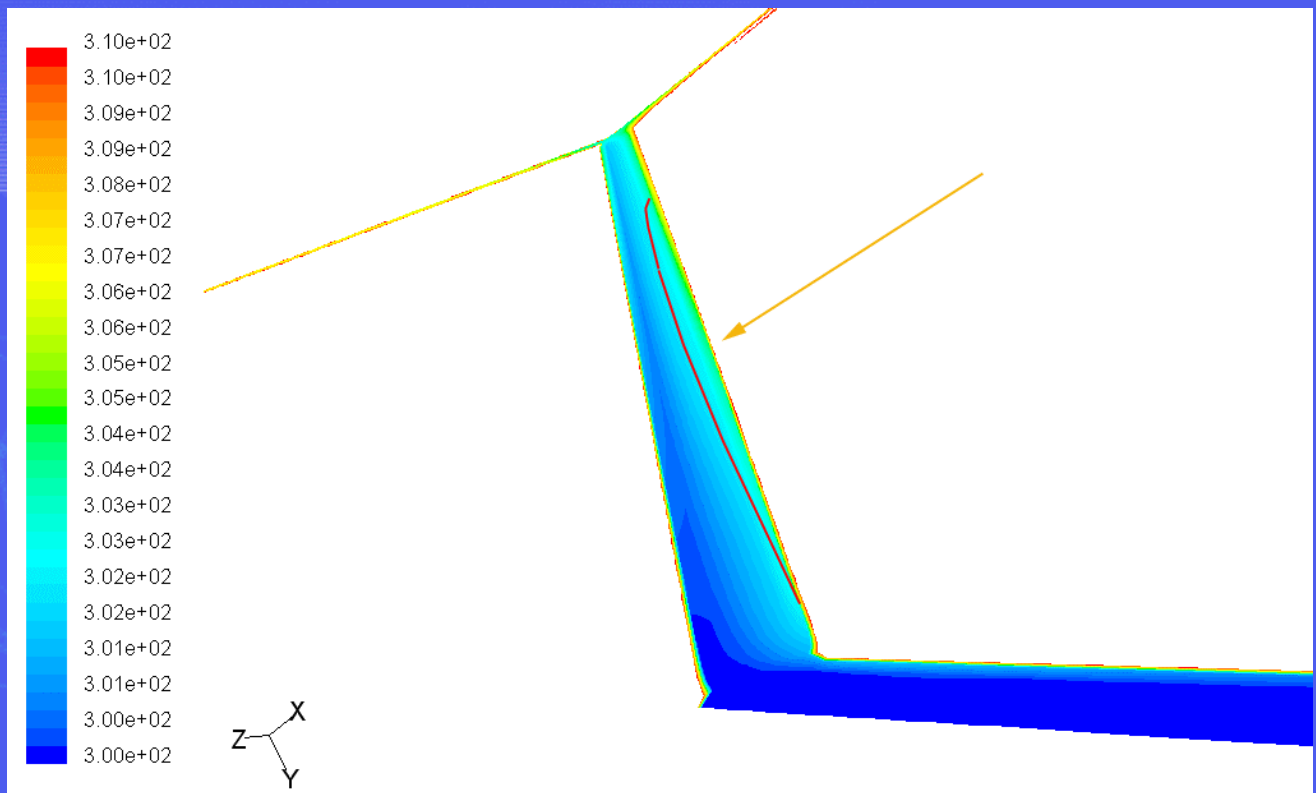




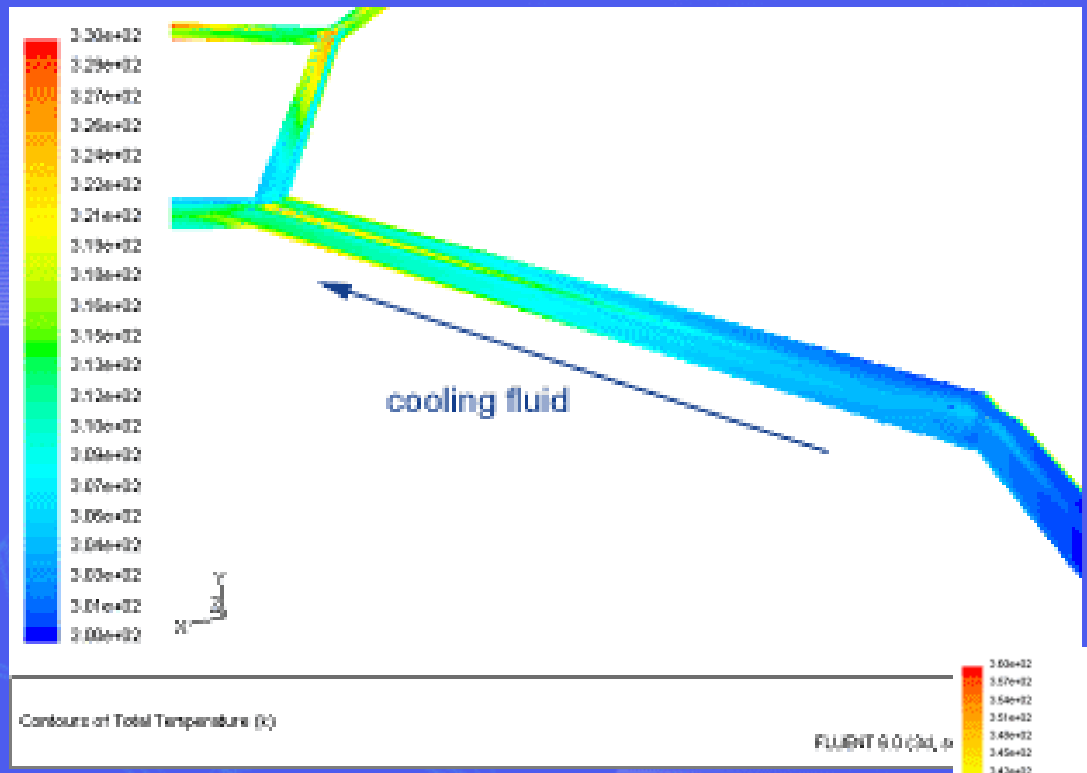


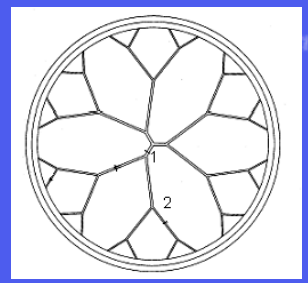
# Zoom on the recirculation bubble (temperature)

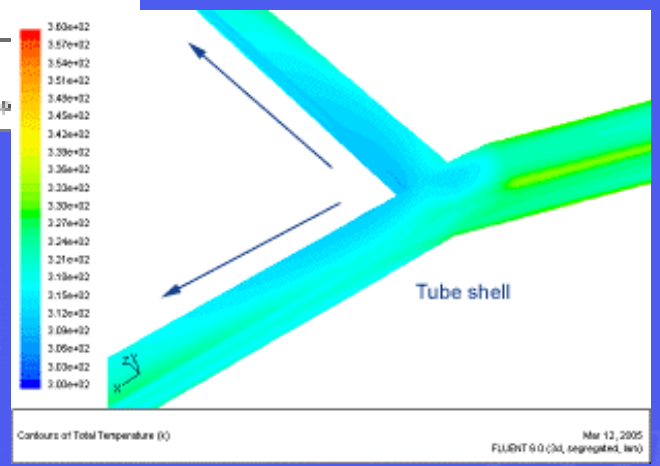


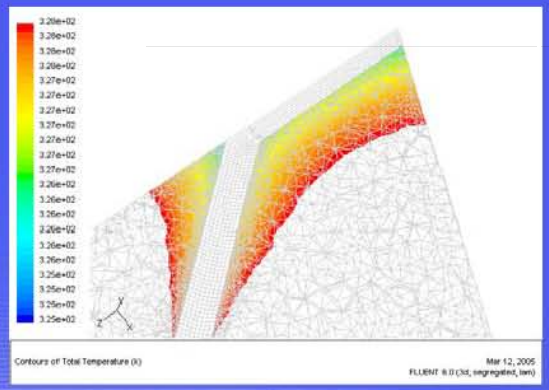


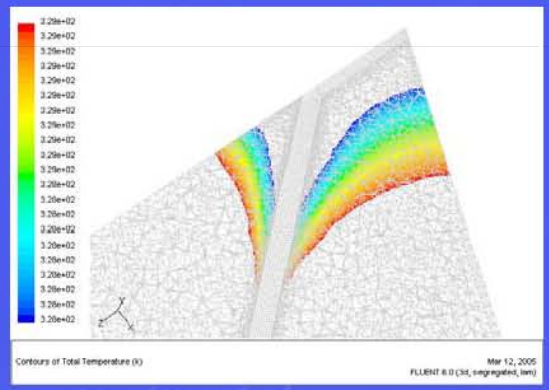
# Temperature profiles – level 0 – In->out

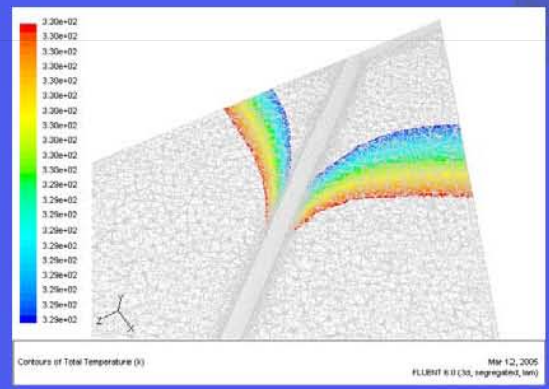


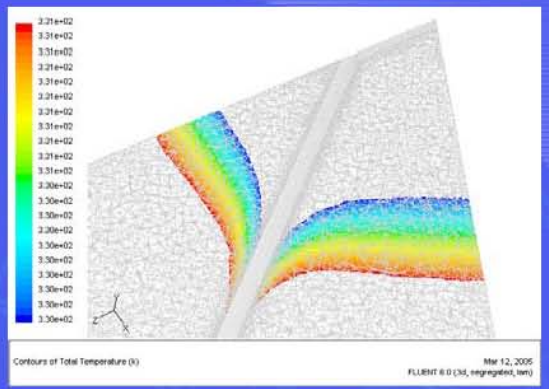



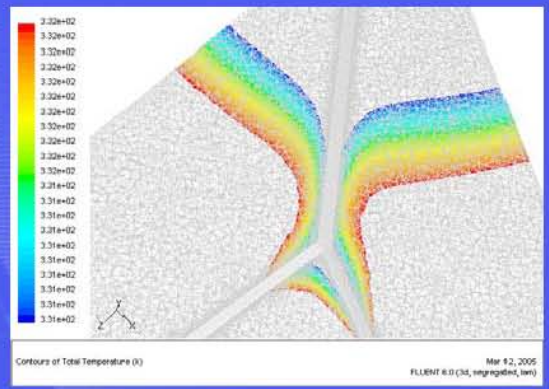



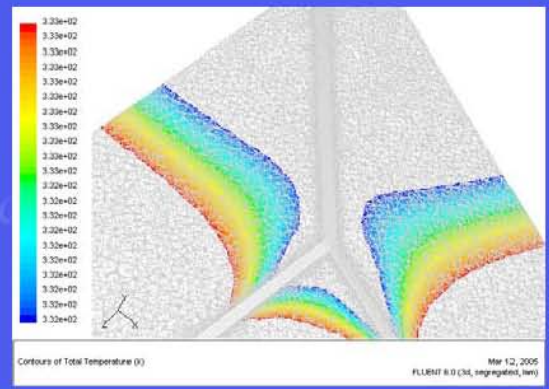

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

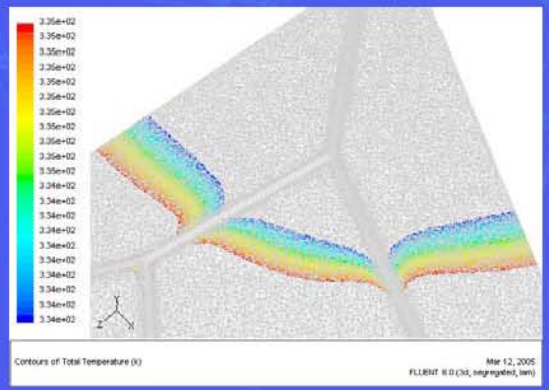

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

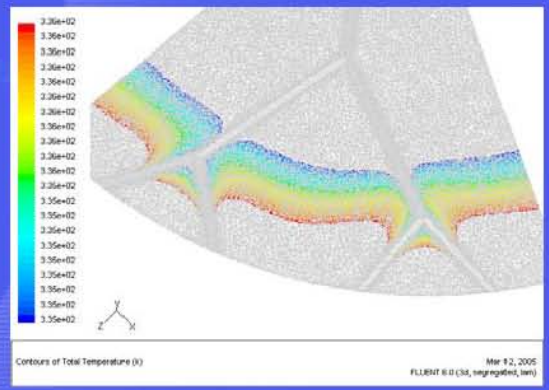

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

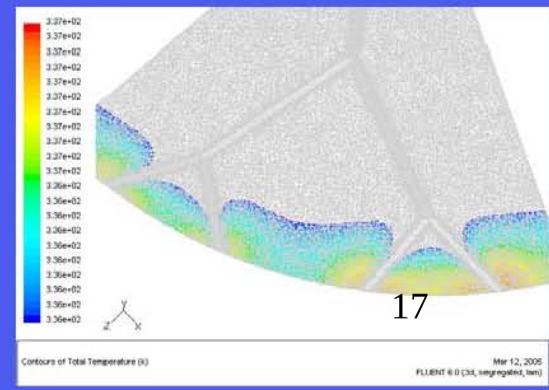

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)


Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)


Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

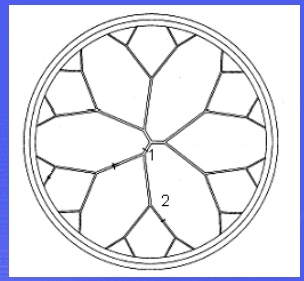

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

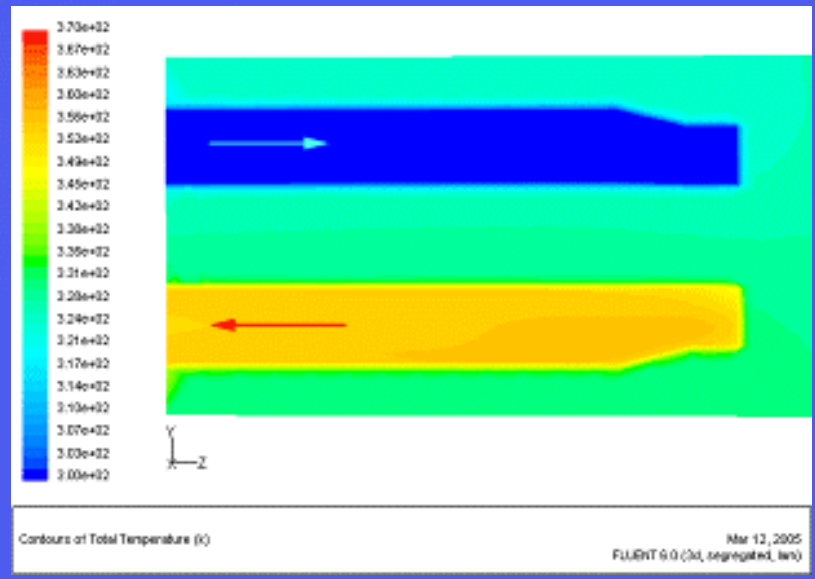

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

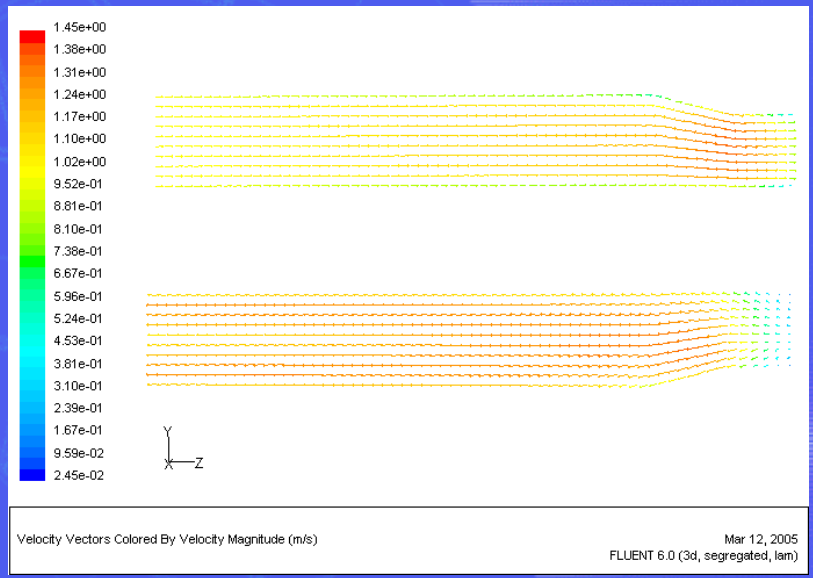

Contours of Total Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

# Temperature profiles – level 0 – In->out

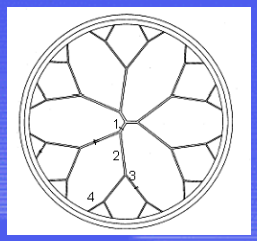
constructal

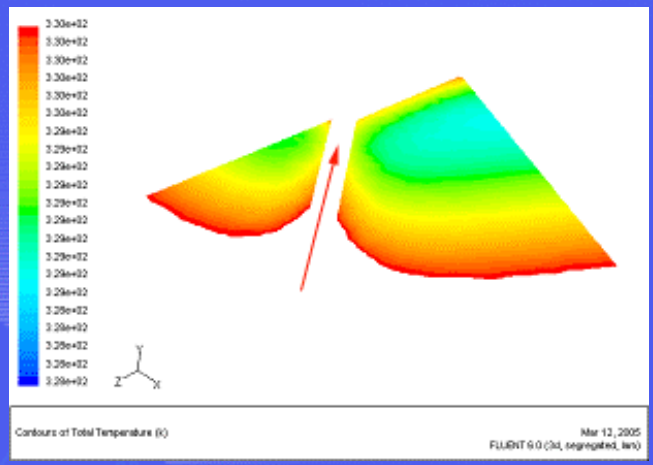


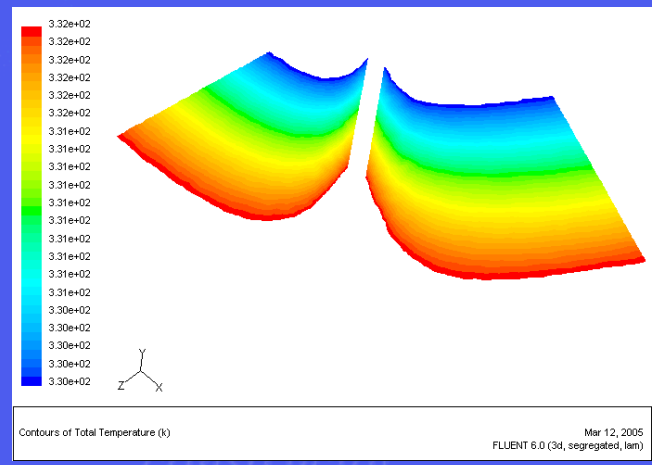



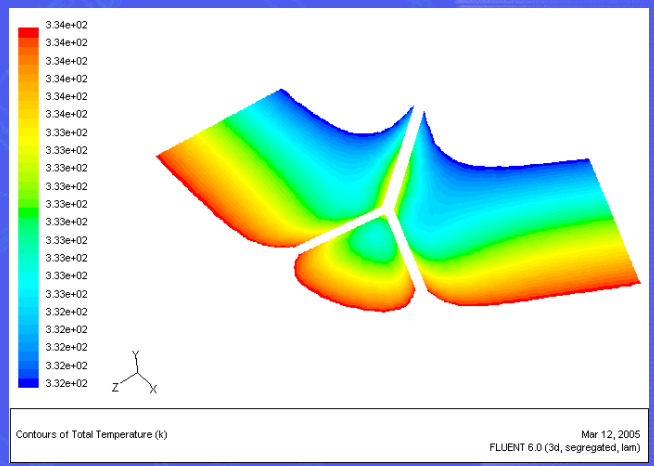



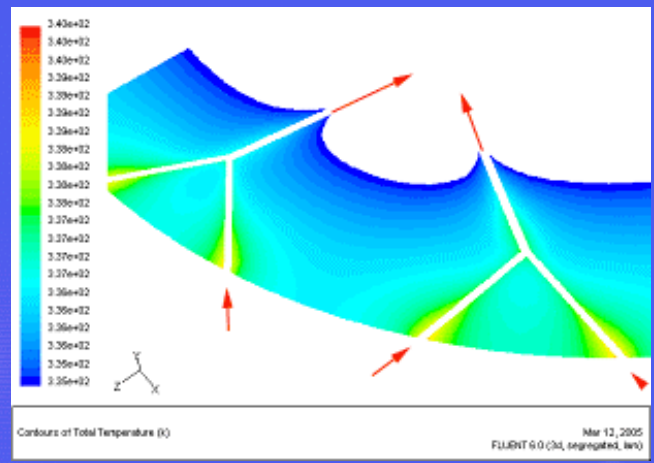
# Temperature profiles – out->in



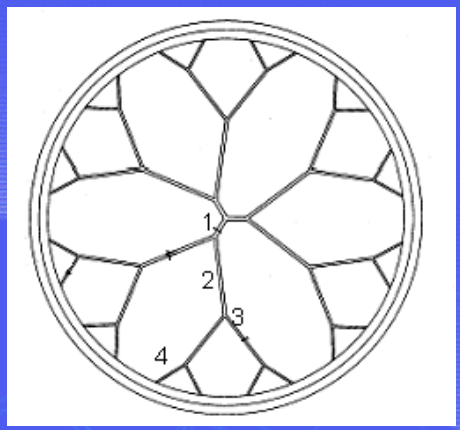



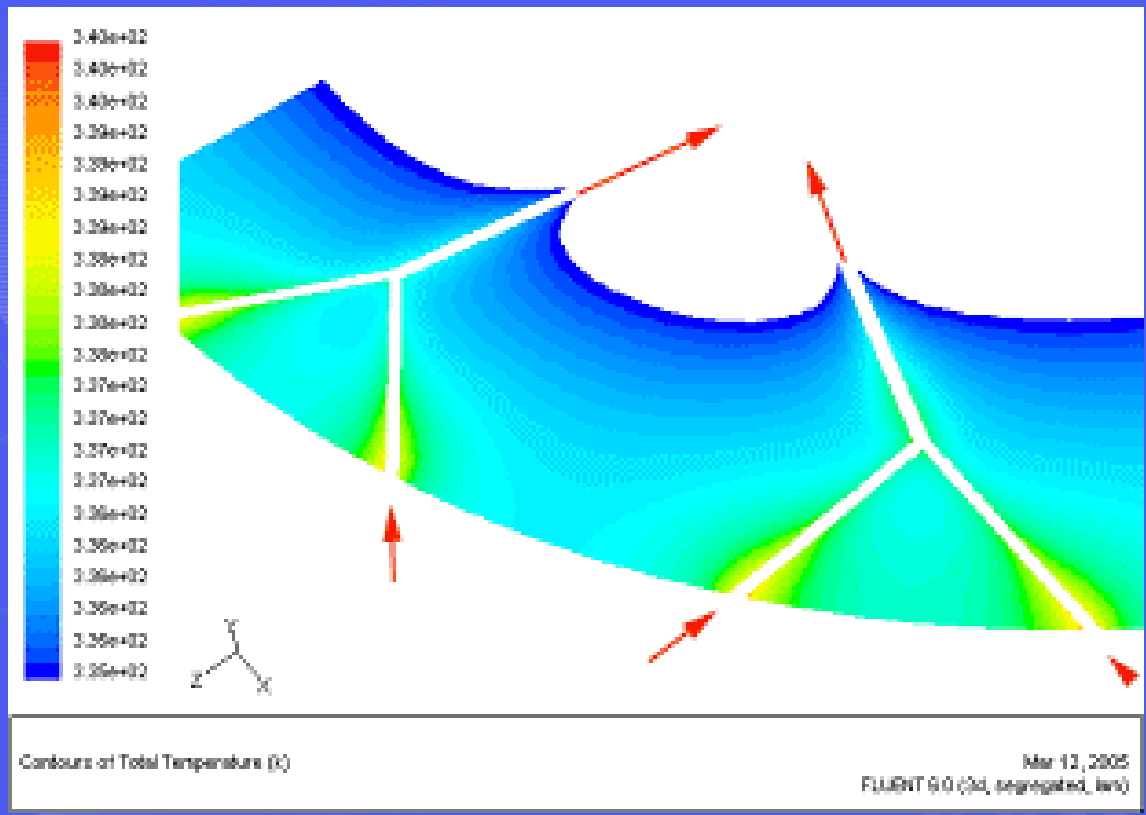



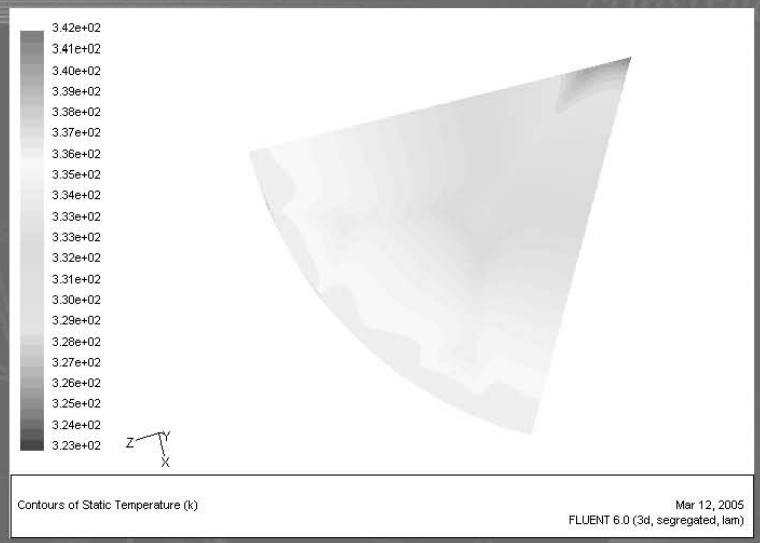
# Temperature profiles at the hot fluid inlet

constructal



# Shells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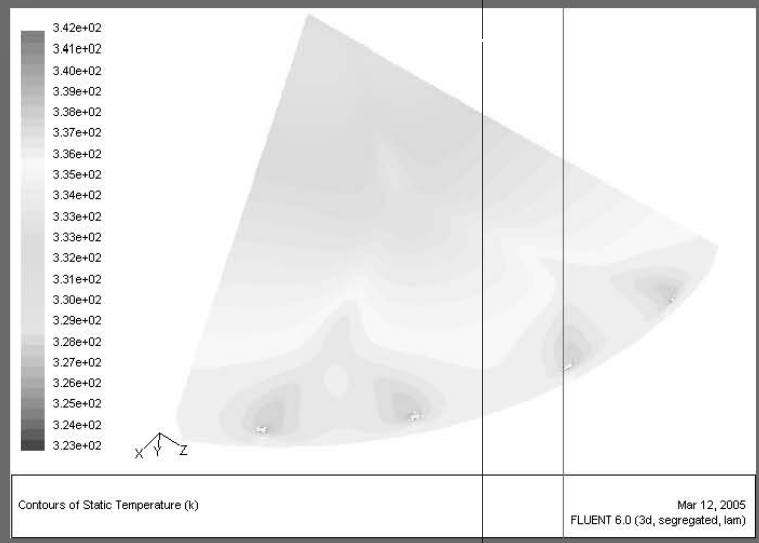
Y
X
Contours of Static Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)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3.24e+02
3.23e+02
X
Y
Z
Contours of Static Temperature (k)
Mar 12, 2005
FLUENT 6.0 (3d, segregated, lam)

