CORNING

Corning ®Advanced-Flow™ Reactor Technologies: from Lab to Production a seamless scale-up

Alessandra Vizza, Roland Guidat, Daniela Lavric
Corning Reactor Technologies
Corning European Technology Center
Avon, France

Corning ® Advanced-Flow™ Reactors

A business based on 160 years of worldwide innovation

Corning Incorporated

Founded:
1851

Headquarters:
Corning, New York

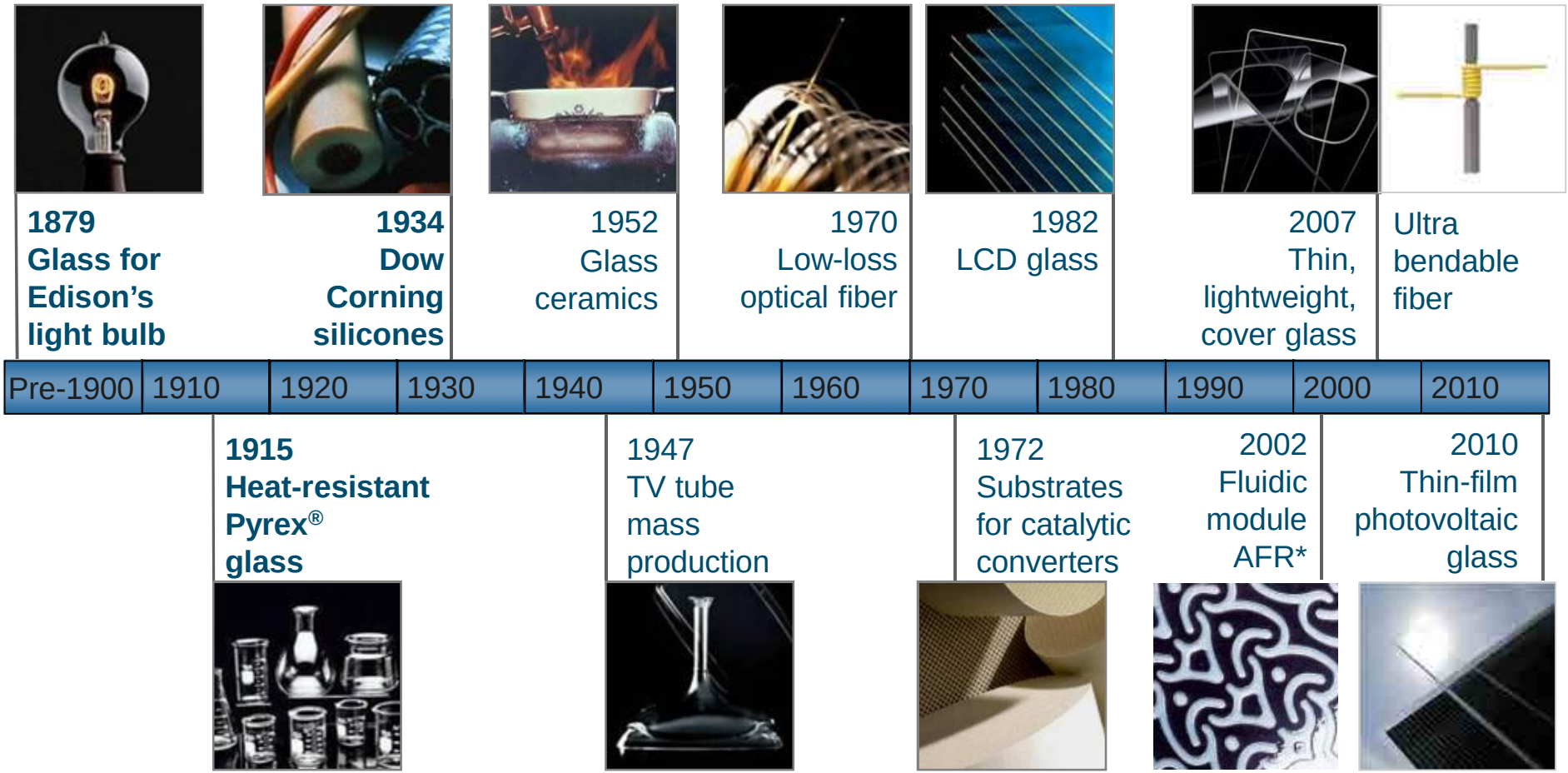
Employees:
~ 29,000 worldwide

2012 Sales:
$ 8.0 Billion

Fortune 500 Rank (2012):
328

- Corning is the world leader in specialty glass and ceramics.
- We create and make keystone components that enable high-technology systems for consumer electronics, mobile emissions control, telecommunications, and life sciences.
- We succeed through sustained investment in R&D, 160 years of materials science and process engineering knowledge, and a distinctive collaborative culture.

Corning's continuous flow reactors build on the company's 160 years of innovation



* Advanced-Flow™ Reactors

History of Corning Reactor Technologies: One decade of expertise

Concept development

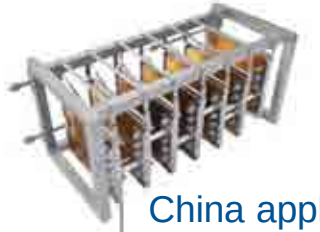
Customers collaborations

G1 reactor

G2 reactor
Bank concept

MIT collaboration

G3 reactor



China applications lab

2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012

European applications lab

India applications lab