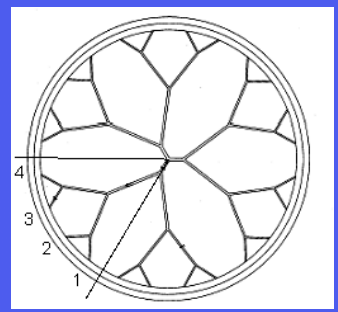
# performance

constructal

| Area-Weighted Average Static Temperature | (k) |
|---|---|
| outflow1 | 321.80 |
| outflow2 | 321.67 |
| outflow3 | 320.00 |
| outflow4 | 320.32 |

| Area-Weighted Average Static Pressure | (pascal) |
|---|---|
| outflow1 | -836.25 |
| outflow2 | -1018.8 |
| outflow3 | -978.87 |
| outflow4 | -748.10 |

| Area-Weighted Average Static Temperature | (k) |
|---|---|
| central_outflow | 350.30 |



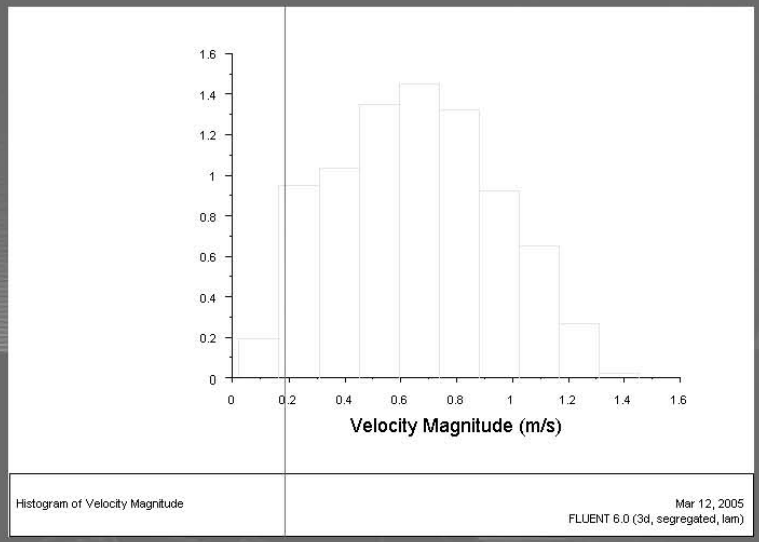
Proposal for an improved model:

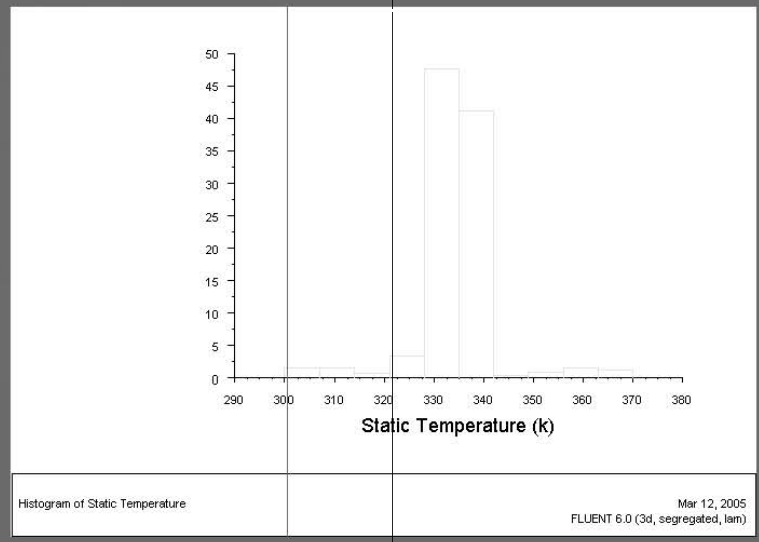
Tubes slightly curved to obtain symmetrical junctions

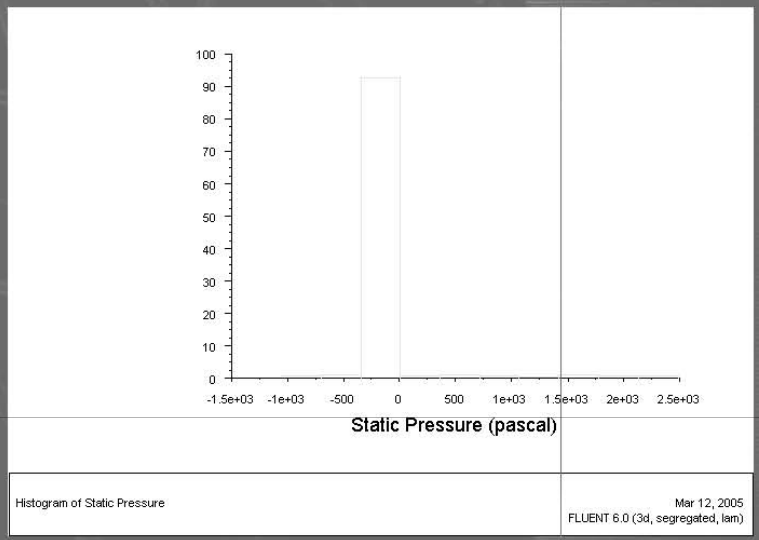
Exploit to the upmost the boundary layer development  along each tube

Splits optimized on the basis of pressure drops

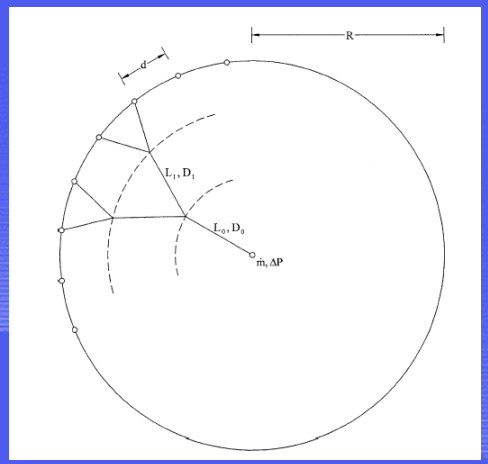
# Solution Hystograms



# Dendritic pattern




Pressure drop

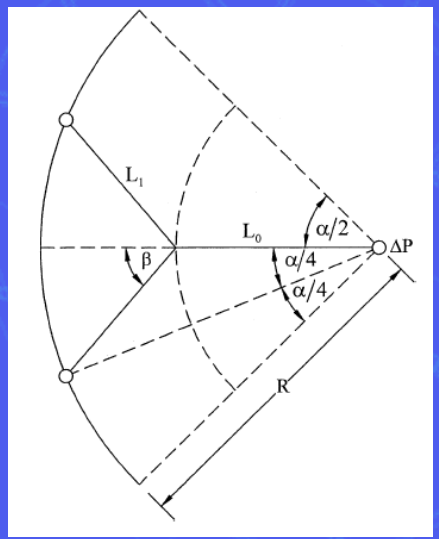
$$\Delta P = \dot{m}\frac{8\pi\nu}{V^2}R^3 f(n_0)$$

Diameter ratio

$$\frac{D_{i+1}}{D_i} = 2^{-1/3}$$

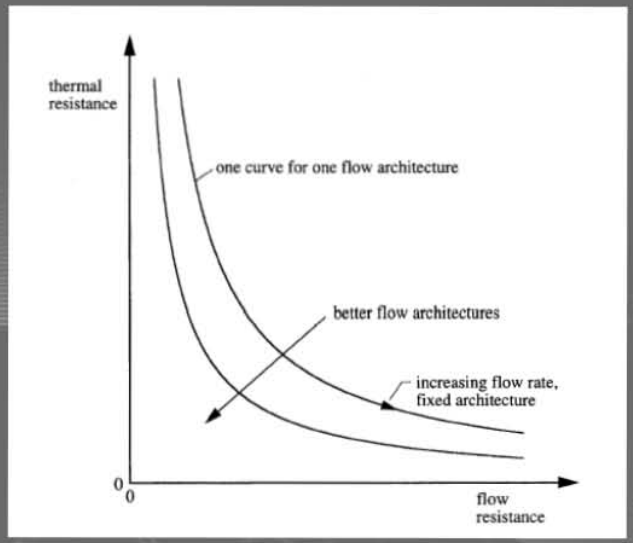
Pressure drop factor

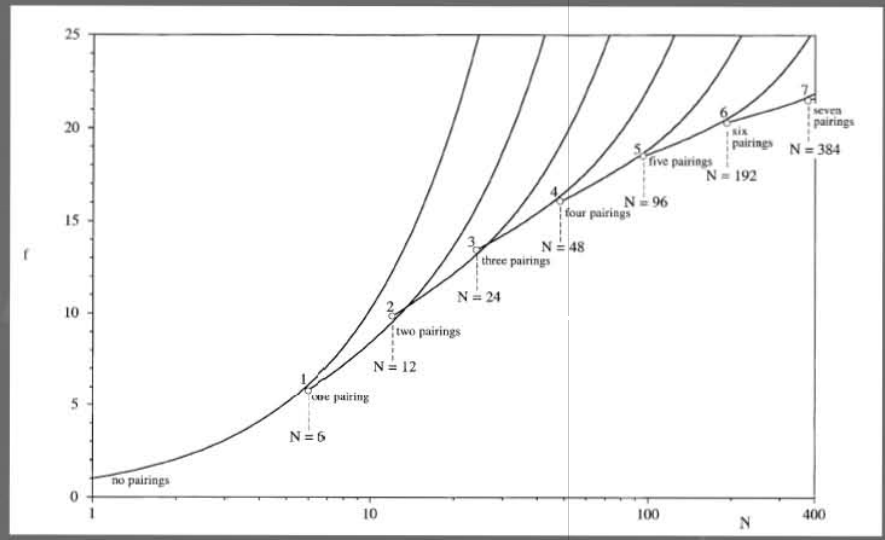
$$f(n_0) = n_0\left[\cos\frac{\pi}{2n_0} + \sin\frac{\pi}{2n_0}\left(\frac{2^{1/3}}{\sin\beta} - \frac{1}{\tan\beta}\right)\right]^3$$

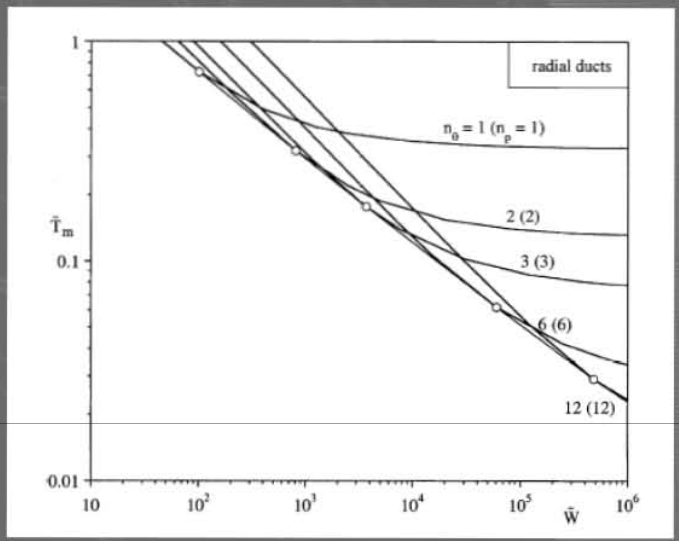



| $n_0$ | $\beta$ | | $\gamma$ | | $\hat{L}_0$ | $\hat{L}_1$ | $\hat{L}_2$ | $\hat{x}_1$ | $\hat{x}_2$ | $f$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | deg | rad | deg | rad | | | | | | |
| 3 | 38.85 | 0.6783 | 36.77 | 0.6420 | 0.157 | 0.509 | 0.432 | 0.482 | 0.361 | 9.82 |
| 4 | 38.64 | 0.6747 | 39.78 | 0.6946 | 0.337 | 0.464 | 0.305 | 0.420 | 0.243 | 11.10 |
| 5 | 38.31 | 0.6689 | 41.65 | 0.7272 | 0.458 | 0.408 | 0.235 | 0.359 | 0.183 | 12.16 |
| 6 | 38.08 | 0.6648 | 42.96 | 0.7501 | 0.543 | 0.358 | 0.192 | 0.312 | 0.145 | 13.16 |
| 7 | 37.93 | 0.6623 | 43.95 | 0.7674 | 0.607 | 0.318 | 0.161 | 0.273 | 0.120 | 14.13 |
| 8 | 37.83 | 0.6605 | 44.73 | 0.7810 | 0.655 | 0.286 | 0.139 | 0.243 | 0.102 | 15.10 |
| 9 | 37.75 | 0.6591 | 45.34 | 0.7917 | 0.693 | 0.258 | 0.123 | 0.218 | 0.089 | 16.07 |
| 10 | 37.70 | 0.6583 | 45.85 | 0.8006 | 0.724 | 0.236 | 0.109 | 0.198 | 0.078 | 17.03 |
| 11 | 37.66 | 0.6576 | 46.28 | 0.8081 | 0.749 | 0.217 | 0.099 | 0.181 | 0.070 | 18.00 |
| 12 | 37.63 | 0.6570 | 46.63 | 0.8142 | 0.770 | 0.200 | 0.090 | 0.167 | 0.063 | 18.98 |
| 13 | 37.61 | 0.6567 | 46.94 | 0.8196 | 0.788 | 0.186 | 0.083 | 0.154 | 0.058 | 19.95 |
| 14 | 37.59 | 0.6563 | 47.21 | 0.8243 | 0.803 | 0.174 | 0.076 | 0.144 | 0.053 | 20.93 |
| 15 | 37.57 | 0.6557 | 47.44 | 0.8283 | 0.816 | 0.163 | 0.071 | 0.134 | 0.050 | 21.91 |
| 16 | 37.56 | 0.6555 | 47.65 | 0.8316 | 0.828 | 0.153 | 0.066 | 0.126 | 0.046 | 22.88 |

# Performance Graphs



Pressure drop on a diverging section

$$\zeta = \frac{\Delta H}{\frac{\gamma w_0}{2g}}$$

*Simulation and measurements of turbulentheat transfer in a channel with a surface mounted heated block* (chen- wang), heat and mass transfer, 31, 1996, 463-473- Springer Verlag

# Energy usage in Aircraft Equipment Systems

## A potential future, from the EC Power Optimised Aircraft project

**Workshop on Constructual Theory**

**Rome, 17-18 March 2005**

**Lester Faleiro, Jacques Herzog**

**Liebherr-Aerospace, Germany**

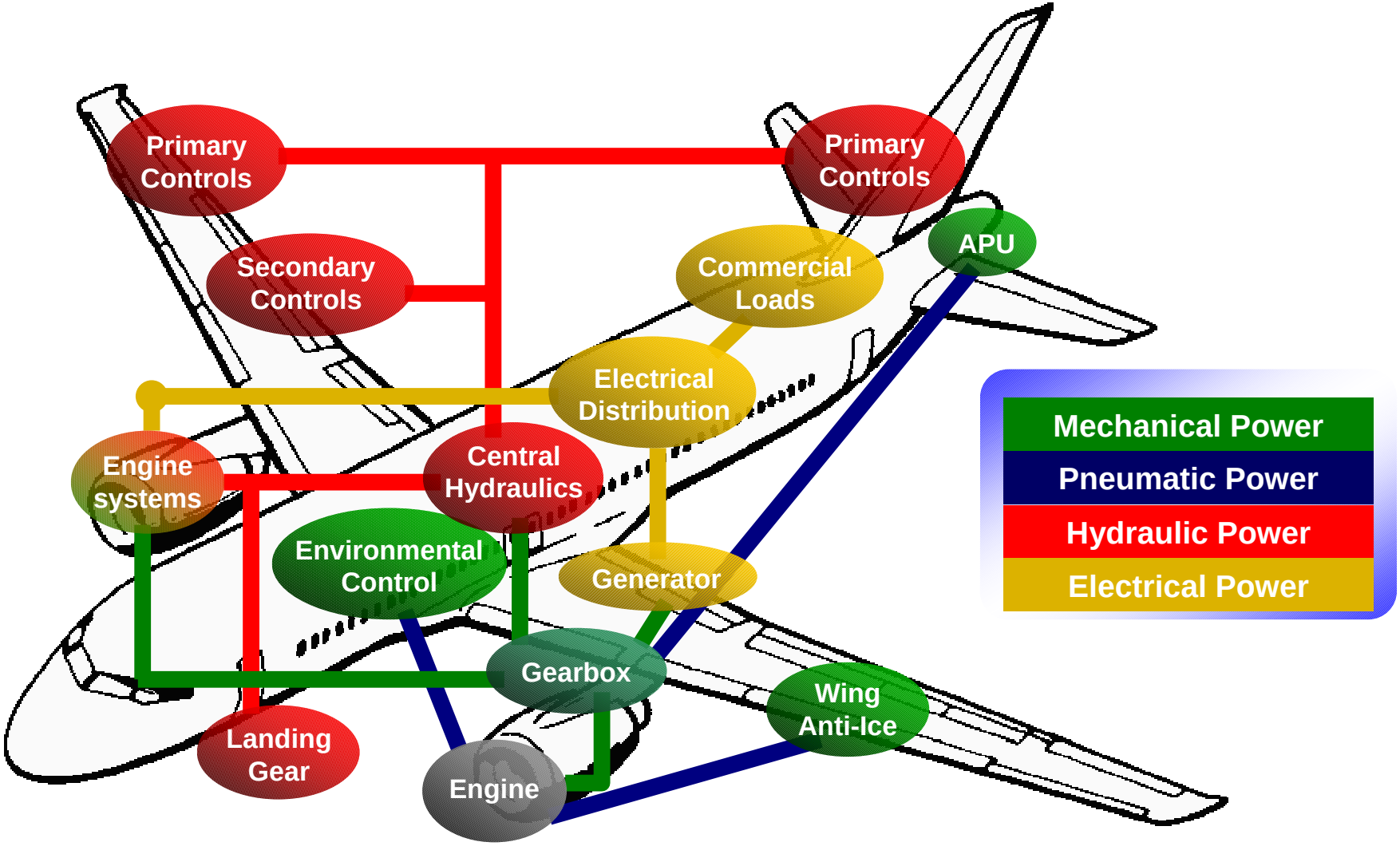
LIEBHERR
Aerospace.

# Project Goals

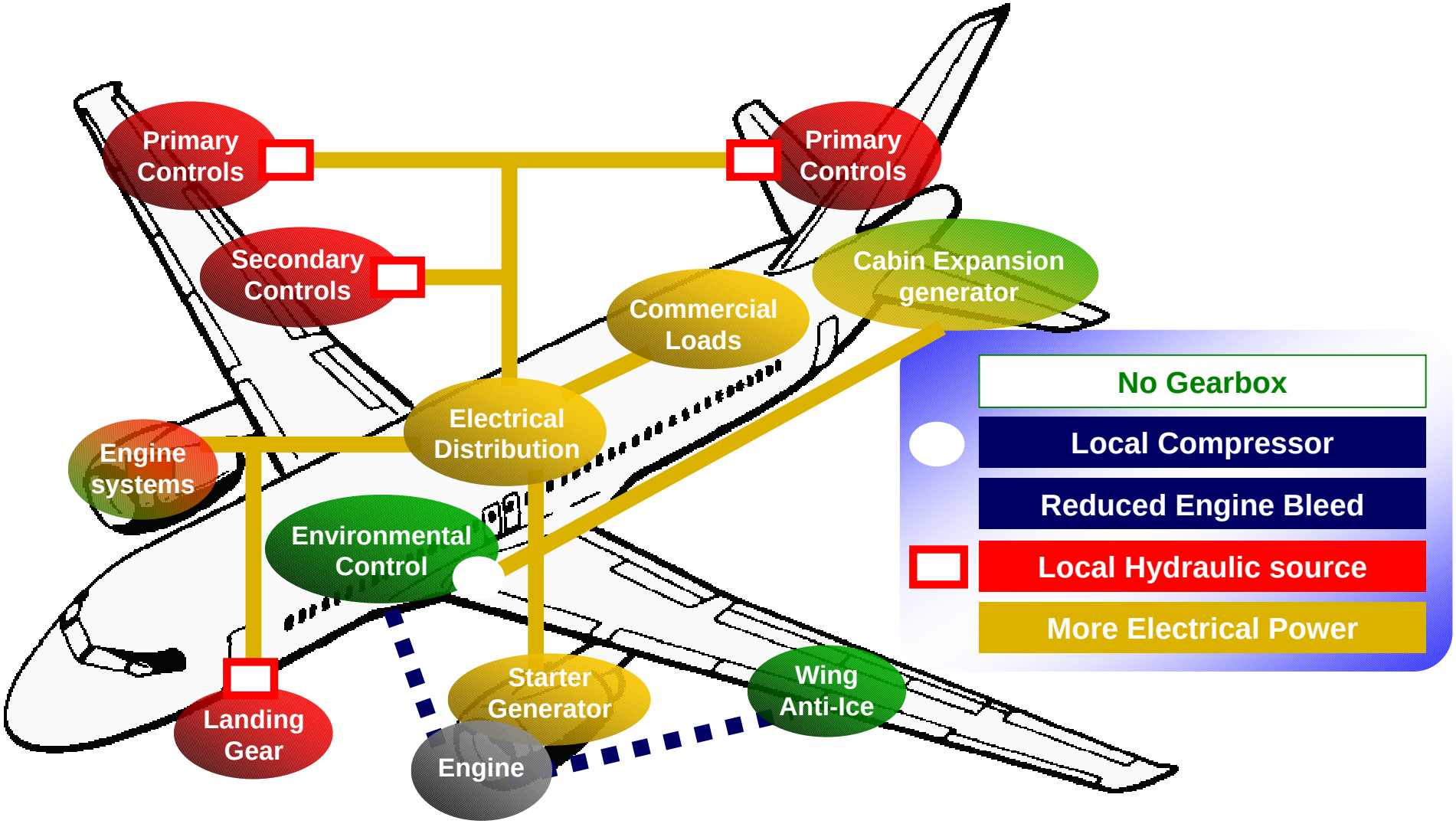
**The target of POA is to validate, at aircraft level and both qualitatively and quantitatively, the ability of next generation aircraft equipment systems to enable the reduction in consumption of non-propulsive power**

- **Drivers**
  - **Safety Standards**
- **Objectives**
  - **Reduction of peak non-propulsive power by 25%**
  - **Reduction of total non-propulsive power**
  - **Reduction of fuel consumption by 5%**
  - **Reduction of total equipment weight**
- **Constraints**
  - **Maintenance Costs**
  - **Equipment production costs**
  - **Reliability**

# Conventional Aircraft Architecture



# Optimised Aircraft Architecture?



# Engine Electrical Systems

Rolls-Royce

## Electric Actuators

MTU Aero Engines

## •Fan Shaft Generator

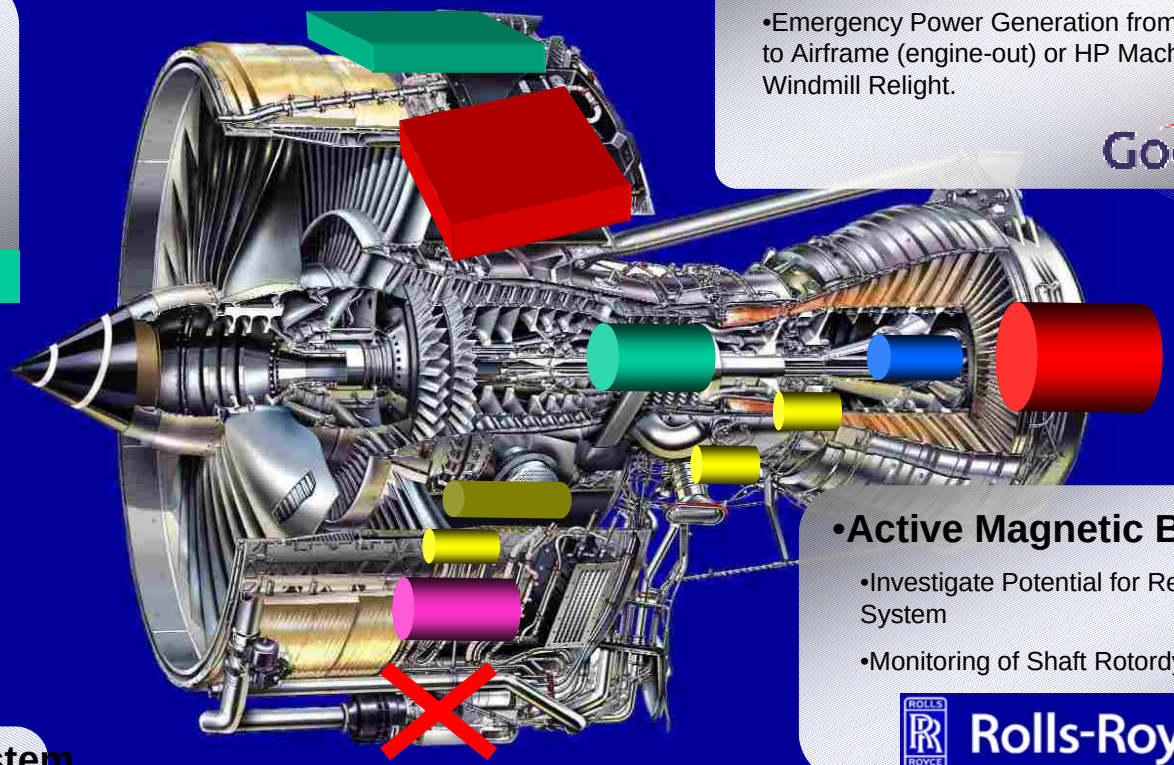
- ~ 150kW main Power Generation at Idle and Above
- •Emergency Power Generation from Windmilling Fan to Airframe (engine-out) or HP Machine for Assisted Windmill Relight.

GOODRICH

## •High Pressure Starter/Generator

- ~ 200kW Motor for Engine Starting.
- •Will Generate Power after Engine Start
- •LP to HP Power Transfer may Improve Fuel Burn and Reduce Thrust During Descent.

THALES AVIONICS ELECTRICAL SYSTEMS



## •DC Power Bus on Engine

- •Simplified Airframe/Engine Interface
- •Each Machine will have a Power Electronic Drive
- •Each Drive will Appear as a Node in a Distributed Control System

Rolls-Royce

## •Active Magnetic Bearing

- •Investigate Potential for Removal of Oil System
- •Monitoring of Shaft Rotordynamics

Rolls-Royce

## •Electric Oil Pump/Scavenge System

- •Optimise Oil Flow to Bearings over Engine Cycle

Techspace Aero
snecma group

## •Electric Oil Breather Model

Hispano-Suiza
groupe snecma

EMS
SAFRAN

## •Electric Fuel Metering Unit

- ~ 100kW Motor
- •Simplified Fuel System
- •Lower Heat Input to Fuel

THALES AVIONICS ELECTRICAL SYSTEMS

Hispano-Suiza
groupe snecma

VOLVO AERO

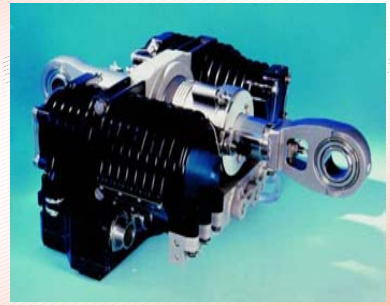
# Actuation Systems

The Objective is to achieve lower life cycle costs, through power optimisation, reduced weight and maintenance costs

## Electro-Hydraulic Actuation (EHA)

Derivation of Standards

Hardware and model verification



2.5 kW EHA

## Nacelle Systems

More Electrical Thrust Reversal

Alternative to pneumatic and hydraulic thrust reversal systems

Mechanical and data bus synchronisation

Large wide-body thrust reverser ball and screw EMA

Hurel-Hispano test facility

## Electro-Back-up Hydraulic Actuation (EBHA)

Novel and versatile hybrid actuation

Wide-body aileron actuator ~2 kW

## Trimmable Horizontal Stabiliser Actuation (THSA)

Proof of concept

More electrical actuation with innovative mechanical technologies

Typical wide-body stabiliser actuator

Spoiler actuator ~25 kW

## Electro-Mechanical Actuation (EMA)

Distributed High-Lift systems

Comparison of hinge line versus rotary technologies

## Landing Gear Systems

Landing Gear system integration

Decentralised actuation for Nose Wheel

More Electrical Actuation for Main Gear

More Electrical Wheel Braking

Airbus A300/A310

# Pneumatic Systems

The Objective is to reduce and optimise the effect of bleed air off-take on power usage, as this is a large consumer of non-propulsive power. Bleed Air Off-Takes are mainly used for the **Environment Control System** and for **Wing Ice Protection**.

## Air Conditioning System (ACS)

To increase the efficiency of the ACS

The main innovation is the combination of a Vapour Cycle (containing an environmentally neutral fluid) with an electrical driven Air Cycle. A variable speed motor for the re-circulation fan and a Cabin Energy Recovery Device will be used.

The main outputs are a Model of a complete ACS and the Test of a Hybrid ACS (Vapour +Air Cycle)

**Re-circulation Fan**

**Motorised Air Cycle machine**

**$CO_2$ Compressor**

## Wing Ice Protection (WIP)

**Ice detection sensor**

To Increase the efficiency of WIP Systems

The main innovation is the use of ultrasonic surface ice sensors (Anti Ice on demand) and hybrid wing heating (electrical and hot air)

The main outputs are Models of WIP Systems and Test of an innovative WIP System

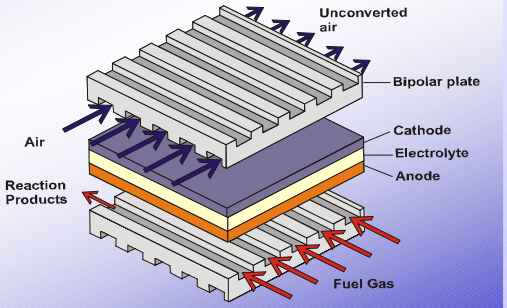
**Wing heat distribution using:** Ultrasonic sensors, Electro-thermal devices, On demand active intelligence control and Monitoring of unprotected surfaces

## Fuel Cells (FC)

To Increase the efficiency of electrical power generation for pneumatic systems

The main innovation is the validation of a Solid Oxide Fuel Cell (SOFC) with its reformer for use with kerosene

The main outputs are a Model of FC System and the Test of a 5 kW Fuel Cell System




**SOFC Principle**

# Project Process so far

- The A330-300 was chosen as a reference for all comparison
- More Electrical systems chosen as technology solutions for POA
  - Perception of more efficiency at the system level
  - Higher synergy when integrated into a more electrical aircraft (MEA)
- Systems combined into various POA (mostly MEA) architectures
  - Each system has been designed and many are being manufactured

- Note: This is NOT optimisation – this is a pre-selection of a few possible combinations that the industrial partners together feel have the greatest potential for application in the near to medium future

# Energy related trends at the Systems Level

- MESys tend to waste less energy
  - No hydraulic leakage
  - No large losses from engine bleed
  - Power on demand
- Many technologies can be demonstrated today
  - MEE technologies
  - High density power generation
  - Reliable electrical distribution architectures
  - Better aeronautical cabling
  - Electro-hydrostatic and electro-mechanical flight control actuation
  - Electrical braking
  - Electrical Environmental Control System

# One challenge for Constructal Theory – The ECS

# Tasks of the Environmental Control System (ECS)

- **Pressurisation** (at altitude Pressure not lower than 752 hPa)
- **Ventilation** (Fresh flow per passenger 0,55 lb/min)
- **Temperature control** (Cabin temperature around 24°C)

- Engine Bleed Air and Pre-cooling with Engine fan air
- Bleed Air with Ram Air
- Turbomachines and Water separation loops
- Mixing chamber and distribution

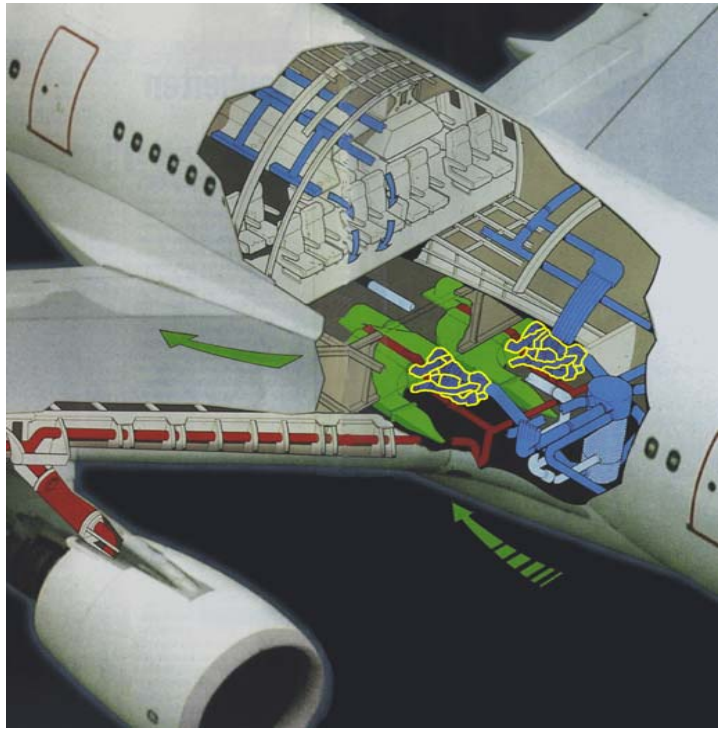


*Fig.1*

# Principle of the current ECS on large civil Aircraft

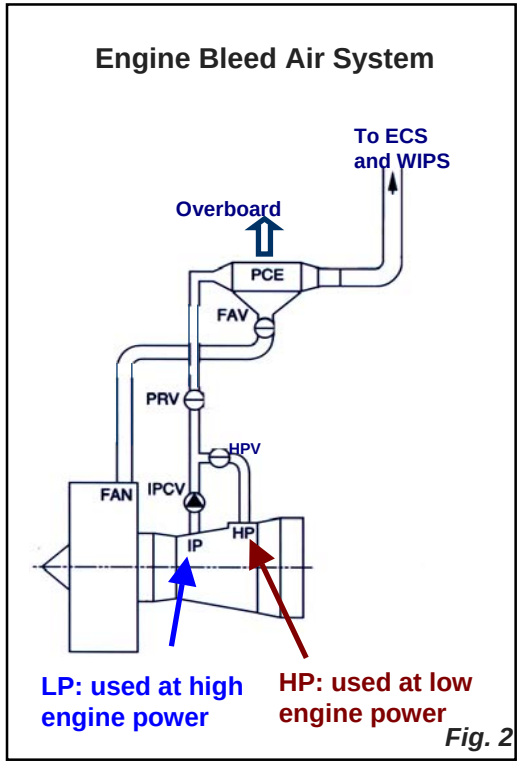


*Fig. 2*

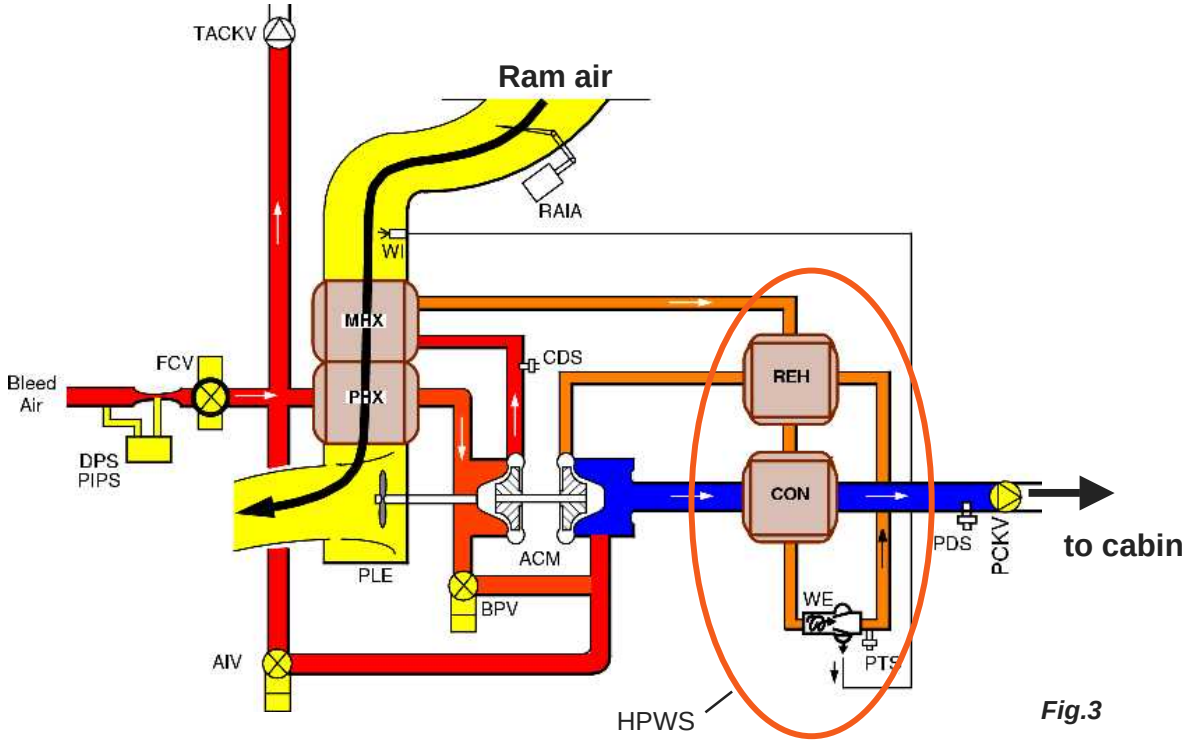


*Fig.3*

- 2 bleed ports: LP port at high engine power and HP port at low engine port.
- Pre-cooler limits the temperature to 200°C using Fan air
- PRV regulates the pressure delivery
- Flow controlled by FCV
- Temperature controlled by Ram air flow (RAI) and Bypass flow (BPV)
- Water extraction realised by high pressure water separation loop (HPWS)

# Energy Impacts of the current ECS on a large civil Aircraft

- **Impact on the Engine - High Specific Fuel Consumption**
- **Losses – high temperature and pressure air has to be cooled and de-pressurised before it is useable**
  - **Weight of components included in order to induce energy losses**
- **Drag for the cooling of the Ram Heat Exchangers**
- **And many more….**

# Power losses due to the ECS on current Aircraft

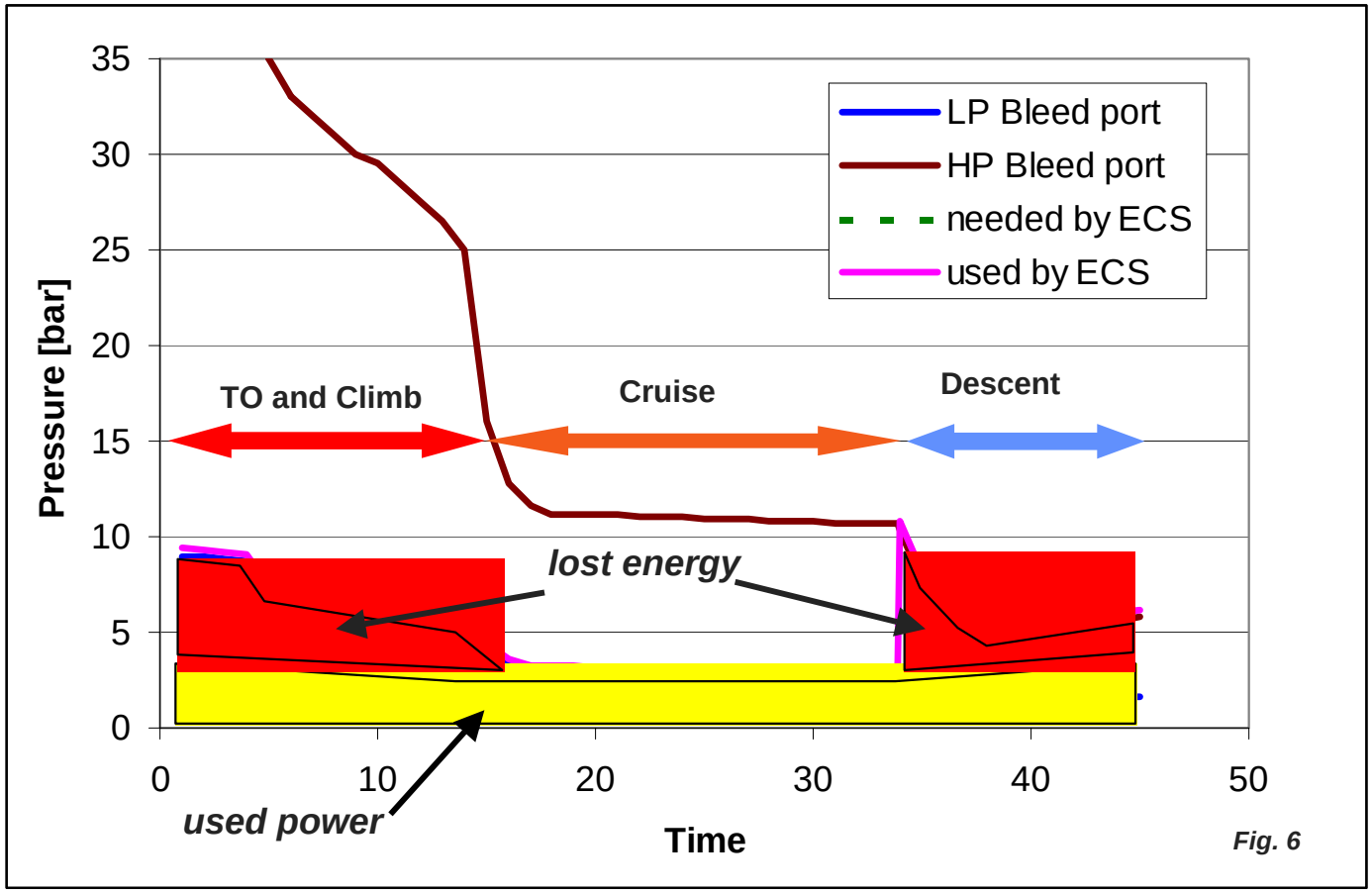



*Fig. 6*

- Currently the Engines provide (pneumatic) power to the ECS. This supplied power is strongly dependent on the flight phase.
- Two bleed ports needed to supply the required power and to limit the impact of Bleed Air on Engine fuel consumption
- Nevertheless a lot of losses are induced by the divergence of needs and supply

# ONE solution to energy “optimisation”: the electrical ECS (Bleed-less)

mechanical energy → Generators → electrical energy → ECS → pneumatic energy → Cabin

- Engines produce mechanical (kinetic) energy from fuel
- Generators convert the mechanical energy into electrical energy
- ECS use the electrical energy to perform its tasks:
  - Pressurisation
  - Ventilation
  - Temperature control

# Adaptability of the electric ECS

- **The power consumption of the electrical ECS is independent of the engine speed (no dissipation of excessive engine power)**
- **Adaptation of the ECS to the cabin needs**
  - **Fresh flow can be adapted to the number of Cabin occupants**
  - **Cooling power can be adapted to the heat loads**
  - **If needed ECS power consumption can be reduced for a short time so as to allow other systems to use the released power**

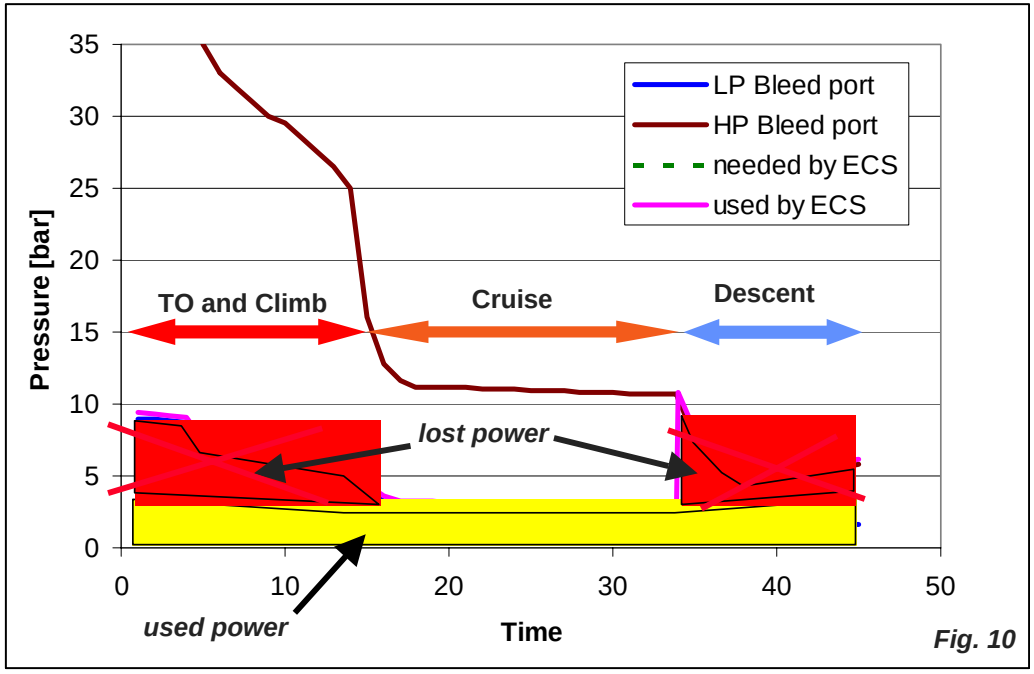



*Fig. 10*

# Impact on engine of pneumatic and electrical power source

- **Mechanical Off-takes (to produce electrical power) and Pneumatic Off-takes have different impacts on the Specific Fuel Consumption of an engine**
  - **to cover the ECS needs, the impact of electrical power on the engine specific fuel consumption is not so strong as the impact of the pneumatic off-takes**

**Potential to reduce the Fuel consumption (energy) by using electrical power – this pseudo-optimisation is what goes on at the equipment systems level**

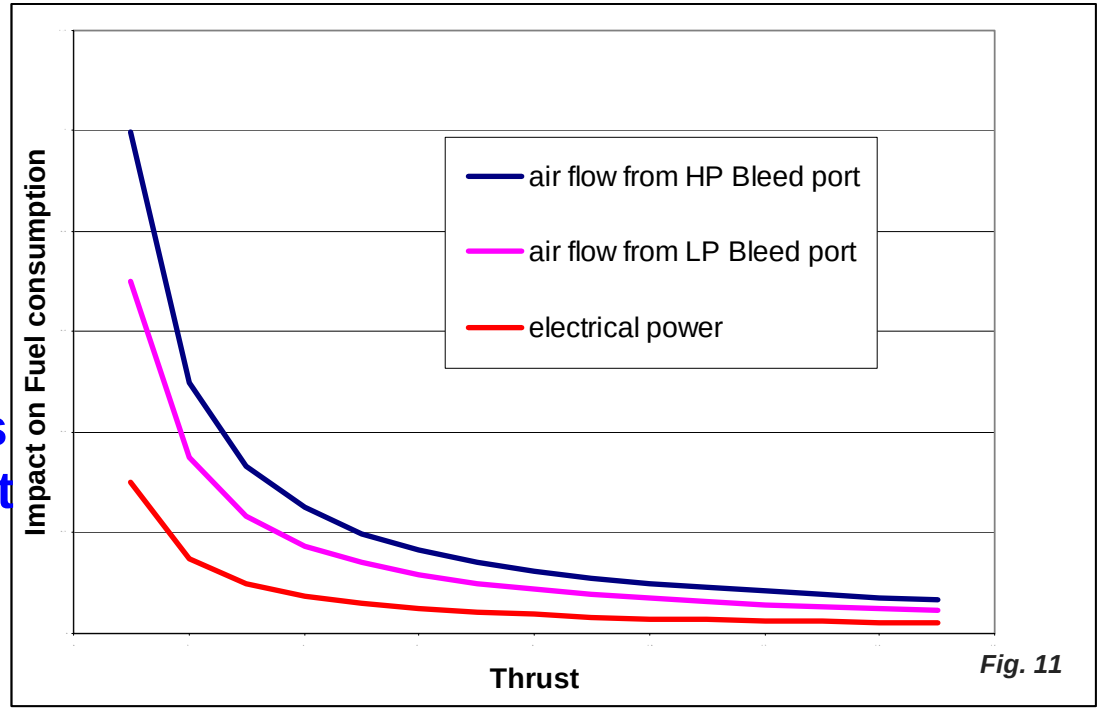



*Fig. 11*

# A role for Constructal Theory?

- A Bejan has published 2 papers to address the issues in an aircraft ECS
  - The method is structured and makes sense, but the problem to solve is complex and multi-faceted.
    - It cannot be solved by only thermodynamic considerations, as the systems involved are multi-physics.
    - The inputs required to address the problem fully are difficult to obtain, as many organisational entities may be involved (aircraft, engine and systems manufacturers)
    - It is difficult to solve problems for one component without addressing the impacts on the other components
    - It is difficult to solve problems for the ECS without addressing the impacts on engine and rest of the aircraft (drag, etc.)
- Could Constructal Theory produce a technological solution such as bleedless ECS, or is something else needed to complement it, such as a palette of potential technological solutions and a palette of constraints?

# Further Challenges for Energy Based Methods

- **Constraints are not easy to include in such methods**
  - **Weight limits**
  - **Volume limits**
  - **Design limitations on the performance and function of Aircraft Equipment Systems**
  - **Safety considerations**
- **Every divergence from the ideal model can reduce the degree of freedom of the method**
  - **The idea of creating an ideal energy based model and then systematically altering the model to include design constraints is good, but the complexity of such a model is enormous**

# Energy Based Methods are probably needed

- **For a really Power Optimised Aircraft (not just MEA), thinking must start to occur at the level of functions, rather than systems**
  - **Design Process Re-engineering for equipment systems integration may be necessary – energy based methods might be useful**
  - **e.g. ECS is currently used to provide pressurisation and cooling. In POA, various architectures that provided these two functions in various numbers of systems and sub-systems were examined**
- **Decreasing Systems Autonomy – energy is the common denominator**
  - **More Electrical Engine (MEE) and MEA go hand-in-hand**
  - **Availability of MEA engine thrust is connected to generation system reliability through the use of electrical fuel pumps**
  - **This trend on interdependency is most visible on Boeing B787: bleedless engine/electrical ECS/electrical generation and distribution – can energy based methods, such as Constructual Theory, come up with such solutions?**

# New Challenges

- Cooling in a MEA
- Thermal management of Power Electronics is a challenge
- MOET Project – European University to look at this?

# Thank you!

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# ON THE SYNTHESIS OF COMPLEX ENERGY SYSTEMS WITH SEVERAL HEAT TRANSFER INTERACTIONS

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# Synthesis, Analysis and Optimization

**(Bejan, Moran, Tsatsaronis, 1996 "Thermal Design and Optimization", Wiley ed.)**

- SYNTHESIS is concerned with putting separate elements into a whole, i.e. the particular equipment items making up the overall thermal system and their interconnections are specified

- The objectives of the ANALYSIS and OPTIMIZATION are to identify the preferred configuration among those synthesized.

# Synthesis, Analysis and Optimization

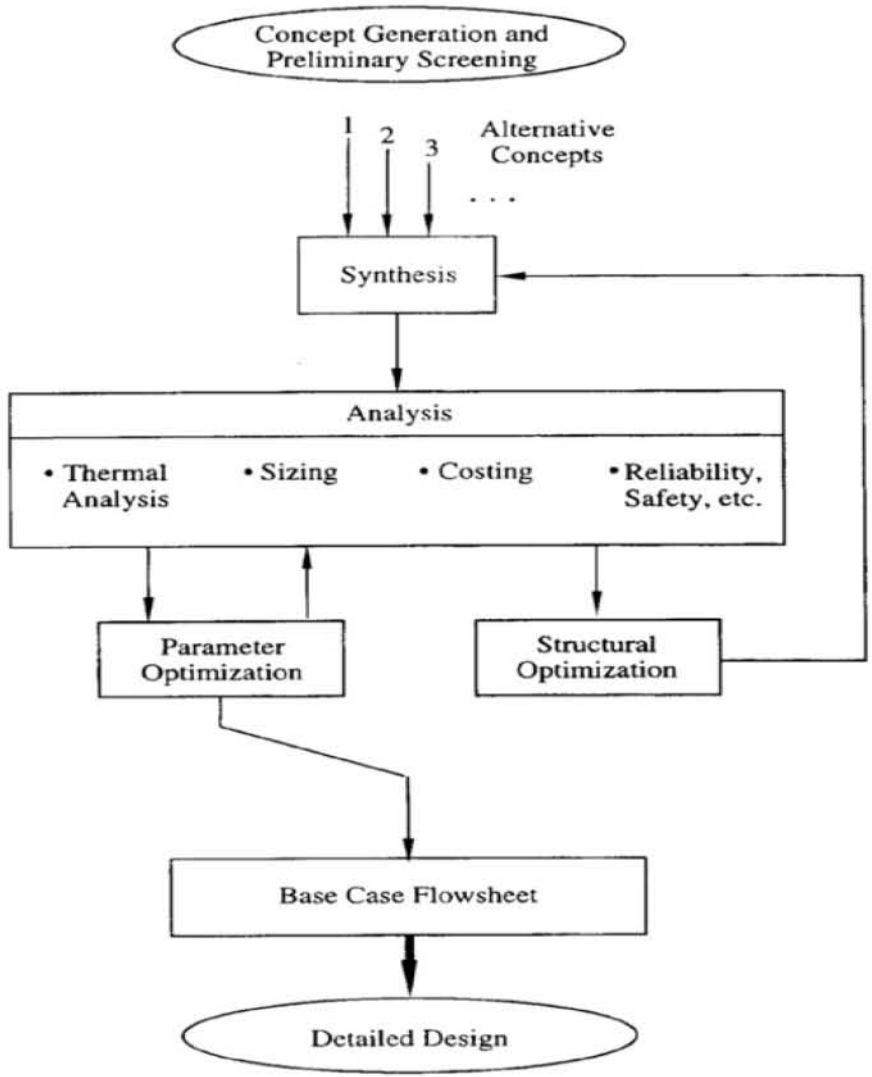
- ANALYSIS generally entails thermal analysis (mass, energy and exergy analysis), costing and sizing of equipment on at least a preliminary basis

- OPTIMIZATION can take two general forms:
  1 ) PARAMETER and 2) STRUCTURAL optimization

1) pressures, temperatures, mass flow rates and chemical composition at various points and/or other system key variables are determined, at least approximately, with the aim of satisfying some desired objectives

2) the equipment inventory and/or interconnections among components are altered iteratively to achieve a superior design

# Synthesis, Analysis and Optimization



# Other criteria to improve thermal system structure

- Definition of a **superstructure** including all feasible structures and optimization of design parameters to "cut" useless branches of the superstructure

- **Criterion applied here** is based on a "**basic plant configuration**" which is defined by subdividing the plant into two zones:

- One including the "*basic components*" that are always included and connected in the same way in the plant structure;

- The *heat transfer zone*, considered as a "*black box*" in which heat is transferred between hot and cold thermal flows (made available from the components in the first zone) independently of the number, type and interconnections among heat exchangers, which are not defined.

# Optimization of the basic plant configuration

- **General problem**: optimal synthesis of the components, i.e. how to interconnect them in order to reach the optimal value of the objective function (here the exergetic efficiency)

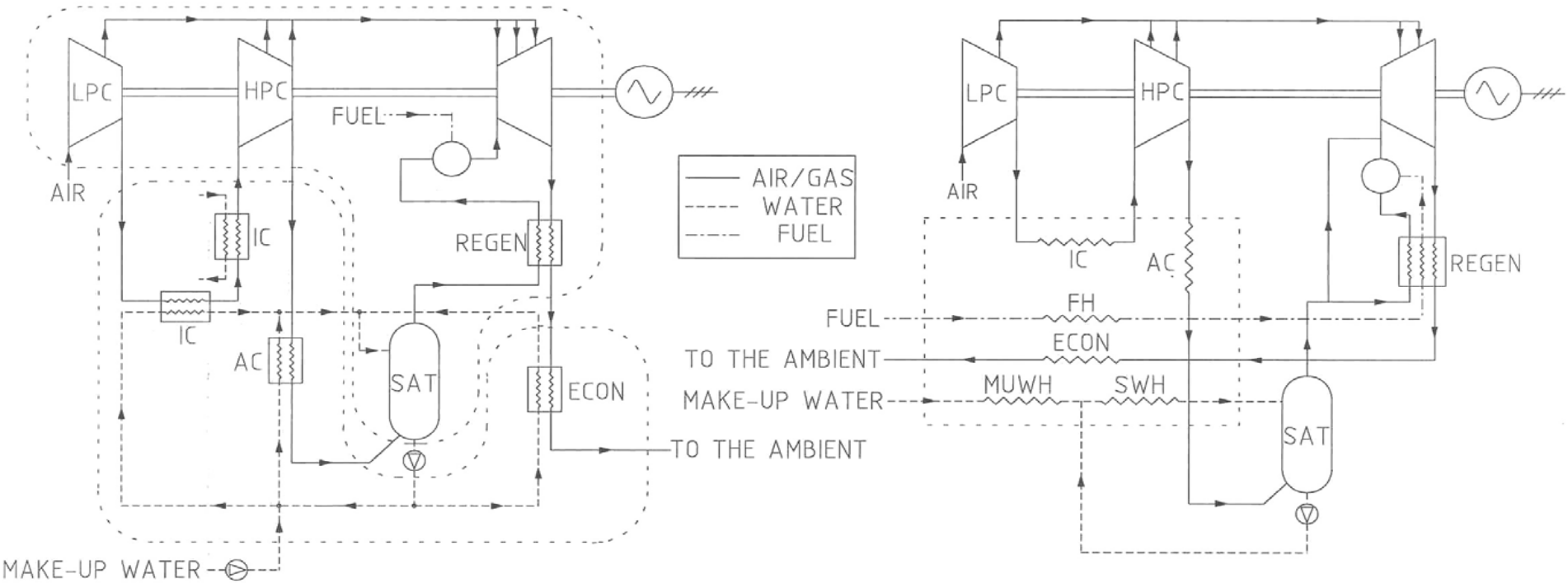
- **Idea**: fix a part of the structure (basic components and their interconnections) and keep the definition of the heat exchanger structure independent of the structure of the overall system

- **Suggested solution**: parameter optimization of the basic plant configuration + construction of the HEN which fulfill the optimal thermodynamic conditions at the black-box boundaries and guarantees the feasibility of the heat transfer

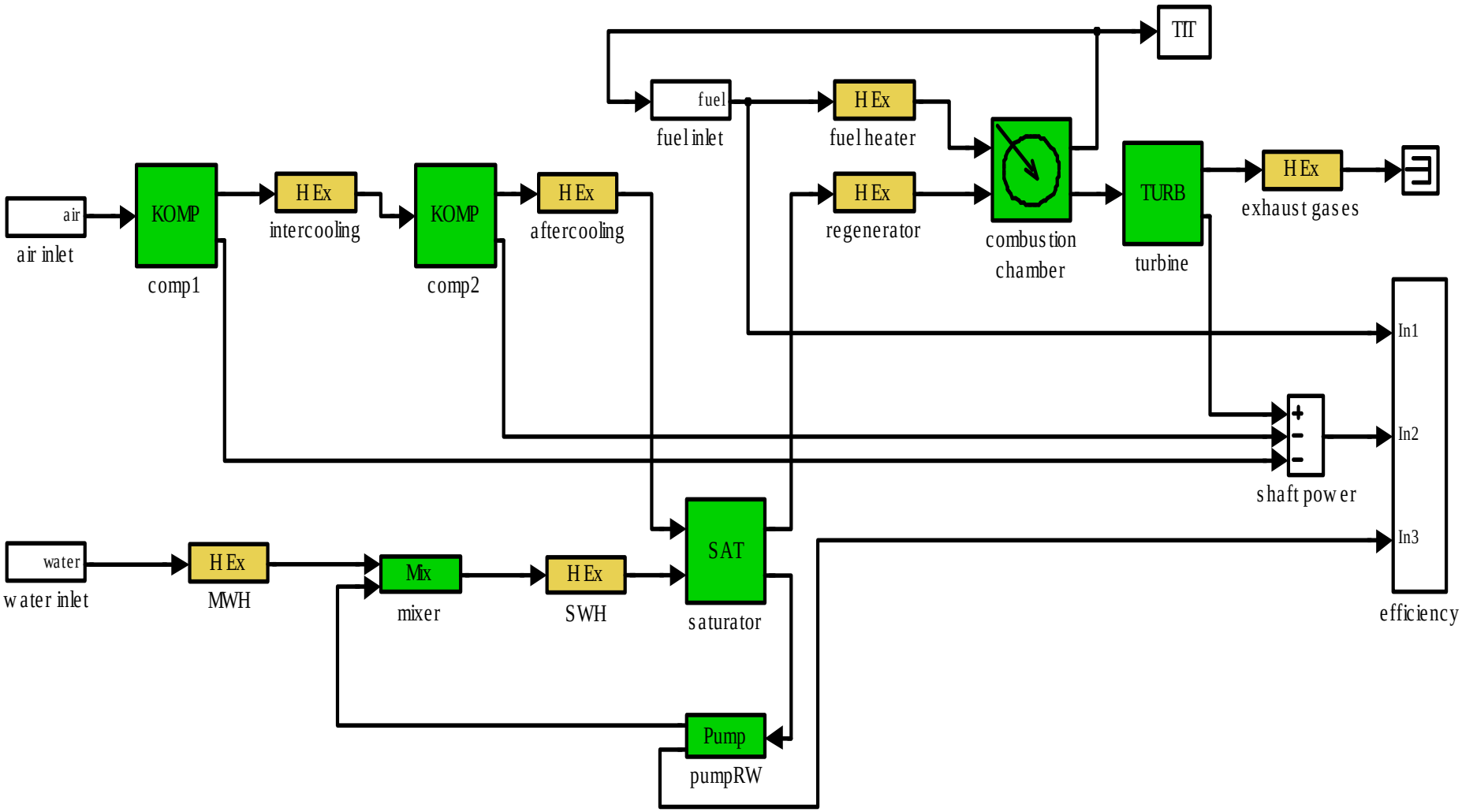
- **Final solution**: find a criterion to generate all possible basic plant configurations and then choose and optimize the best one according to the objective of the analysis

# HAT cycle " Basic Plant Configuration "

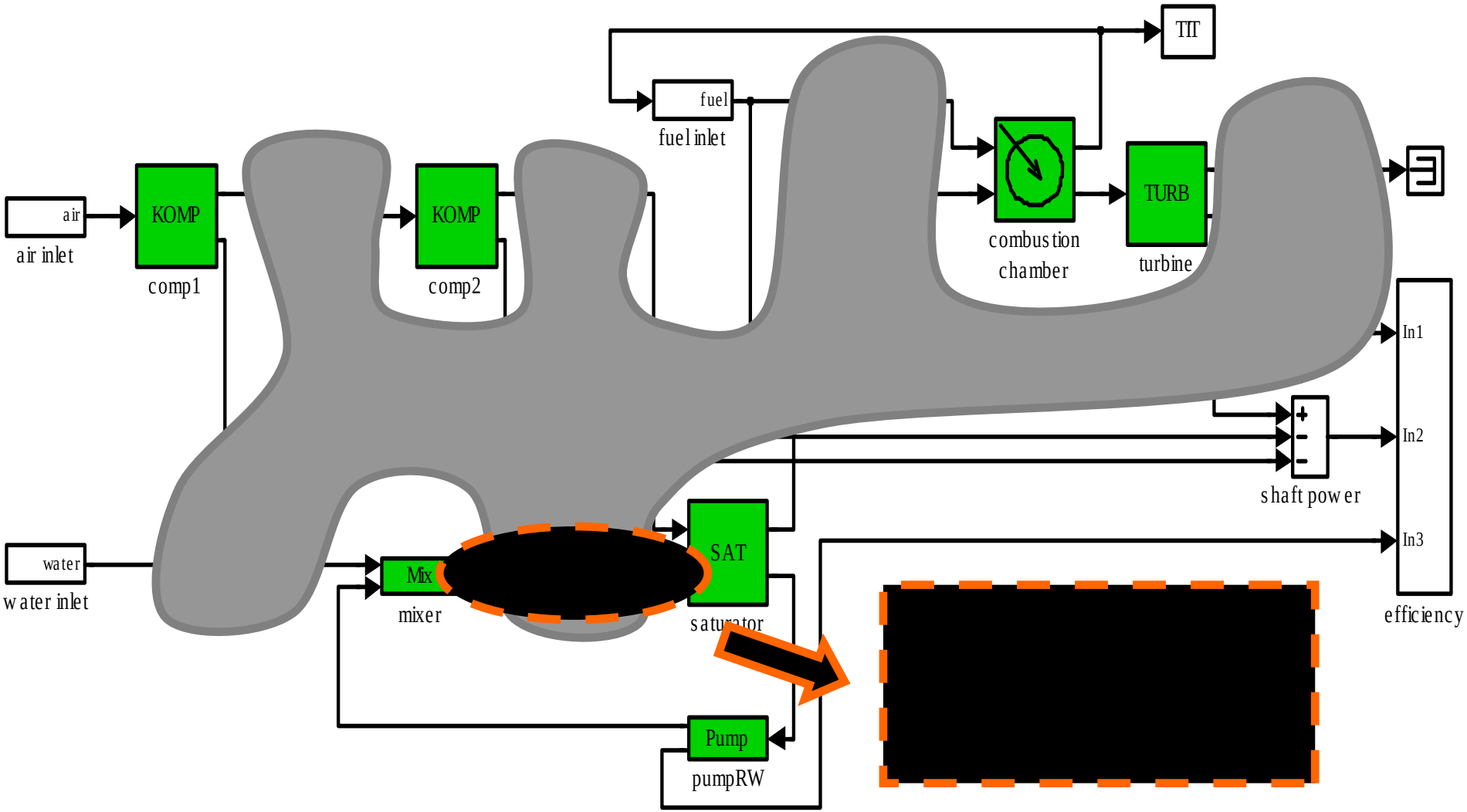
**Lazzaretto, Segato, 2001, Thermodynamic Optimization of the HAT cycle Plant, J for Eng. of Gas Turbine and Power**



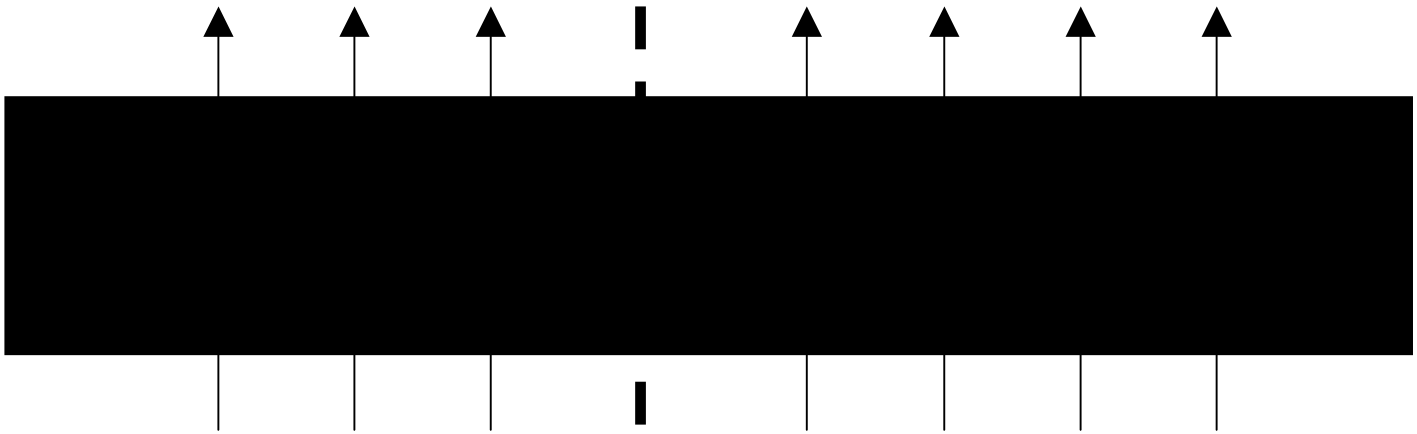
# HAT cycle " Basic Plant Configuration "



# Heat transfer interactions within the basic plant configuration



# Heat transfer section (black-box)



# HAT cycle " Basic Plant Configuration "

- Basic components: compressors (c1, c2), combustion chamber (cc), turbine (t), saturator (s)

- Order:
  air/gas loop: (c1, c2), (cc), (t)
  water loop (s), (cc), (t)

- Temperature links between basic components are "virtually" cut, i.e. the temperature at the inlet of a component is left independent of the temperature at the outlet of the preceding component
  (with the exceptions of the links between hot source (cc) and turbine (t) and between cold source (ambient) and compressor (c1) where additional heat transfer is not meaningful)

# Structure of complex energy systems

- One or more thermodynamic cycles are involved
- Each cycle involves a loop of one or more materials
- In each cycle the order of the basic components is defined
- Additional basic components can be added to improve the system performance (e.g. compressor and/or turbine stages, combustion stages)

# Parameter optimization (thermodynamic) of the basic plant configuration

- Objective function: total plant exergetic efficiency

- Decision variables are the degrees of freedom needed to set the thermodynamic conditions at the inlet/outlet of the basic plant components ->

  once their values are fixed, inlet and outlet temperatures and mass flow rates at the black-box boundaries are fixed

- Optimization problem is subject to the heat transfer feasibility constraint, simply expressed by the condition that the minimum temperature difference between composite curves should be greater than a minimum $\Delta T$

# Composite Curves

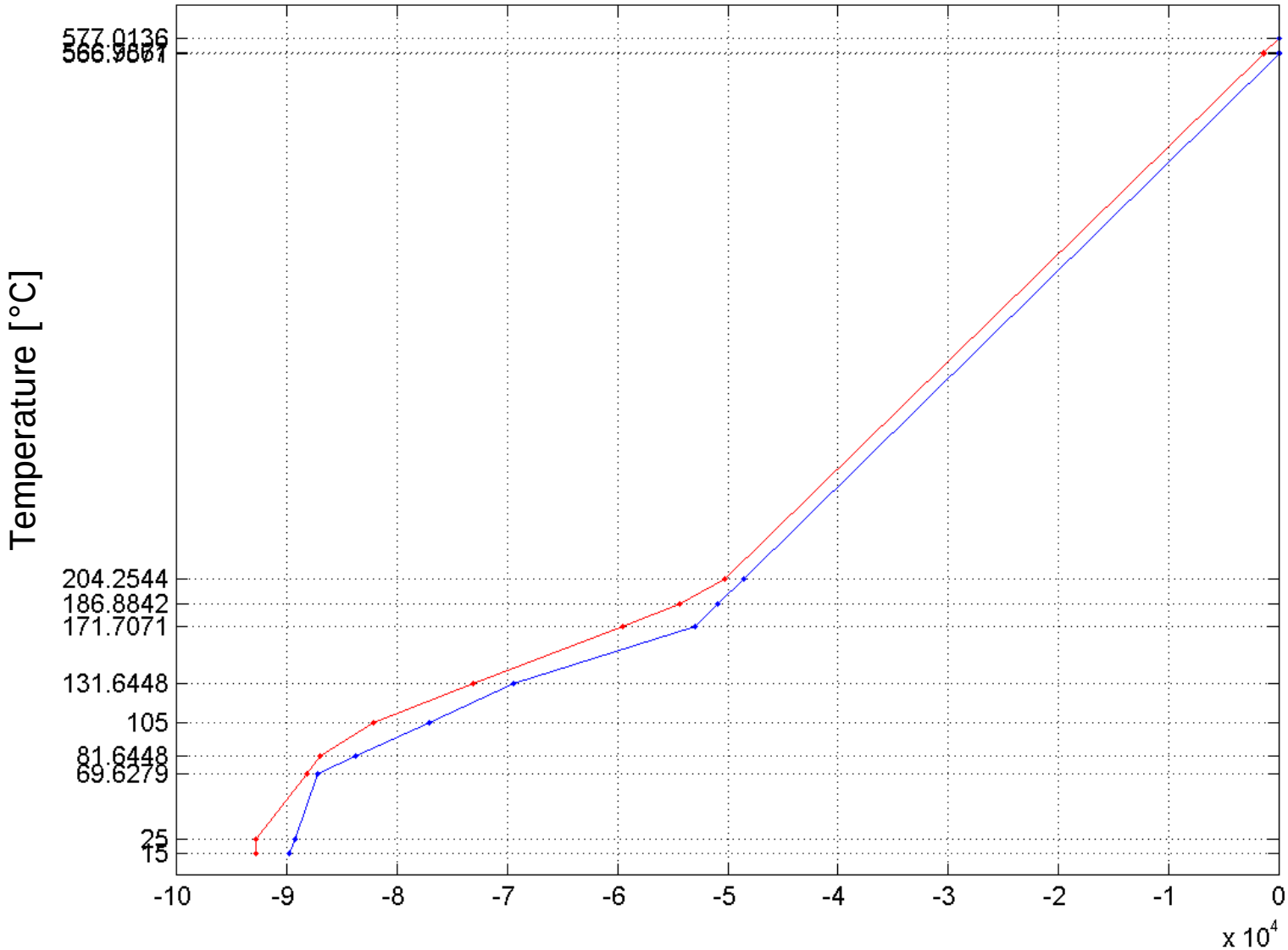
- Thermal capacities of flows which transfer heat in the same direction (hot to cold or vice versa) and in the same temperature interval are summed up.

- A Hot and Cold Composite Curves (HCC, CCC) are so drawn in a heat-temperature diagram, showing the sequence of the heat transferred at increasing temperature values according to the thermal capacities calculated for hot and cold flows, respectively

- No external hot sources exist -> HCC and CCC have the same ending abscissa

- The black-box may release heat to the ambient -> the projection of the HCC on the abscissa is longer than that of the CCC

# Composite Curves

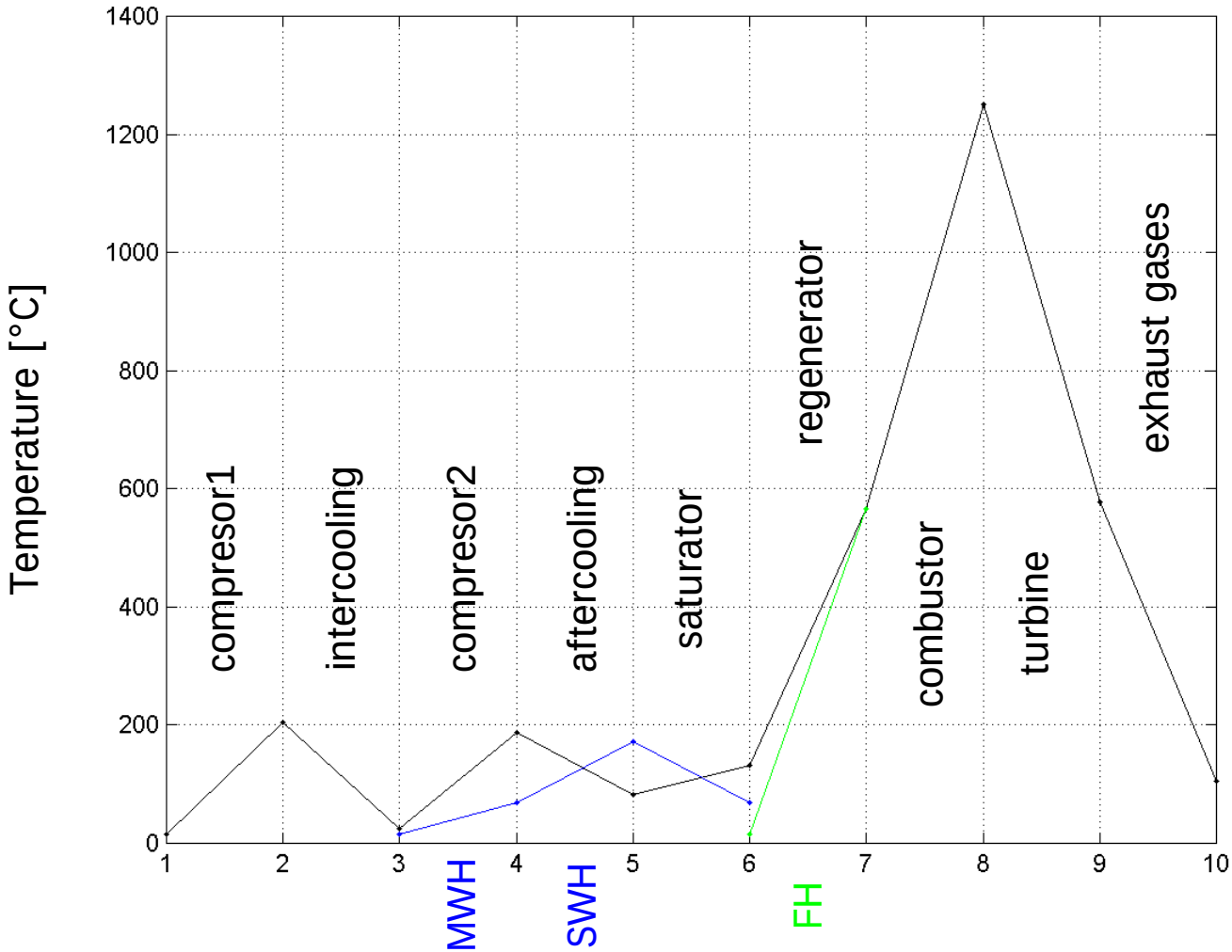


# Heat transfer in the black-box

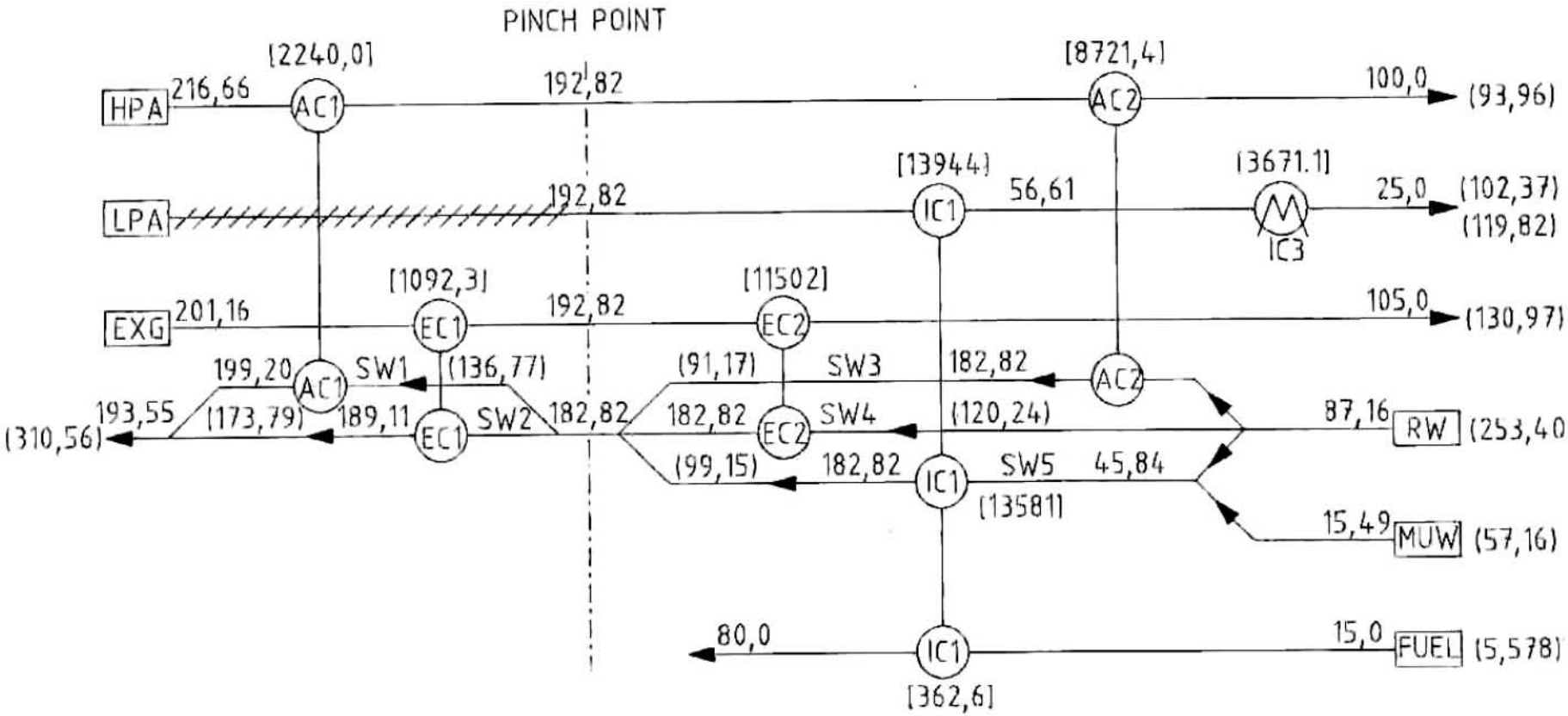
- In the search for the optimum total plant exergetic efficiency, the optimization algorithm ***finds implicitly*** the condition of most efficient heat transfer in the black-box (optimum matching between hot and cold thermal flows)

-> optimum matching is meant as the set of inlet and outlet temperatures and mass flow rates of the hot and cold streams deriving from the independent variables set which minimizes the distance between the CC

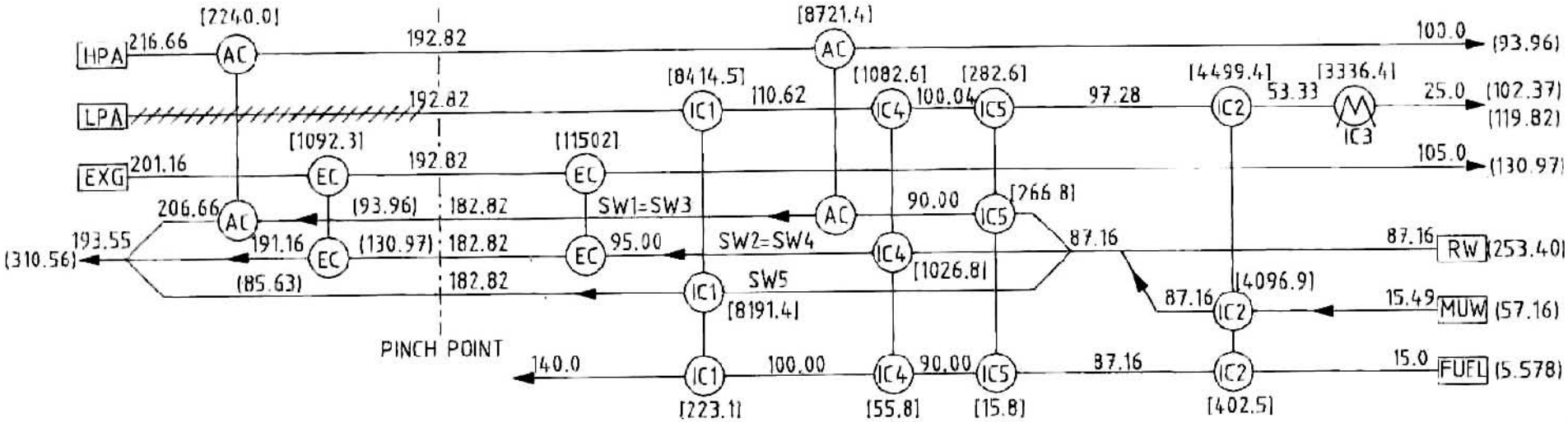
# Temperature Profiles



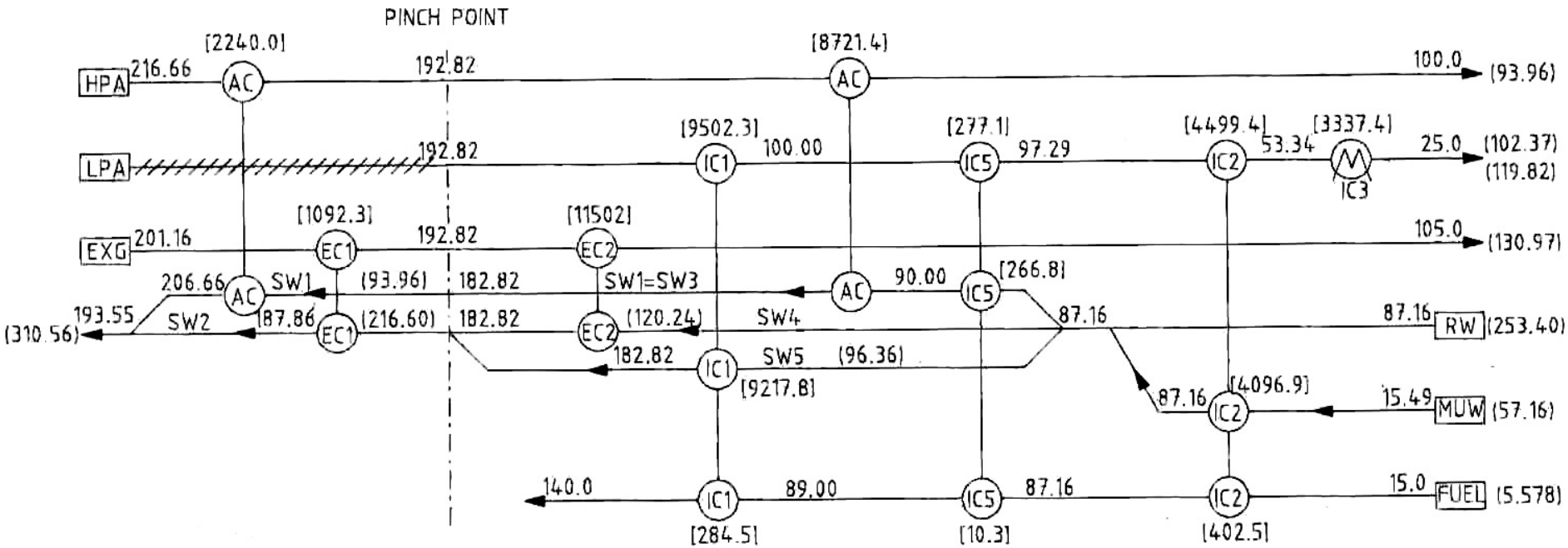
# HAT cycle heat exchanger network (1)



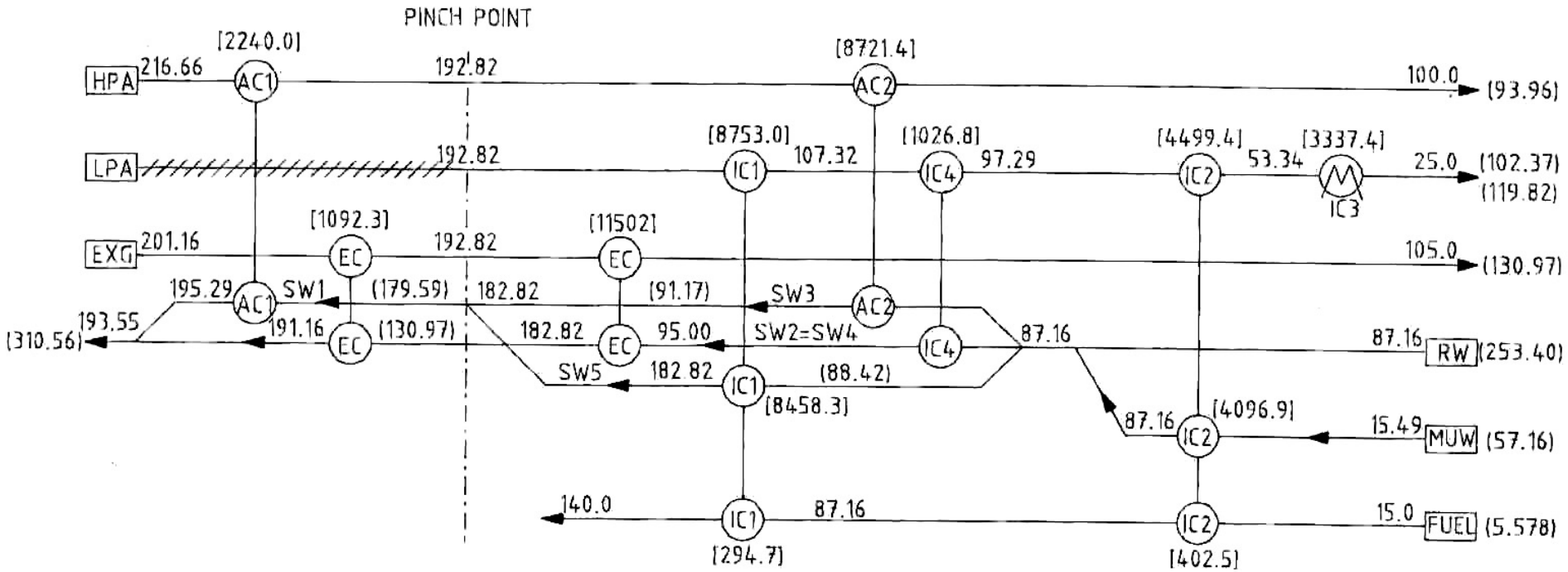
# HAT cycle heat exchanger network (2)



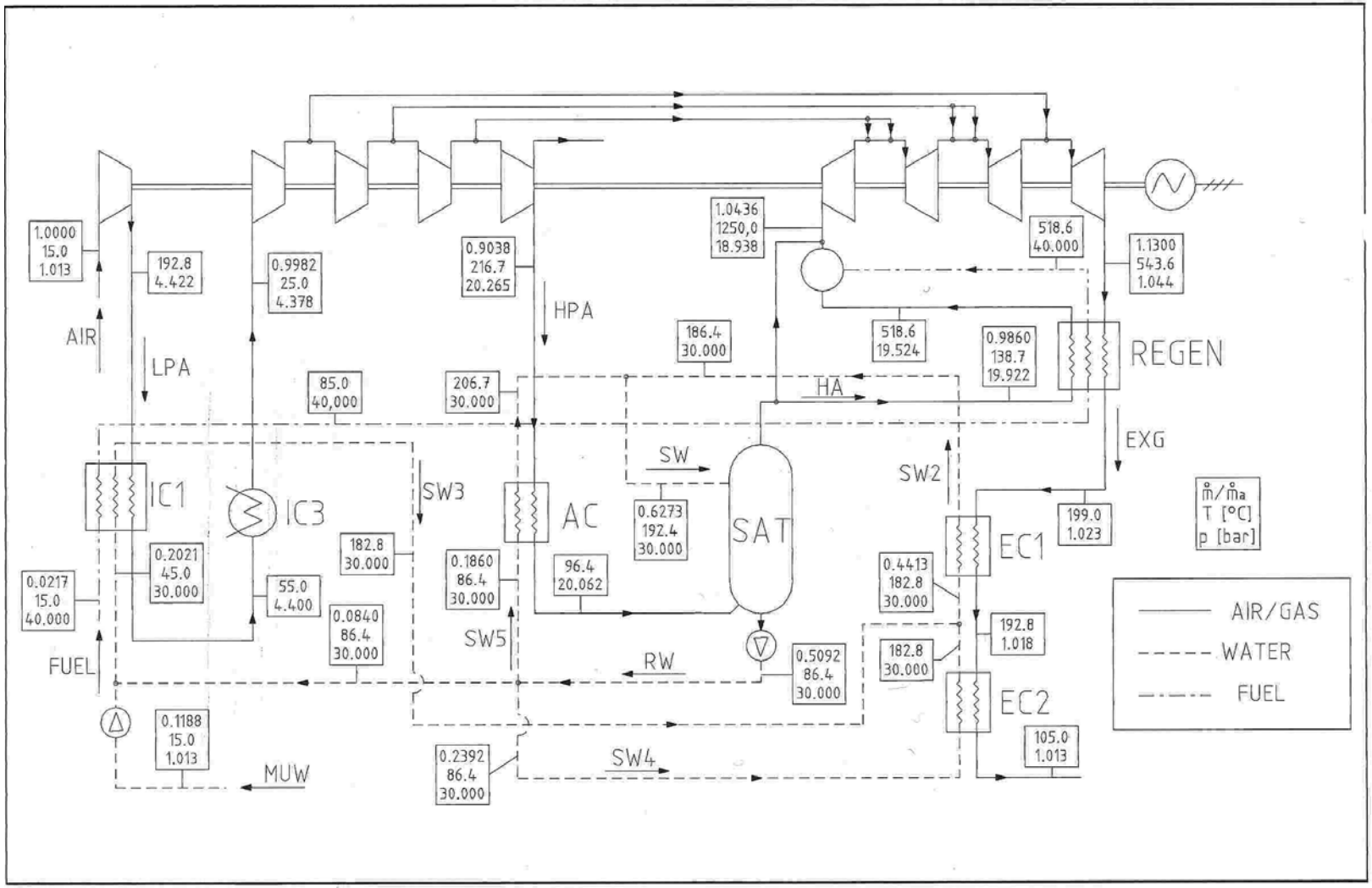
# Heat exchanger network (3)



# Heat exchanger network (4)



# HAT cycle plant



# Building the heat exchanger network (HEN)

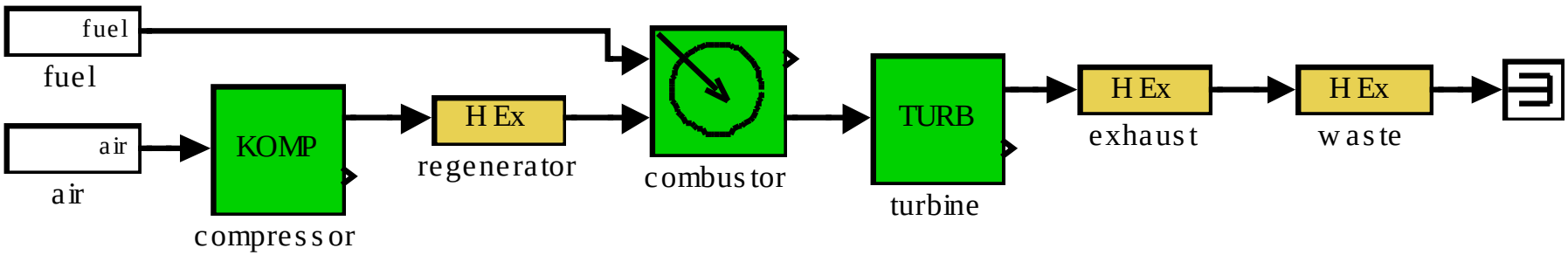
Need of fulfilling black-box optimal boundary conditions (corresponding to achieving the maximum total plant exergetic efficiency) and minimum pinch point ($\Delta T_{PP}$)

HEN can be built in two different ways:

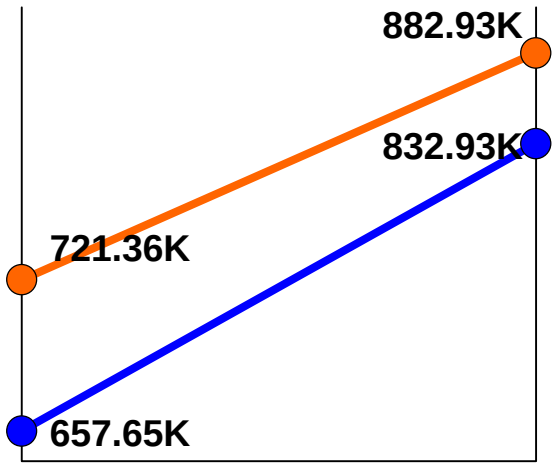
1) No mixing at different temperatures
   -> same composite curves;
2) Mixing at different temperatures
   -> different composite curves ($\Delta T_{PP}$ may or not be fulfilled)

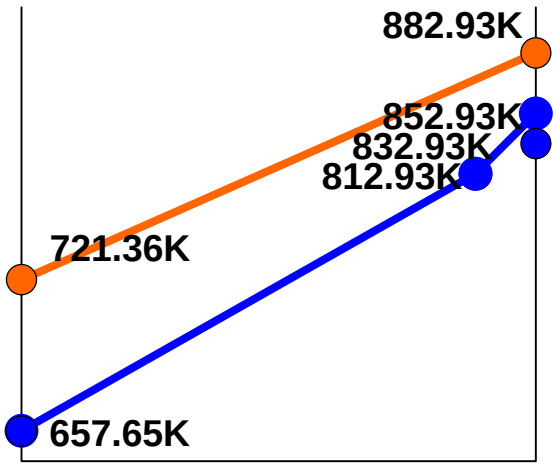
Other solutions in which $\Delta T_{PP}$ is respected but boundary conditions are not fulfilled -> lower exergetic efficiency - different composite curves

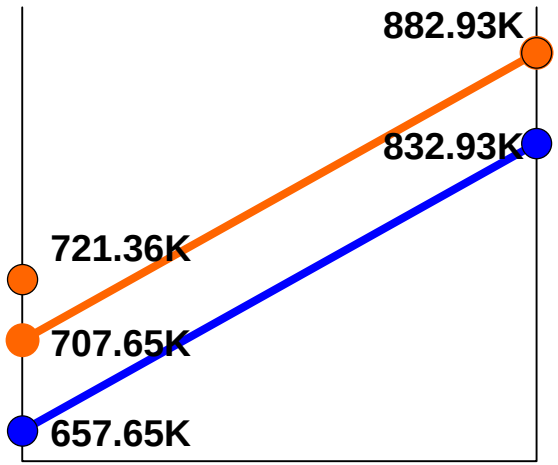
# Basic Plant Configuration
# Regenerative gas turbine cycle

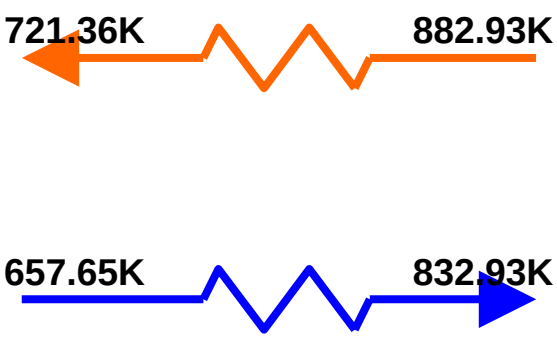


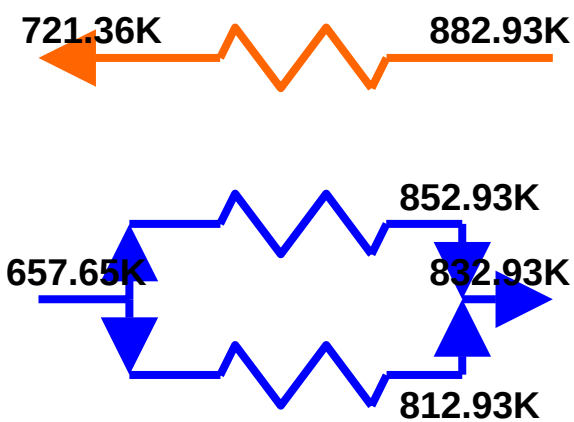
# Air preheating - composite curves

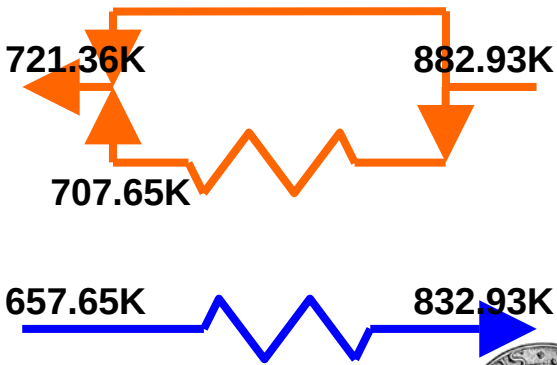


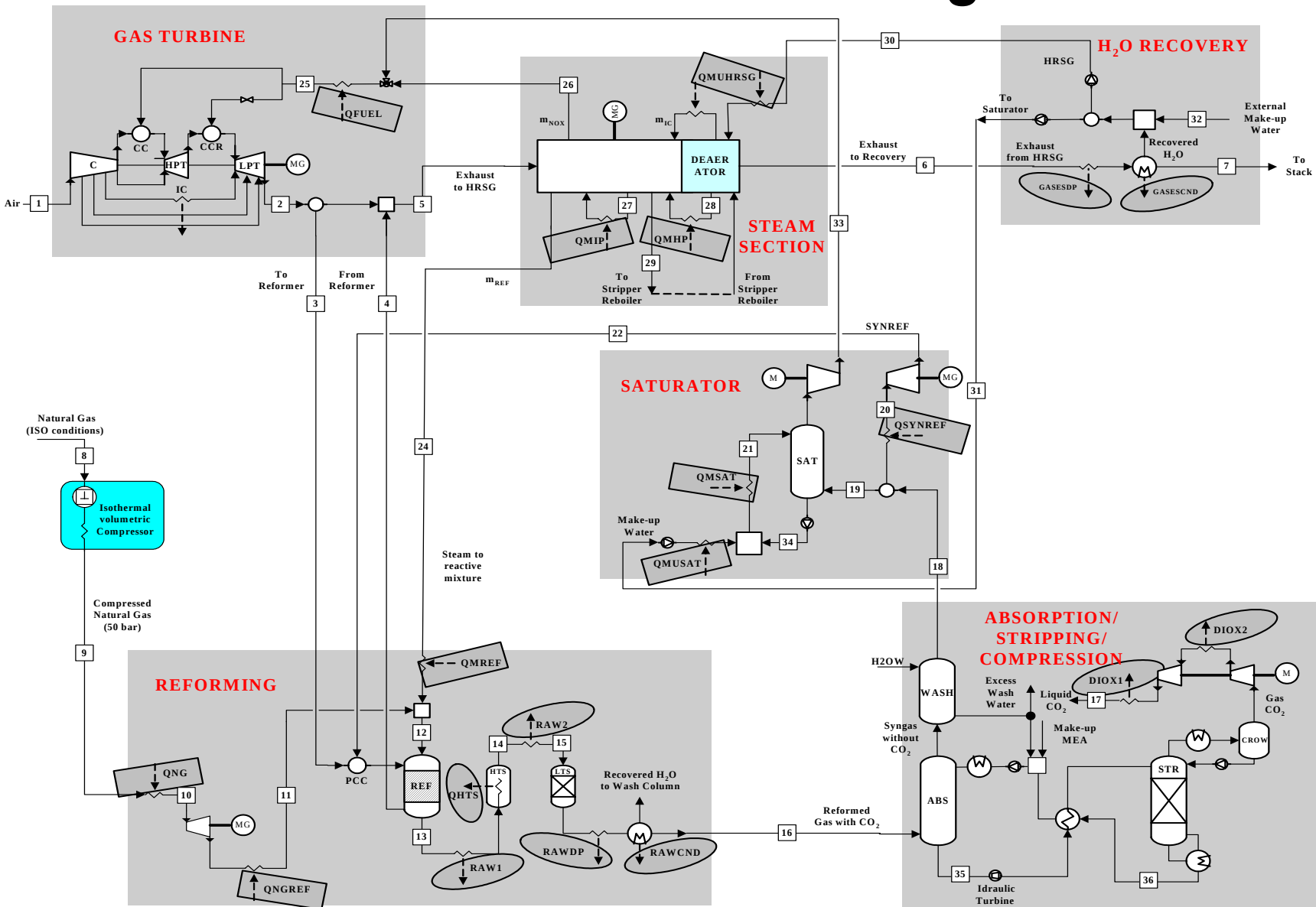



# CRCC “ Basic Plant Configuration “



# CRCC heat transfer section

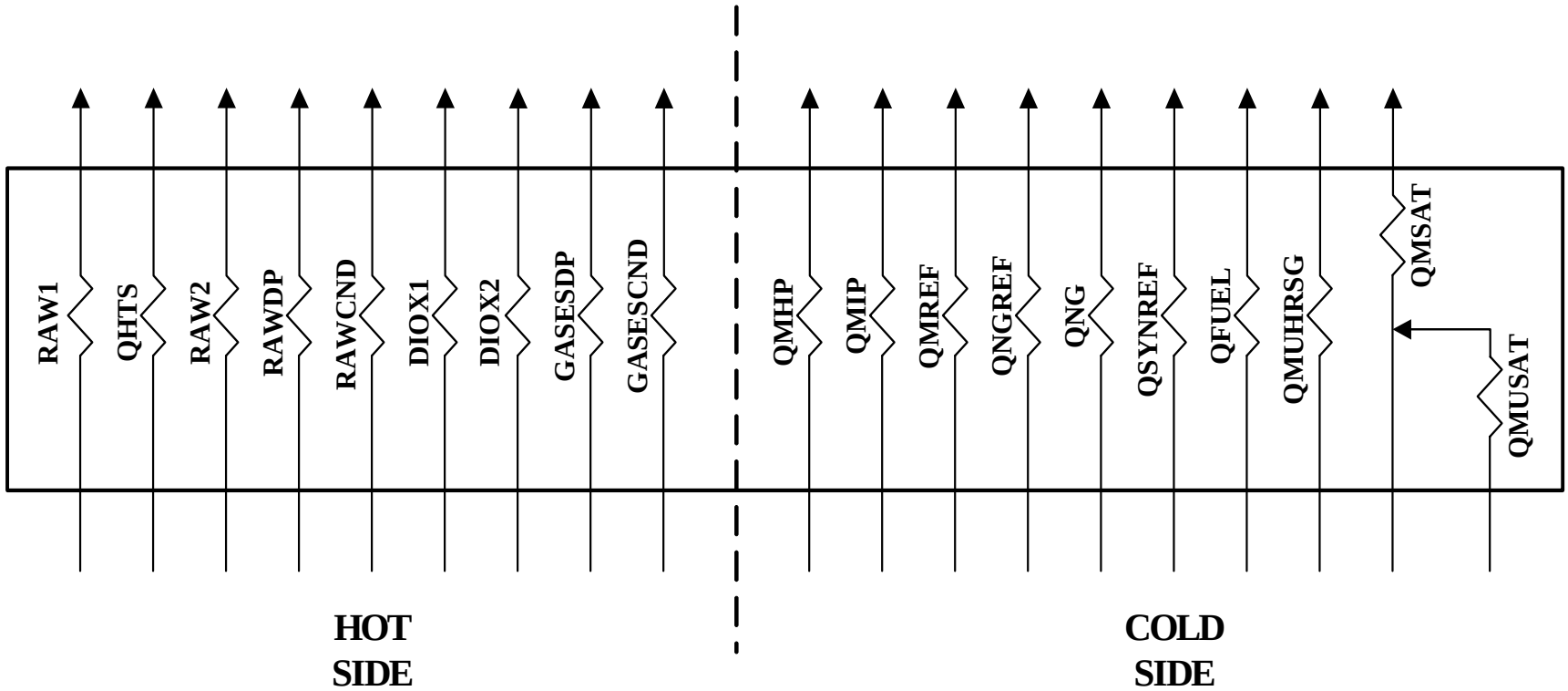
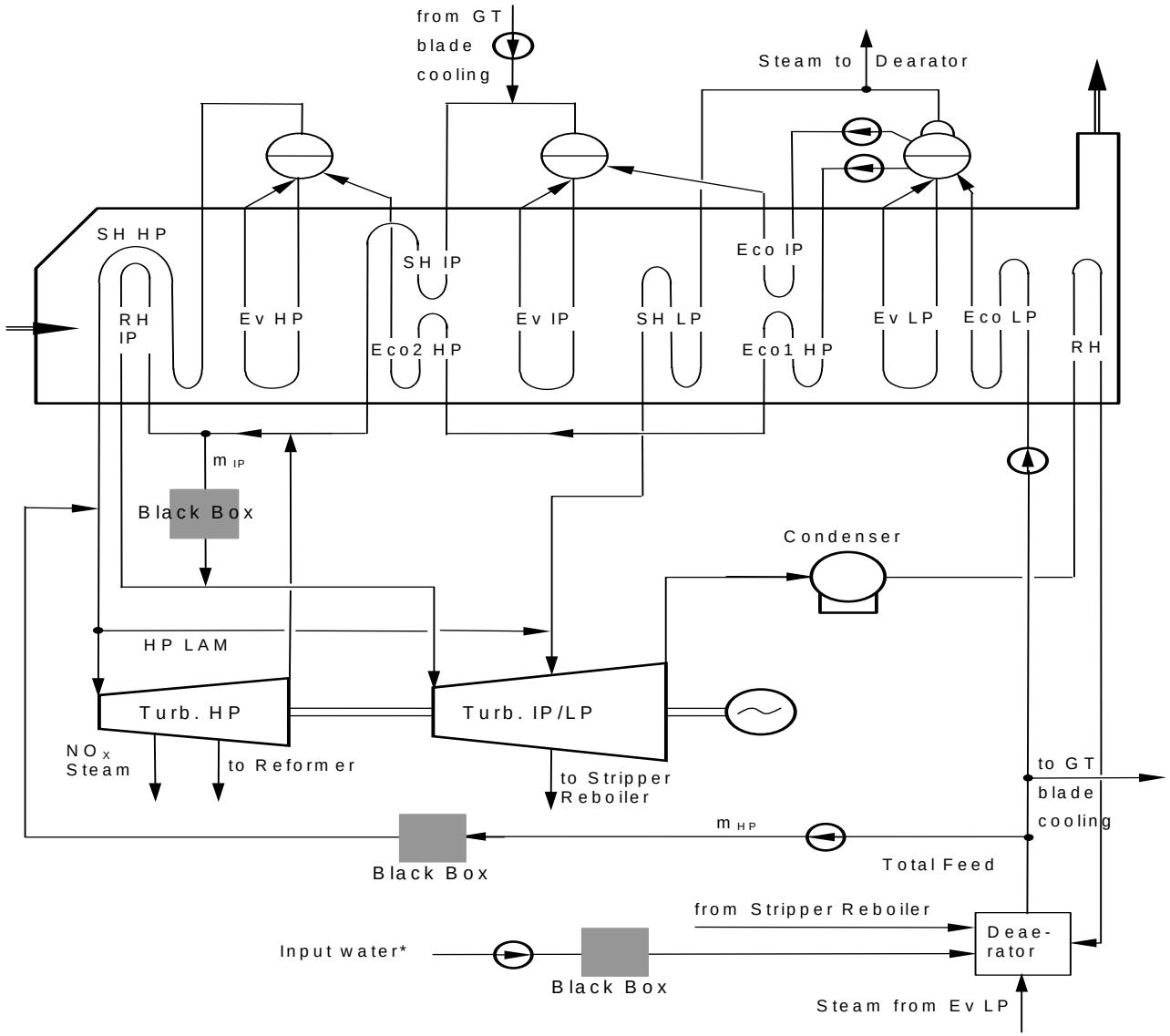



Fig.2 Black-box representing the heat transfer section in the basic plant configuration

# Interactions between HRSG and black-box




*Input water = Recovered $H_2O$ + Ext. Make Up – Saturator Make Up

# Design improvement procedure for the "CRCC Basic Plant Configuration"

- **Problem**: high number of free variables in the design improvement procedure:

  1) decision variables in the components outside the heat transfer section

  2) variables at the boundaries of the heat transfer section (inlet/outlet temperatures and mass flow rates of the thermal flows in the black-box)

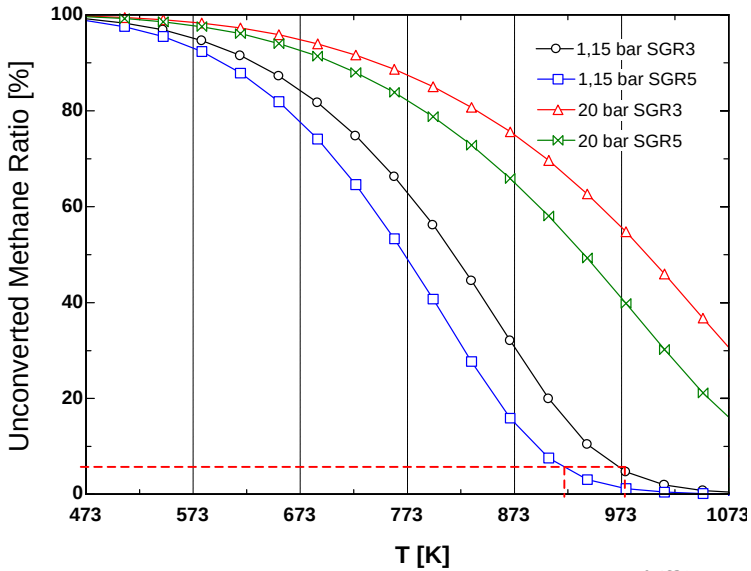
-> need of reduction of the degrees of freedom at the heat transfer section boundaries

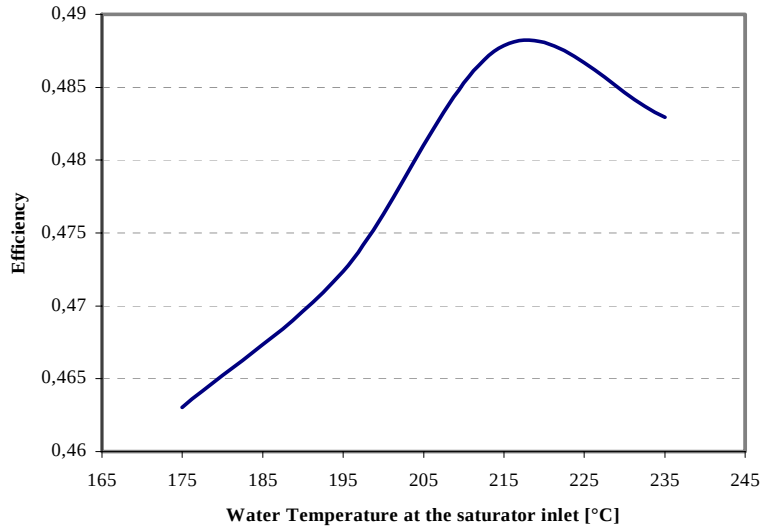
-> Because of the system complexity, system is simulated into parts (sections), no optimization algorithms are used

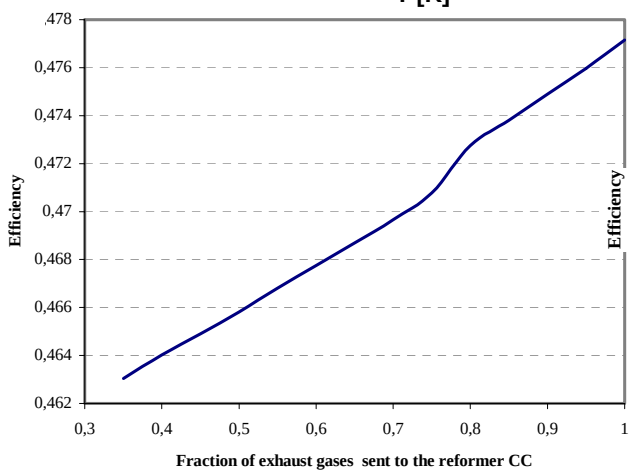
# Design improvement procedure for the "CRCC Basic Plant Configuration"

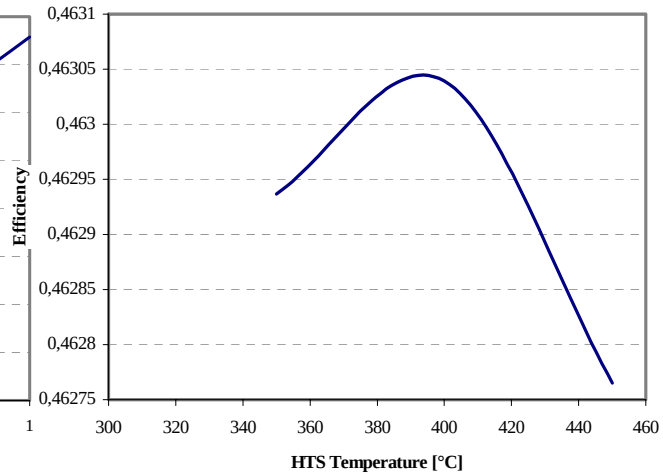
- Preliminary thermodynamic analyses are performed to understand whether some of the decision variables can be fixed as parameters or show predictable trends
- Series of simulation runs of the total system are carried out by varying the remaining decision variables one at a time
- Basic importance of a correct choice of the reformer operating variables

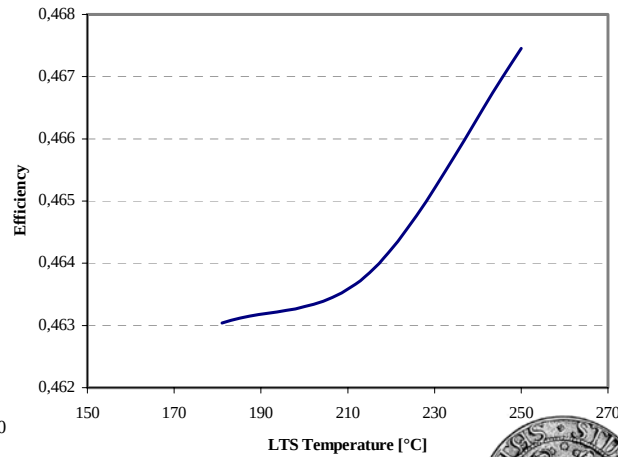
# Preliminary thermodynamic analysis



# Independent variables of the "basic plant configuration"

| VARIABILE | | TARGET |
|---|---|---|
| Reformer Pressure | $p_{REF}$ | Optimize (10 - 22- 30 bar) |
| Gas Temperature at the reformer outlet<br>Steam / Natural Gas Ratio | $T_{REF}$<br>SGR | $T_{REF}$ and SGR are functions of $p_{REF}$ and they are related if methane conversion ratio is fixed (95%) |
| HTS Temperature | $T_{HTS}$ | Optimize (range: 350-475°C) |
| LTS Temperature | $T_{LTS}$ | Optimize (range: 180-250°C) |
| Water temperature at the saturator inlet | $T_{in,SAT}$ | Optimize |
| Water mass flow rate at the saturator inlet | $m_{in,SAT}$ | Fix at constant value (mole frac. $H_{2)}$ |
| Exhaust gas mass flow rate to reformer | $m_{PCC}$ | Optimize (range: 35-100% GT outlet |
| Reformer reactive mixture temperature | $T_R$ | Optimize (450 - 500 - 565°C) |
| Exhaust gas temperature at the reformer outlet | $T_{FUMI,REF}$ | Optimize (range: 480 - 540°C) |
| Preheating of SYNGAS | $T_{PRE,SYNGAS}$ | Minimize |
| Preheating of natural gas | $T_{PRE,NG}$ | Optimize (range: 500-800°C) |
| IP steam mass flow rate superheated with heat recovered in the black-box | $m_{IP}$ | Optimize (range: 10-20 kg/s) |
| HP water mass flow rate heated, evaporated and superheated with heat recovered in the black-box | $m_{HP}$ | Maximize |

# Heat transfer maximization

- In order to have the maximum feasible heat transfer in the “black-box”, a Fortran routine is included in the plant simulation model to set the last of the decision variables ($m_{HP}$) while keeping the other variables as constant parameters varied in selected ranges

As in previous examples:

- the heat transfer feasibility constraint applies, i.e. the minimum temperature difference between composite curves should be greater than a minimum $\Delta T$ (it is directly applied to solve for $m_{HP}$)

- no external hot sources exist -> HCC and CCC have the same ending abscissa

- the black-box may release heat to the ambient -> the projection of the HCC on the abscissa is longer than that of the CCC

# Heat transfer maximization

- The only HP water mass flow rate re-circulated outside the HRSG ($m_{HP}$) is considered as decision variable in the black-box sub-optimization (heat transfer maximization) while keeping the other variables as constant parameters (varied in selected ranges)

- Each $m_{HP}$ value corresponds to a specific shape and position of the Cold Composite Curve.

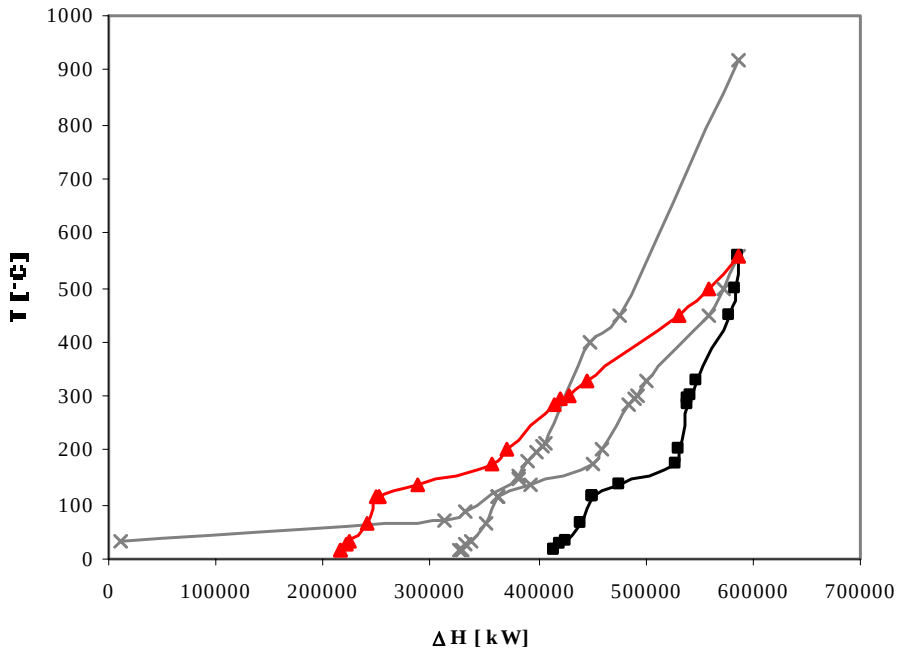



Fig. 9 Cold composite curves obtained using values of $m_{HP}$ lower than (CCC1), greater than (CCC2) and equal to (CCC) the maximum one.

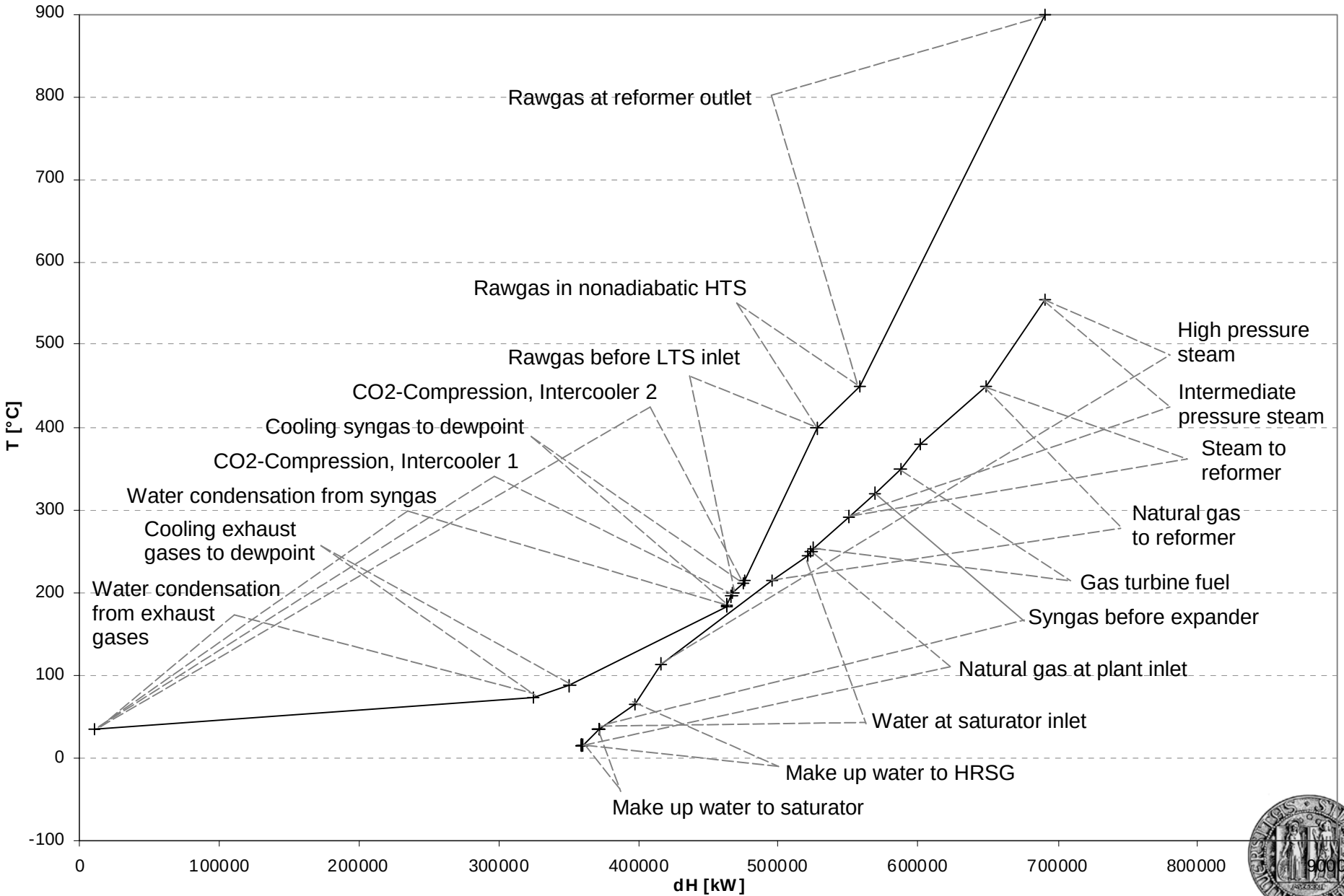
# Decisions about thermal flows to be included in the black-box

- In general, to have maximum freedom in the definition of the system structure and parameters, all thermal flows should be included in the heat transfer section (black-box)

Thermal flows not “directly” included in the black-box of the CRCC plant:

- structure of the HRSG is considered to be fixed (is part of the basic components of the system), but HP and IP steam can be produced also outside the HRSG using heat available from the black-box (p and T levels decided in advance)
- p and T levels of thermal flows taken from the black-box and used in the Section for Absorption/Stripping/Compression of the $CO_2$ decided in advance

# On the synthesis of complex energy systems with several heat transfer interactions by Andrea Lazzaretto



# Influence of variations of the design variables on the composite curves

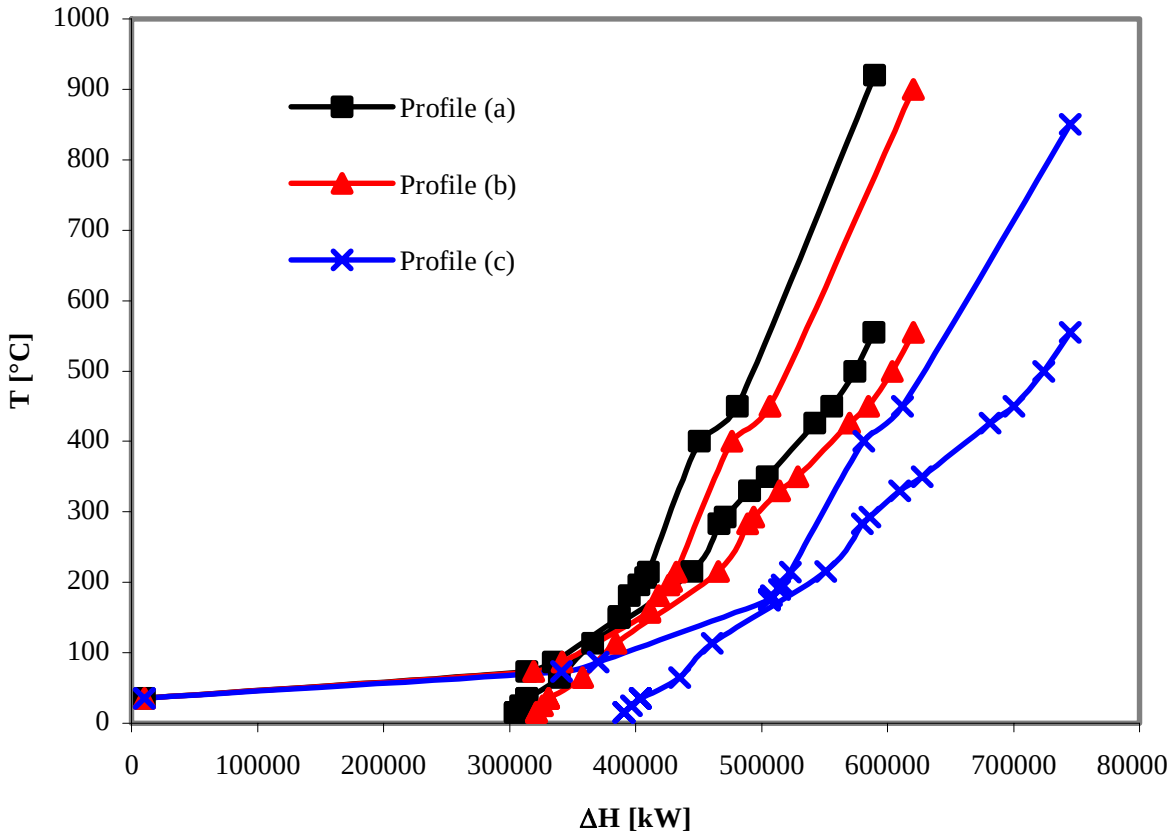



**Fig. 12 "Composite Curves" at maximum total plant efficiency for three different thermal profiles (numbered according to the order in Figure 10) of the reformer reactor operating at 22 bar.**

# Influence of variations of the design variables on the black-box composite curves

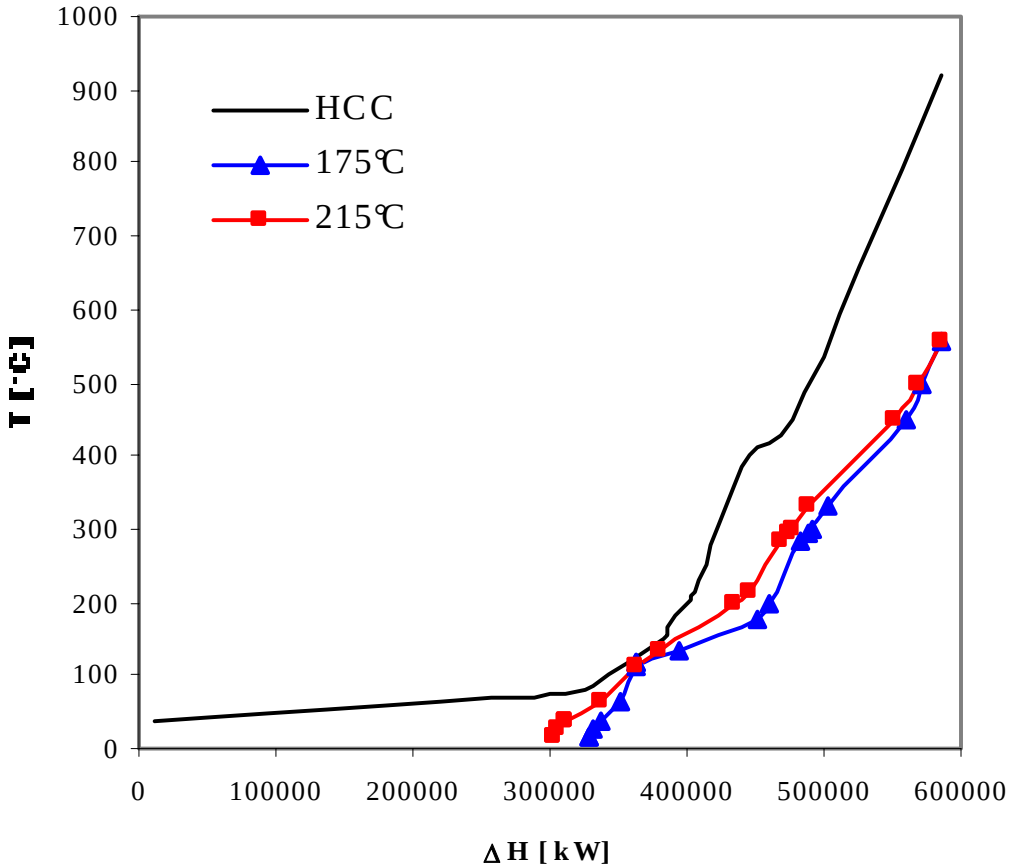
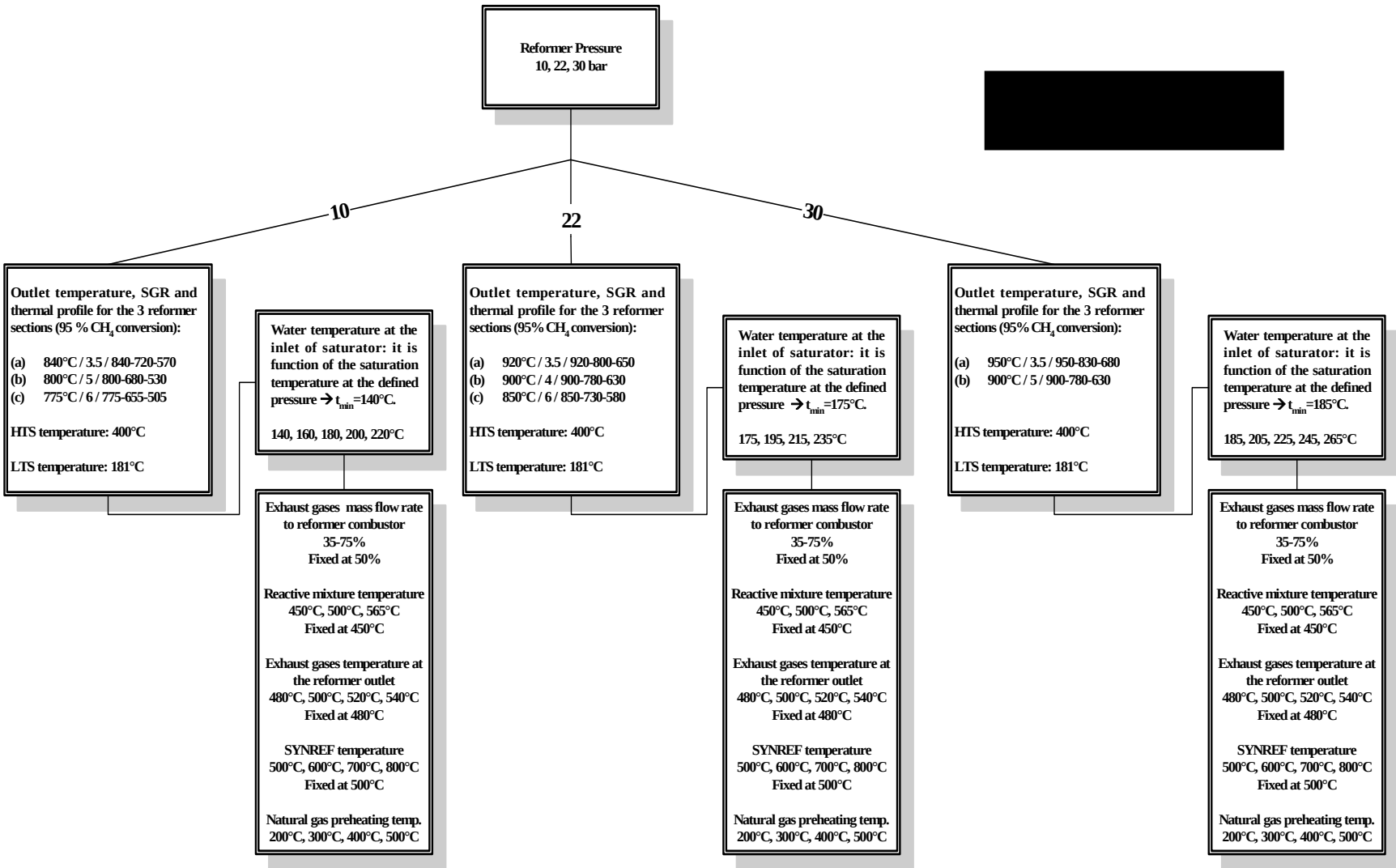



**Fig. 11 "Composite Curves" for two values of the water temperature at the saturator inlet and reformer pressure fixed at 22 bar.**

# Priority order in the variation of the decision variables in the First Series of simulation runs



# Design improvement procedure: First series of simulation runs

Design variables are varied in the ranges of Figure 10, and

- the intermediate pressure mass flow rate re-circulated outside the HRSG ($m_{IP}$ = 20 kg/s), and

- the $H_2$ molar fraction at the saturator outlet equal to 65%

The high pressure mass flow rate re-circulated outside the HRSG calculated by the Fortran routine in order to maximize the heat transfer in the black box is $m_{HP}$ = 115 kg/s and the maximum thermal efficiency of the total plant is 50.96%

# Indications for design improvement from the composite curves

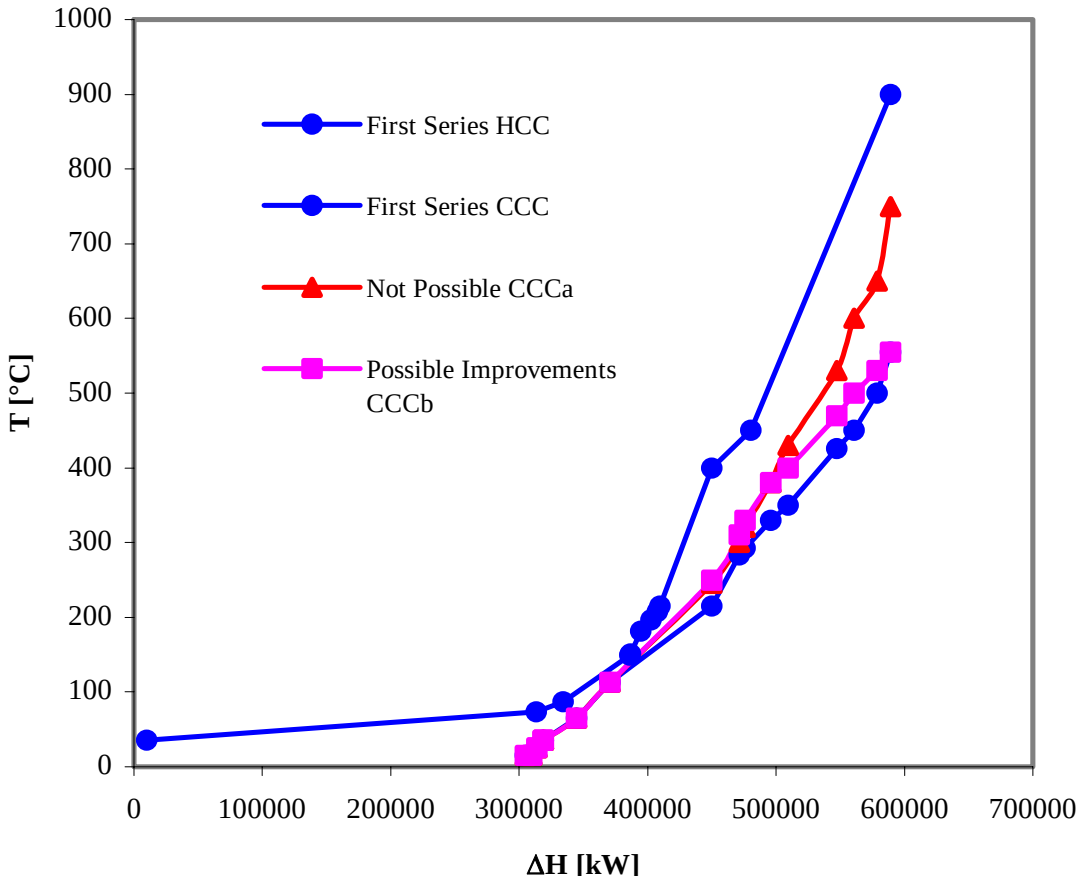



**Fig. 13 Possible actions on the cold composite curve (CCC) for improving the performances of the best plant configuration obtained in the first series of simulation runs (reformer pressure equal to 30 bar).**

# Second Series of simulation runs

- In the second series:

  - The intermediate pressure mass flow rate ($m_{IP}$) re-circulated outside the HRSG is decreased from 20 to 10 kg/s;

  - The $H_2$ molar fraction at the saturator outlet is increased from 65% to 70%.

  Among the variables indicated in Figure 10:

  - The preheating temperature of the syngas to the reformer before expansion is set to 250°C, instead of 500°C

  - The temperature of the exhaust gases from the reformer is set at 400°C, instead of 480°C

- Using these values, the high pressure mass flow rate re-circulated outside the HRSG obtained by the Fortran routine to maximize the heat transfer in the black box is $m_{HP}$ = 120 kg/s instead of 115 kg/s and the maximum thermal efficiency of the total plant is 52.32%.

# Results of the design improvement procedure

| Series of Simul. Runs | $p_{ref}$ [bar] | SGR | Temperature Profile [°C] | $T_{SAT}$ [°C] | $P_{TOT}$ [MW] | $P_{spec}$ [kJ/kg] | $CO_2$ Spec. Emissions [kg$CO_2$/kWh] | $\eta_t$ [%] |
|---|---|---|---|---|---|---|---|---|
| Reference Simple Combined Cycle Configuration | | | | | | | | |
| | / | / | / | / | 396 | 717.4 | 0.363 | 57.76 |
| Optimization Steps | | | | | | | | |
| I | 10 | 3.5 | 570-720-840 | 200 | 392 | 770.71 | 0.061 | 47.25 |
| | | 5 | 530-680-800 | 200 | 383 | 763.3 | 0.057 | 46.16 |
| | | 6 | 505-655-775 | 200 | 375 | 751 | 0.058 | 45.22 |
| | 22 | 3.5 | 650-800-920 | 215 | 405 | 870.17 | 0.055 | 48.98 |
| | | 4 | 630-780-900 | 215 | 404 | 832.4 | 0.054 | 48.82 |
| | | 6 | 580-730-850 | 215 | 395 | 833.6 | 0.051 | 47.65 |
| | 30 | 3.5 | 680-830-950 | 245 | 410 | 847.54 | 0.058 | 49.37 |
| | | 5 | 630-780-900 | 245 | 423 | 893.7 | 0.0514 | 50.96 |
| Final Optimized Configuration | | | | | | | | |
| II | 30 | 5 | 630-780-900 | 245 | 434.16 | 900 | 0.05 | 52.32 |

**Tab. 4 Results obtained by the first (I) and second (II) series of simulation runs.**

# Comparison between the composite curves of the two series of simulations runs

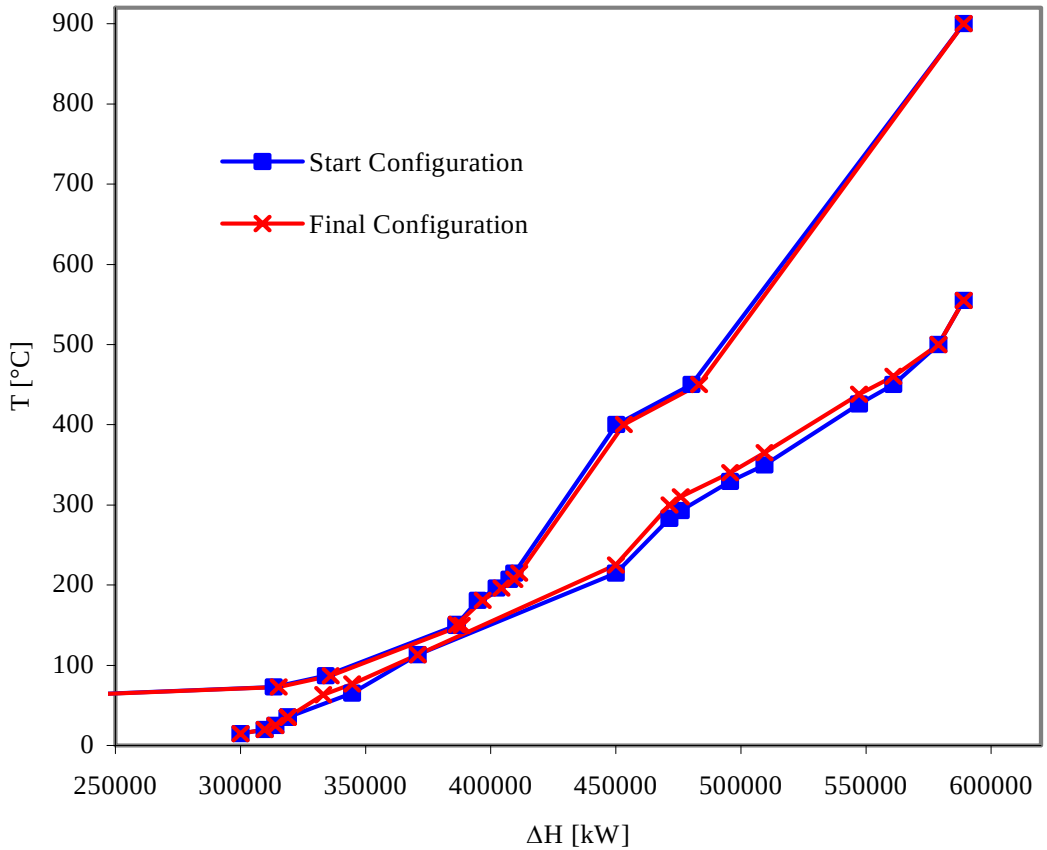



**Fig. 14 Comparison between the CCs obtained in the two series of simulations with a reformer pressure of 30 bar.**

# CONCLUSIONS

- Method for the design improvement of a plant configuration (named “basic”) in which heat is transferred in a “black-box” without having the heat exchanger structure defined
- The method keeps the problem of the structural optimization of the system independent of the structure of the HEN
- When an optimization problem is set up for the basic plant configuration, the most efficient heat transfer in the black-box is directly found by the optimization algorithm
- If, conversely, a design improvement procedure is performed through a series of simulation runs, the optimum matching between thermal flows in the black-box is found at each step of the procedure using a sub-optimization procedure that maximizes the heat transfer between hot and cold flows

# CONCLUSIONS

- The method improves the comprehension of the heat transfer internal processes

-> it helps locate cold thermal flows to be heated and properly match them with all the hot thermal flows available

-> it helps minimize temperature differences in the heat transfer processes, and heat rejected to the environment -> maximize plant efficiency

-> it helps find directions for design improvement (new values for the design variables to be fixed as parameters)

# CONCLUSIONS

APPLICATION TO THE CRCC PLANT

- High reformer pressure (30 bar) with high methane conversion ratio (95%)
- Expander to recover the pressure content of the hydrogen sent to the reformer
- Saturator to lower NOx production and improve thermal recovery at low temperature
- Further advantages by the water recovery section because of the heat recovered in the black-box at low temperature

# Air Force Research Laboratory

*Defending America by Unleashing the Power of Innovative Aerospace Technology*

## Energy and Thermal Management

**David M Pratt, PhD**

U.S. AIR FORCE

*Integrity - Service - Excellence*

# Need For Energy and Thermal Management Program Planning

- **Current And Future Air Force Weapons Systems Lack The Necessary Power and Cooling Capacity To Provide Full Systems Level Capability**
- **Cooling Capacity Of Fuel Already Fully Utilized Leaving Little Room For Additional Cooling Needs**
- **Increasing Speed, Power, And Miniaturization Of Future Systems Continue To Stress Any Thermal Management Capability We Can Now Deliver**

Focused, High Level Initiative Is Needed To Support Today's And Tomorrow's Weapon Systems

# Need For Energy and Thermal Management Program Planning

- Define Focused Technology Transition Capability
  - Enhanced Systems Engineering Process Implementation
  - Better "Rules And Tools" for System Level Assessments
  - Understand Impact Of Technologies on System Performance
- Apply Systems Engineering Principles -- Thermal Management Considered Early in System Design
  - Assure Thermally Efficient Designs
  - Understand Power and Heat Generation Impacts
- Generate "Game Changing" Approaches To Thermal Management
- Develop Innovative and More Effective Material Systems
  - Fuels, Lubes And Seals
  - Power, Electronics, Actuation

Solution Requires Both Better Assessment Capabilities and More Robust Technologies

# Workshop Goals and Expectations

Address the Big Questions – How Much, How Bad

- **What are the stressing drivers**
- **Focus first on directed energy on airborne platforms**

Guide Technology Development

- **From your perspective, what are some key energy and thermal management technologies for challenges such as directed energy weapons on airborne platforms?**

Provide Information to Guide Resource Allocation, Technology Choices, Technology Designs, and Research Needs

- **What are highest payoff areas for energy and thermal management research investments?**
- **What systems-of-systems analysis methods are needed?**
- **How do we measure system level effectiveness?**

# Capablity Focused Tech Investment

## A Process for Integrating Solutions

**Col Michael B. Leahy, Jr.**
**Material Group Director**
**Air Vehicles Directorate**
**Air Force Research Laboratory**

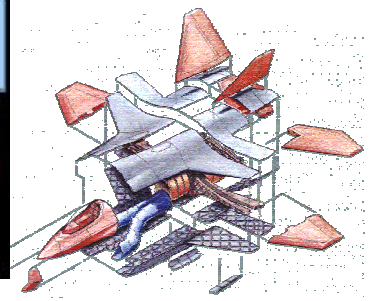
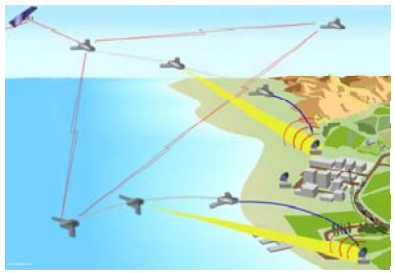
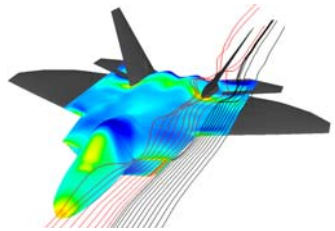
*"We give the Air Force its Wings"*

# Air Vehicles Directorate

Technology Developer and System Integrator

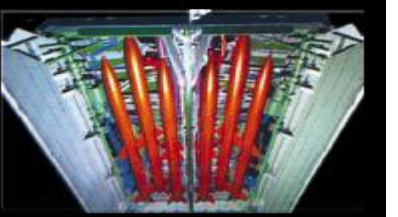
***AFOSR – Basic Research***

**Structures** | **Control Sciences** | **Aero Sciences**

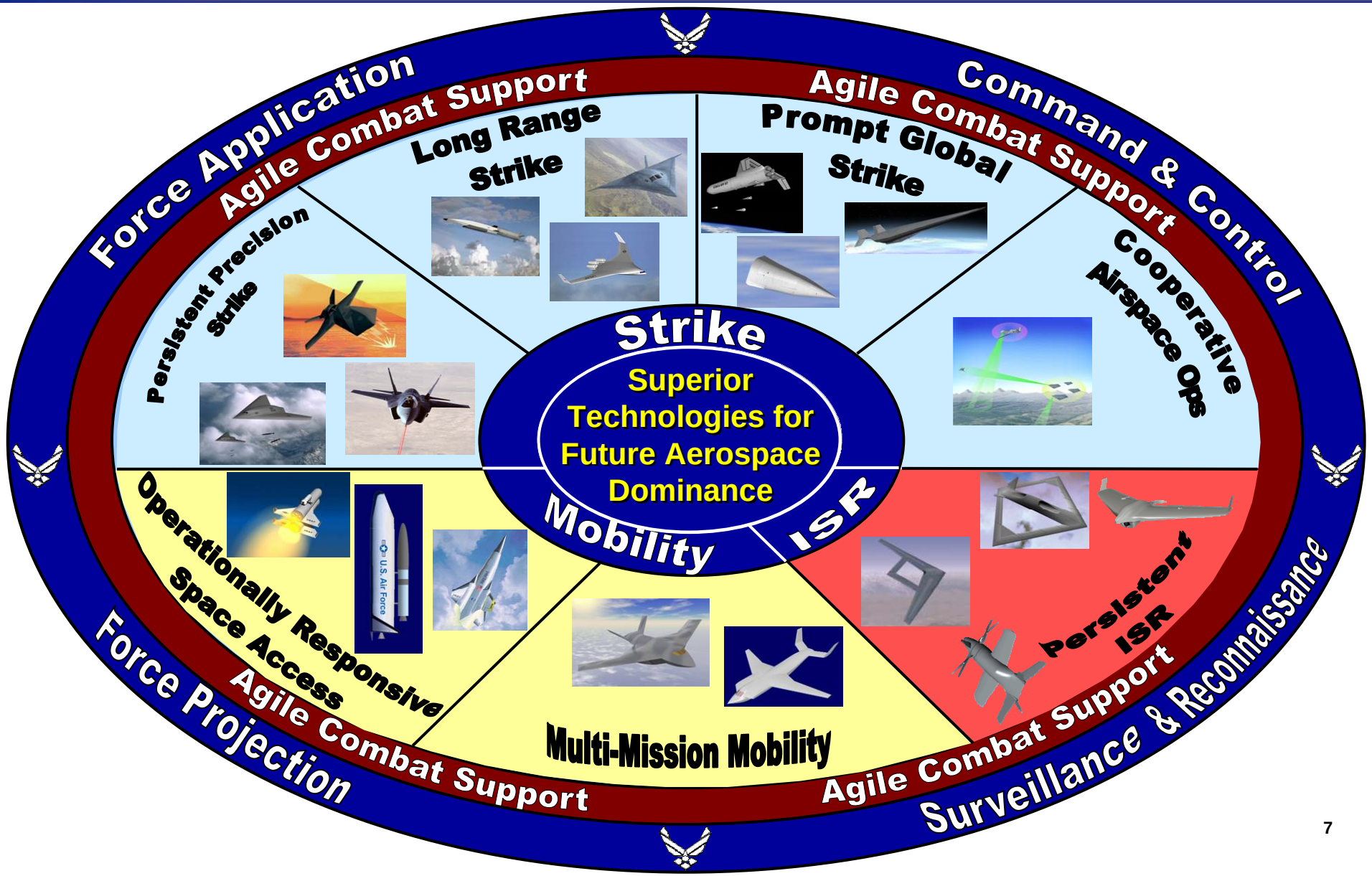




## *Aerospace Systems Integration*

*Develop and transition superior air vehicle technology solutions that enable dominant military aerospace vehicles*



# What we bring to the fight



# Capability Focused Tech Investment

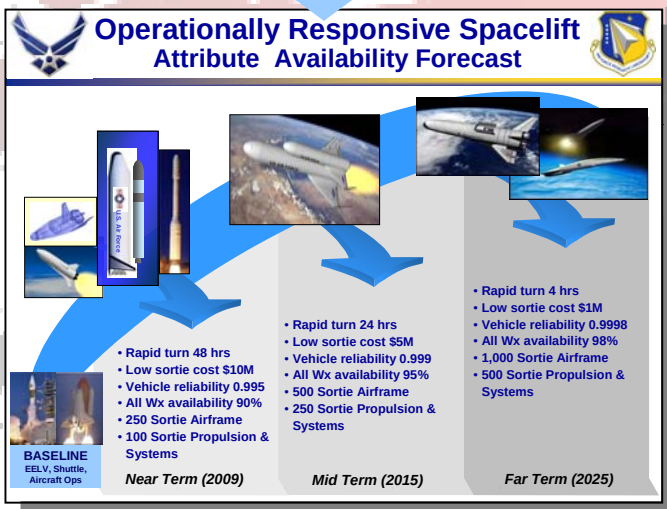
## Top Down Capability Driven Process to Support Strategic System Tech Investment Decisions

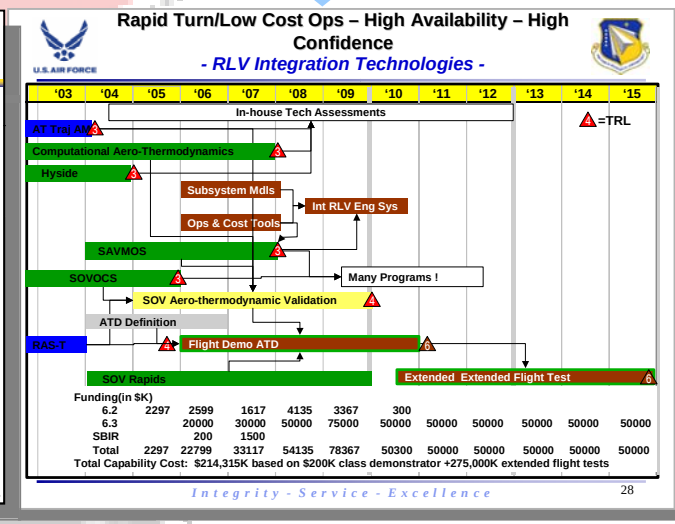
**Capability** — Attributes — Product (s)

Effects needed? When?

S&T needed? When?

What do we have to do to deliver it?




**Directly links tech programs to capability gaps/desires**

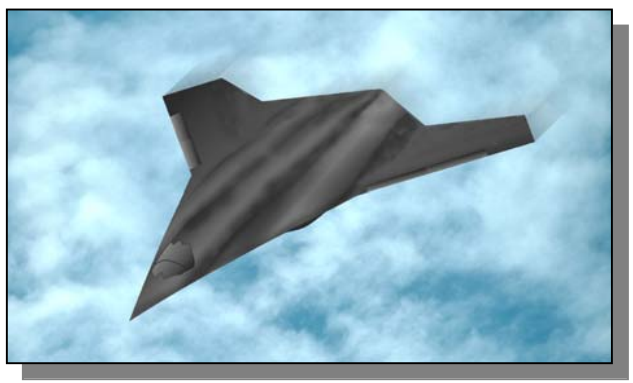
# Capability Focused Tech Investment

# Long Range Strike

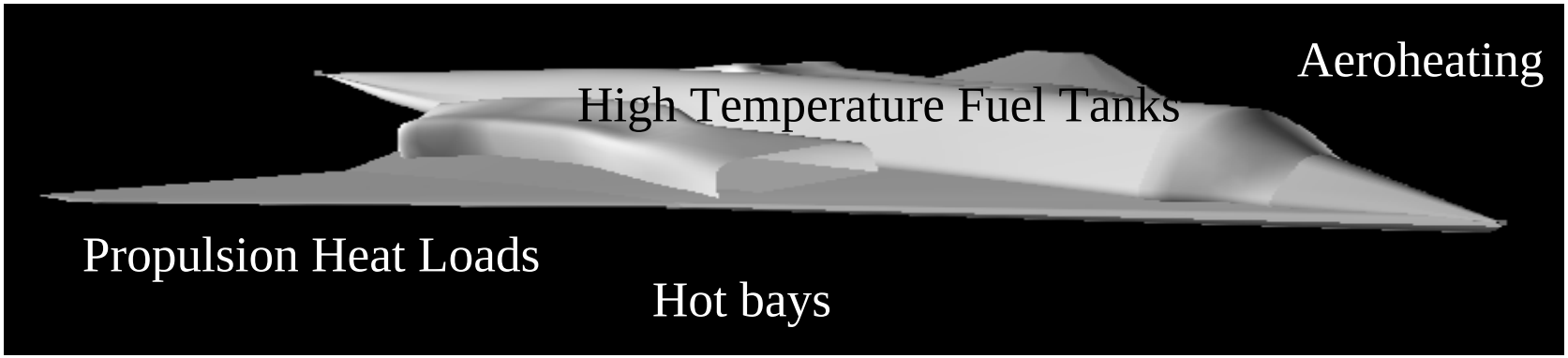
***"The capability to achieve a desired effect(s) rapidly and/or persistently, on any target, in any environment, anywhere, at any time."***

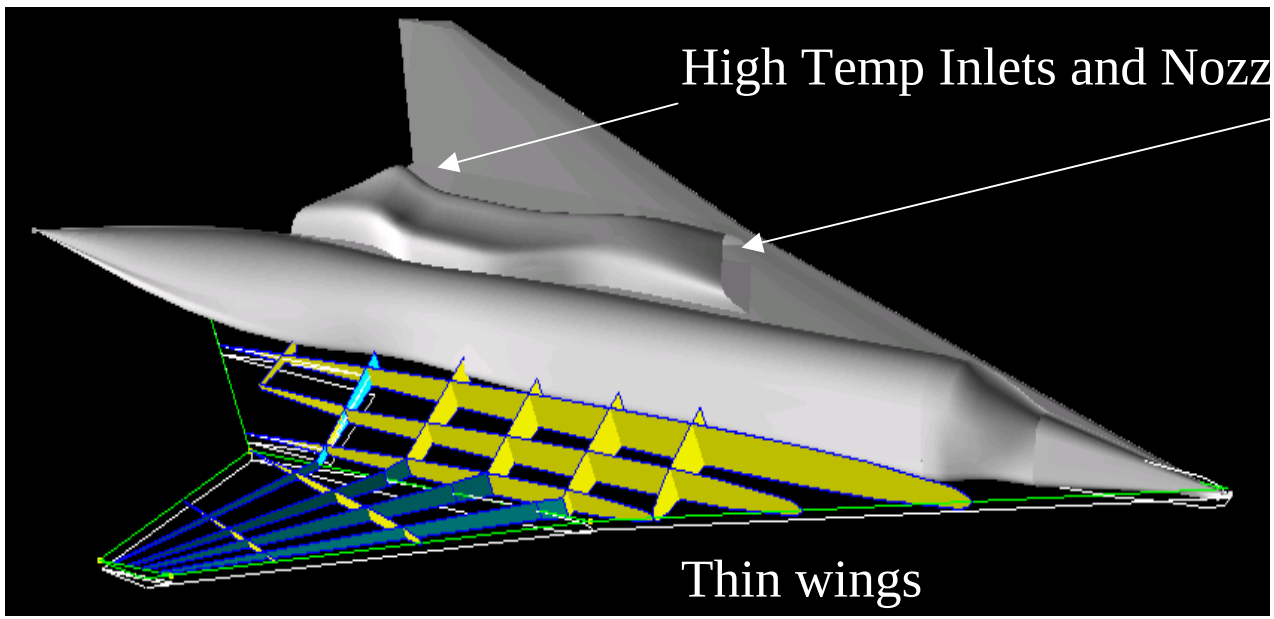
- **Regional to Intercontinental Reach**
- **Hold Targets at Risk for Extended Time**
- **Survive & Operate in Anti-Access Environment**
- **High Volume and Flexible Payload**
- **Network Centric Operability**

**Based on LRS AoA FY07 and Multiple LRS Studies FY01-03**



# Thermal Structures for Responsive Global Strike



# Responsive Global Strike

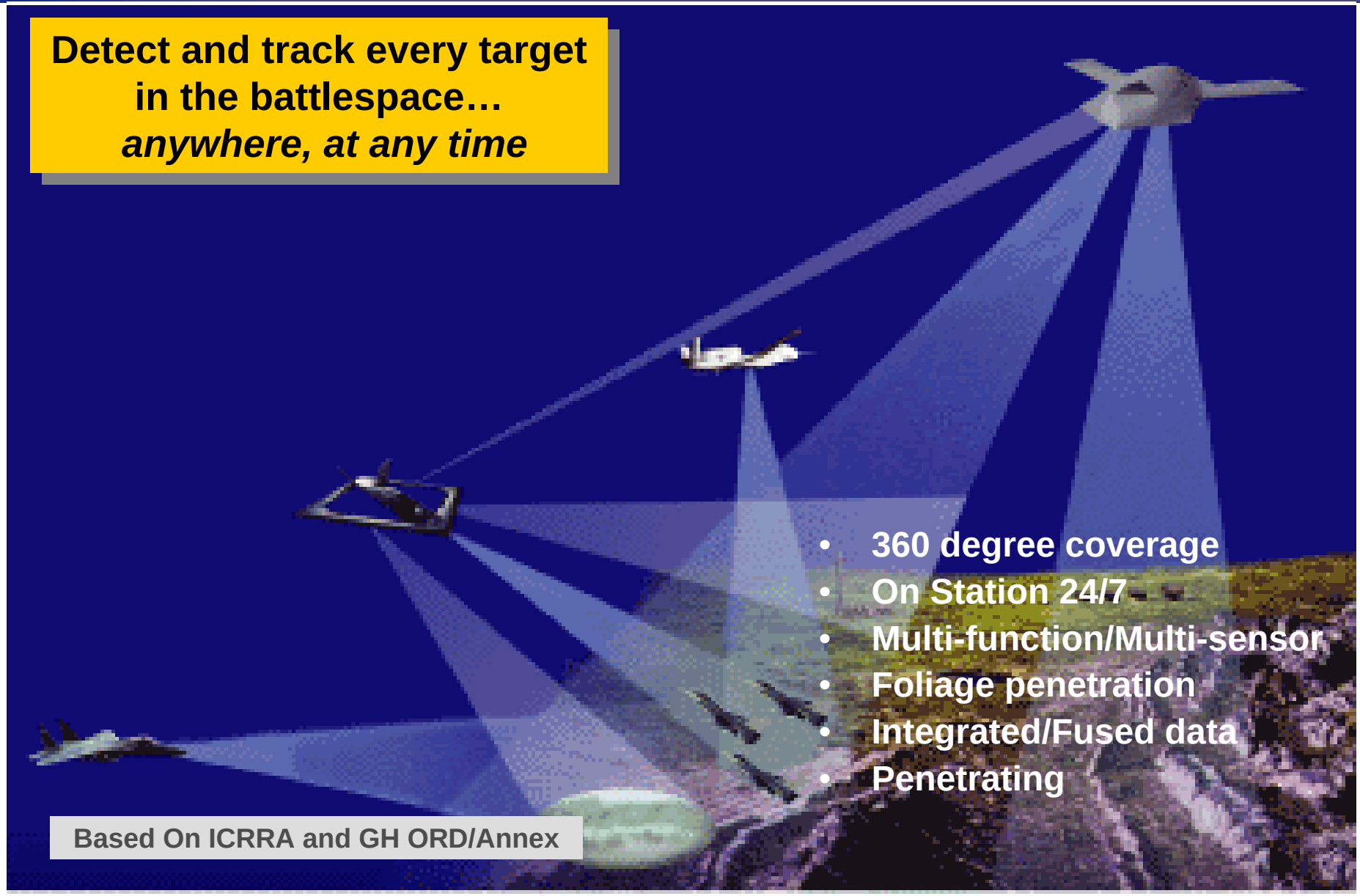
- **Flight vehicle system heat loads** engine,
  - environmental control systems,
  - hydraulic systems, and
  - electrical systems
- **High temperature stealth structures -**
  - Analytical capabiliti and integrate energy systems
  - Inno cooled
  - heir
- No

**A system level approach to thermal management is required**

# Capability Focused Tech Investment

# Persistent ISR

**Detect and track every target in the battlespace…**
***anywhere, at any time***



- 360 degree coverage
- On Station 24/7
- Multi-function/Multi-sensor
- Foliage penetration
- Integrated/Fused data
- Penetrating

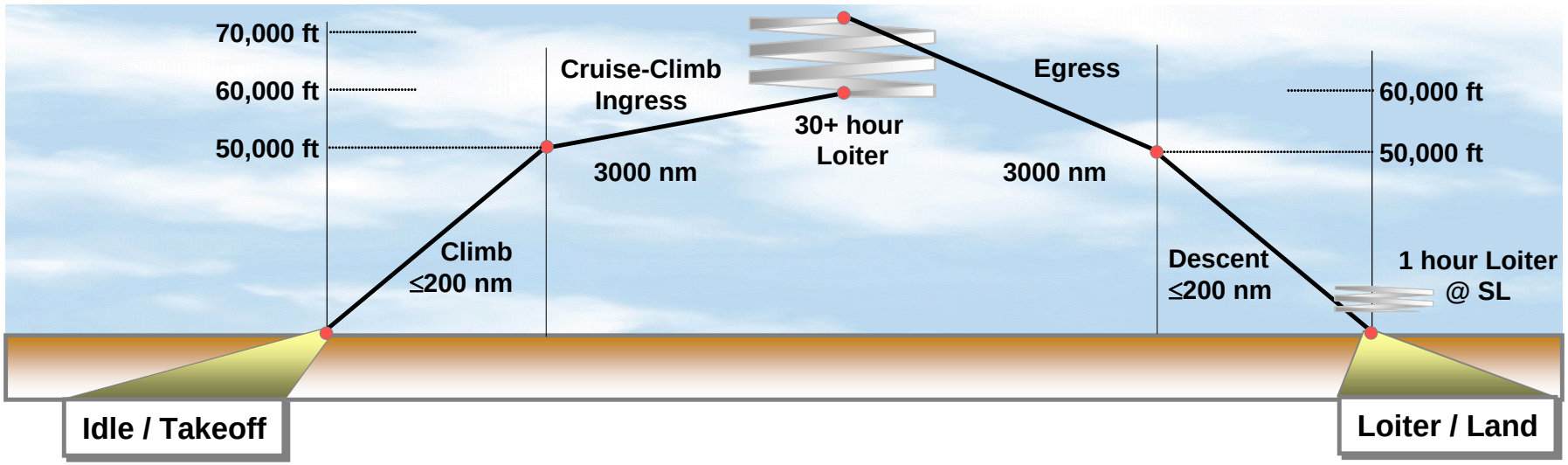
Based On ICRRA and GH ORD/Annex

# Sensor Mission Power Requirement

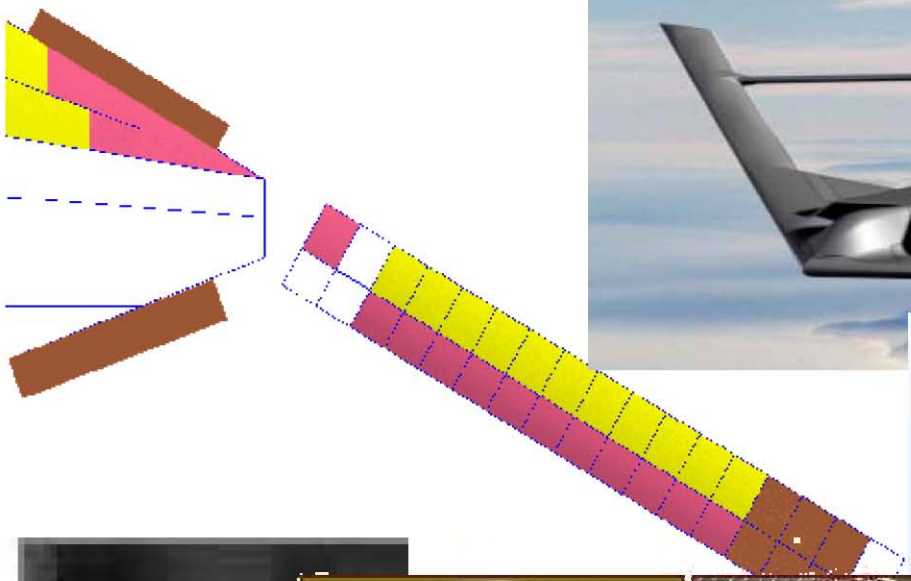
| | Vol. ft3 | Wgt lbs | Pow. Kw |
|---|---|---|---|
| **Radar** | 0.73 | 820 | 62 |
| **Radar** | 0 | 2000 | 75 |
| **Radar** | 0 | 100 | 1.2 |
| **IFF** | 0 | 50 | 1 |
| **ELINT** | 0 | 500 | 0 |
| **COMINT** | 0 | 0 | 0 |
| **E/O** | 12 | 450 | 3.5 |
| **Comms** | 0.8 | 52 | 1 |
| **Receiver Subsystem** | 18 | 533 | 10 |
| **Processor Subsystem** | 7.8 | 192 | 4.8 |
| **TOTAL** | 39.33 | 5000 | 160-200 |

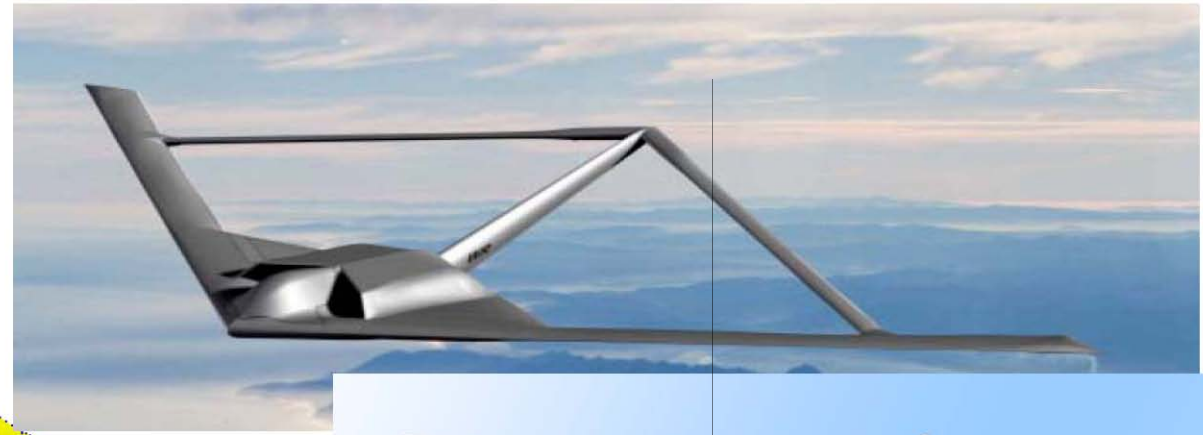
**For comparison, Global Hawk Integrated Sensor Suite (ISS) weighs about 900 lbs, and requires 6.5 kW of power**

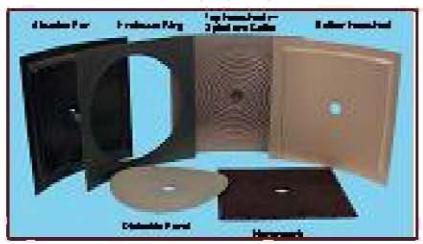
# SensorCraft Profile



# Airframe Around Sensors



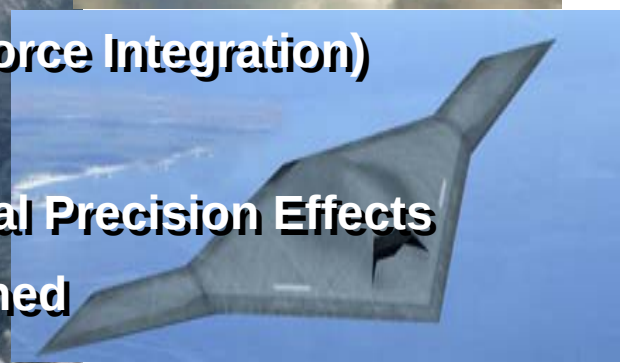




# Capability Focused Tech Investment

# Persistent Precision Strike

**Persistent delivery of lethal and non-lethal precision effects**



- Long Duration
- Rapid Deployment
- Survivable
- Interoperable (Force Integration)
- Affordable
- Lethal/Non-Lethal Precision Effects
- Unmanned/Manned

# AADS System

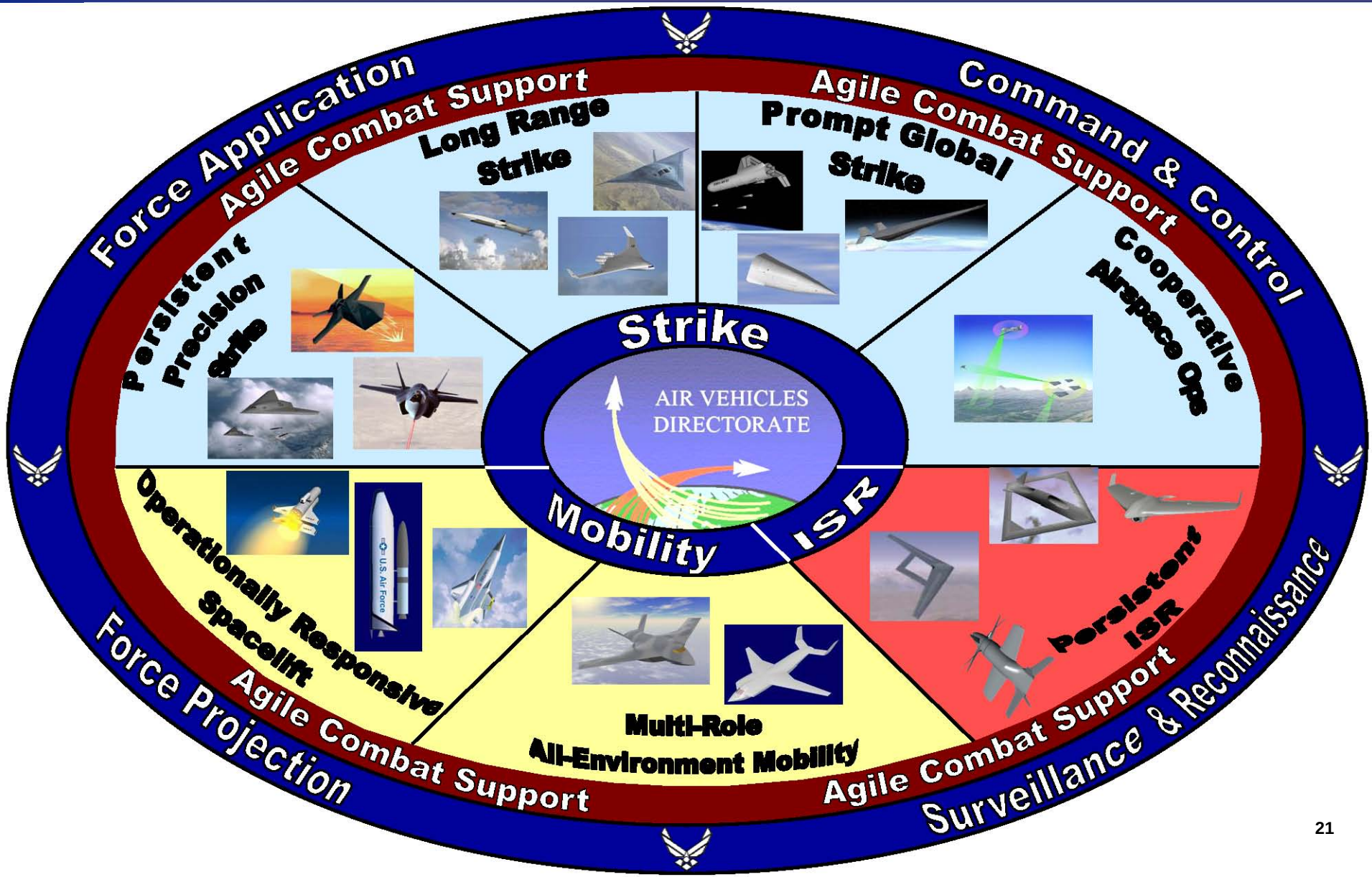
- **5-10 MW electrical**
  - **4 kW Input Power for Cryogenic Cooler (30K) ~1 kW Input Power for Cathode Heater**

**<50% efficient**

Idea duty cycle is 100% availability

- **1-2 kHp in**
- **~10% efficient**
- **1000 W/cm$^2$**
- **Seconds between shots**

# Stressing Scenario Focus



# Air Force Research Laboratory

*Defending America by Unleashing the Power of Innovative Aerospace Technology*

U.S. AIR FORCE

## Energy and Thermal Management Executive IPT and Technical Advisory Group

## ETM Workshop Outbrief

***…Enabling Airborne Directed Energy Weapons…***

*Integrity - Service - Excellence*

# Major Themes

- **System Level Assessments (Must Do Now)**
  - Focus:  Get arms around three concepts –and hold true to them
    - 50 kw SSL on a Mid-Sized Airborne Platform
    - 100 kw SSL on a Tactical Platform
    - Airborne Active Denial on a Mid-Sized Airborne Platform
  - Bound Problem to create realm of possible, not preselect point solution

# Sim Based R&D
# The Engine in Capability Planning

Capability

Attributes

Products

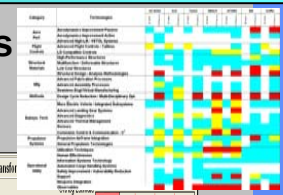
Tech Programs

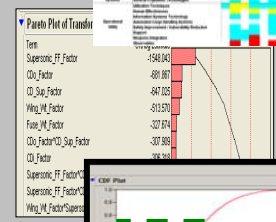
- Requirements
- Metrics

Conceptual Studies

- Vehicle Concepts
- Technology Assessment

Sensitivities Studies



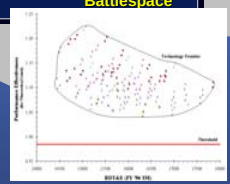


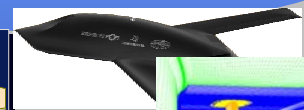
Automated
Iterative
Archived

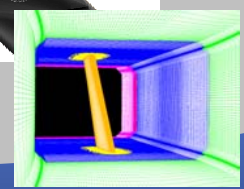
Mission Effectiveness

Campaign Analysis

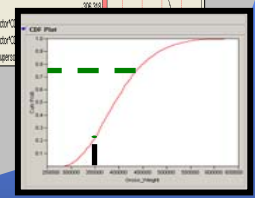
Impact of Key Performance Parameters







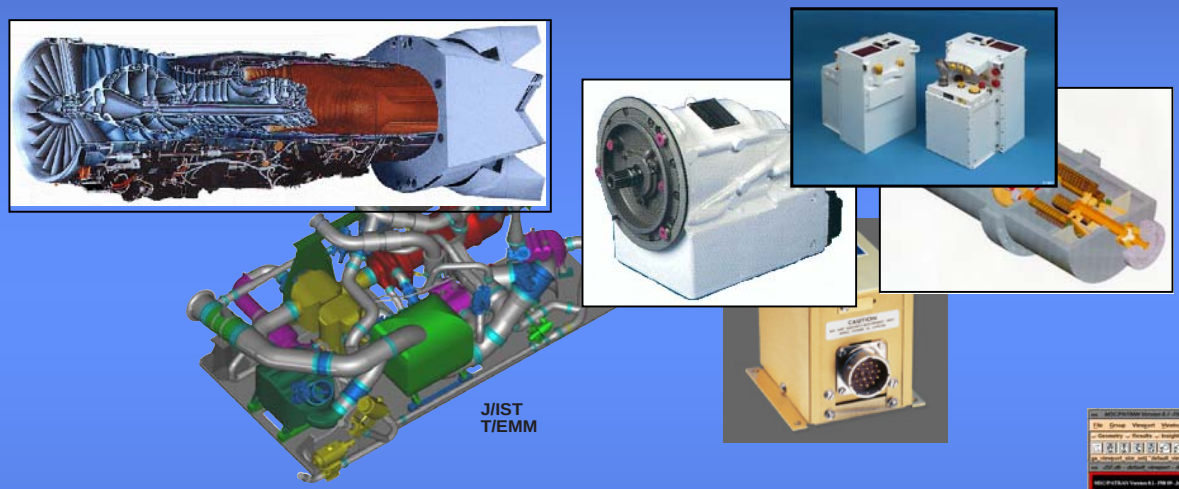
High Fidelity Analysis

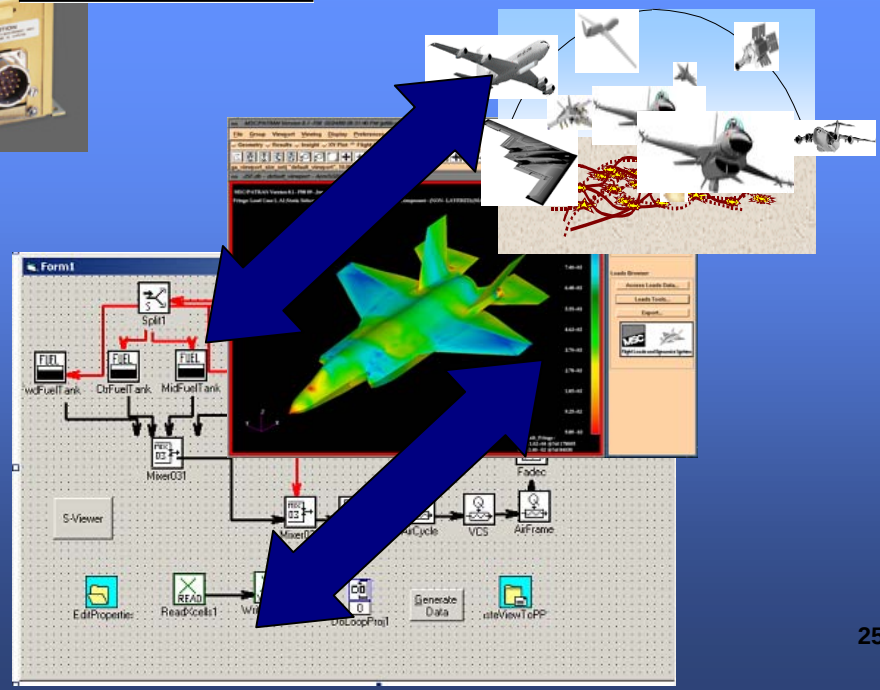


Technology Trades

# Current Status

Thermal and Energy Management Being Worked At Component And Subsystem Level




## Shortfall

- **Methods And Capabilities To Rapidly Understand The Impacts Of Technologies At The System/Capability Level**

# Assessment

- Identified Key Technology Development Drivers
- What is Required to…
  - Fly how Long
  - Shoot so Far
  - Carry How Much
- Mission Definition and Analysis
- Effectiveness and LCC Assessments
- Assessment of Technology Impacts
  - Power Generation
  - Device
  - Thermal Tech Trades
  - Power and Thermal Storage
- Linkage of KPPs to Capability
- Link to Technology Demonstrations
  - High Fidelity Cooling Analysis
  - Structural Analysis
  - Sophisticated Device Modeling

# Major Themes (Con't)

- Theme: Increasing Weapon Efficiency will only help the thermal management issues, not solve the issue
- Theme: Need for advanced fluids and materials
- **Theme: Mature Two-Phase Flow**
- Theme: Energy Harvesting (Way Cool If…)
- Theme: Energy Storage Systems
  - Phase Change Materials (PCM), Adsorption, Chemical reaction, …

EAGLES

# Energy and Thermal Management Executive IPT Vision

Includes all players & schedules

The systems approach

The pipeline
The legacy

**To develop/promote & establish a robust energy and thermal management research & development program that is:**

- **Integrated across AFRL -- Maximizes use of other organizations' efforts**
- **Focused on capabilities at the system level**
- **Provides for a balance of 6.1, 6.2 and 6.3 research & development**

***… to unleash the power of innovative technology…***

**Cross Cutting Executive IPT Formed and Working Integrated Approach**

# Air Force Research Laboratory

*Defending America by Unleashing the Power of Innovative Aerospace Technology*

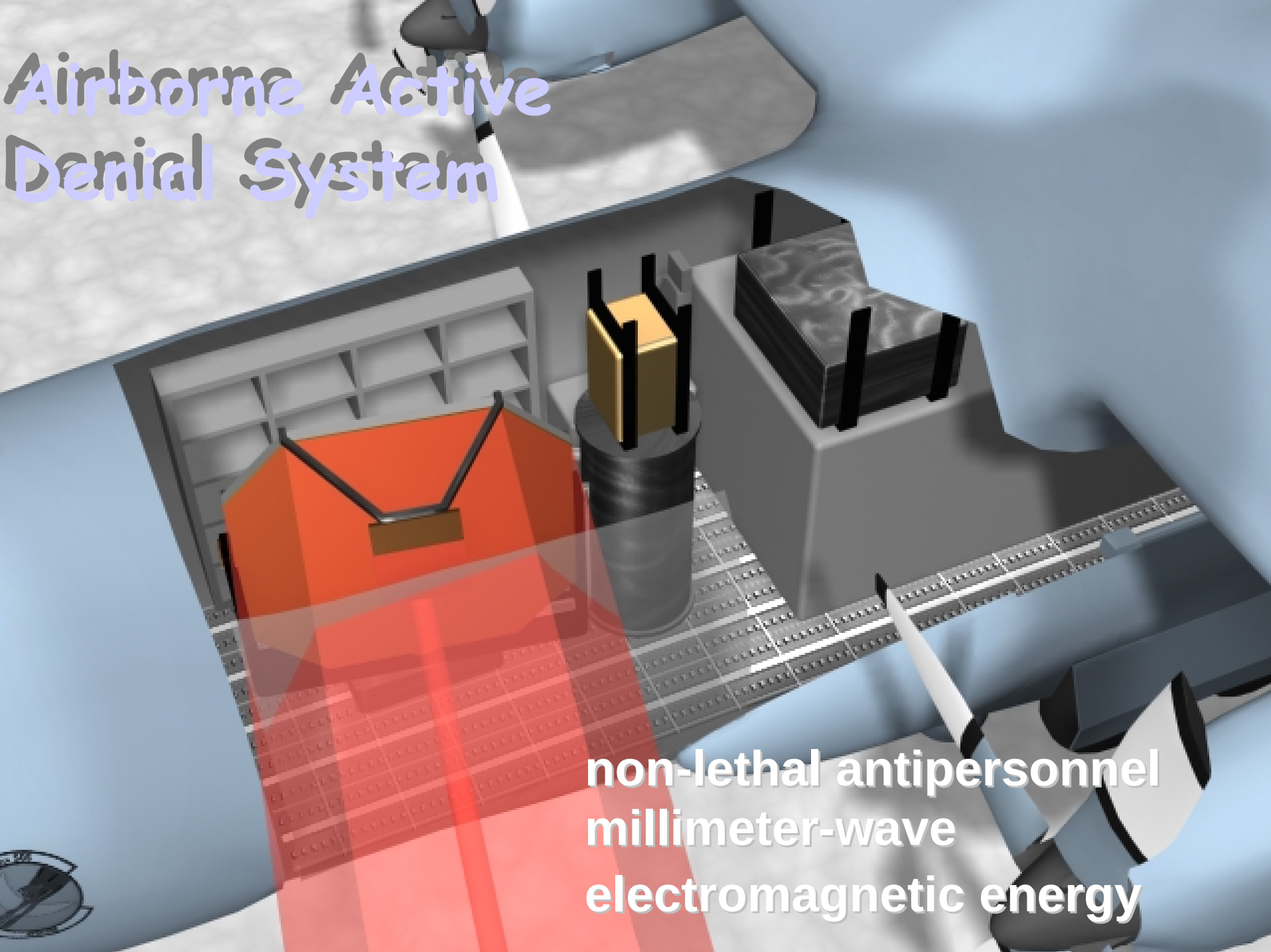
## Energy and Thermal Management Stressing Scenarios

### An Air Vehicles Directorate Point of View

**David M Pratt, PhD**

U.S. AIR FORCE

*Integrity - Service - Excellence*


Airborne Active
Denial System
non-lethal antipersonnel
millimeter-wave
electromagnetic energy

# Tactical Laser
# Mid-Sized Airborne Platform

# TMS Requirements

- 1-2 kHp in
- ~10% efficient
- 1000 W/cm$^2$

- Seconds between shots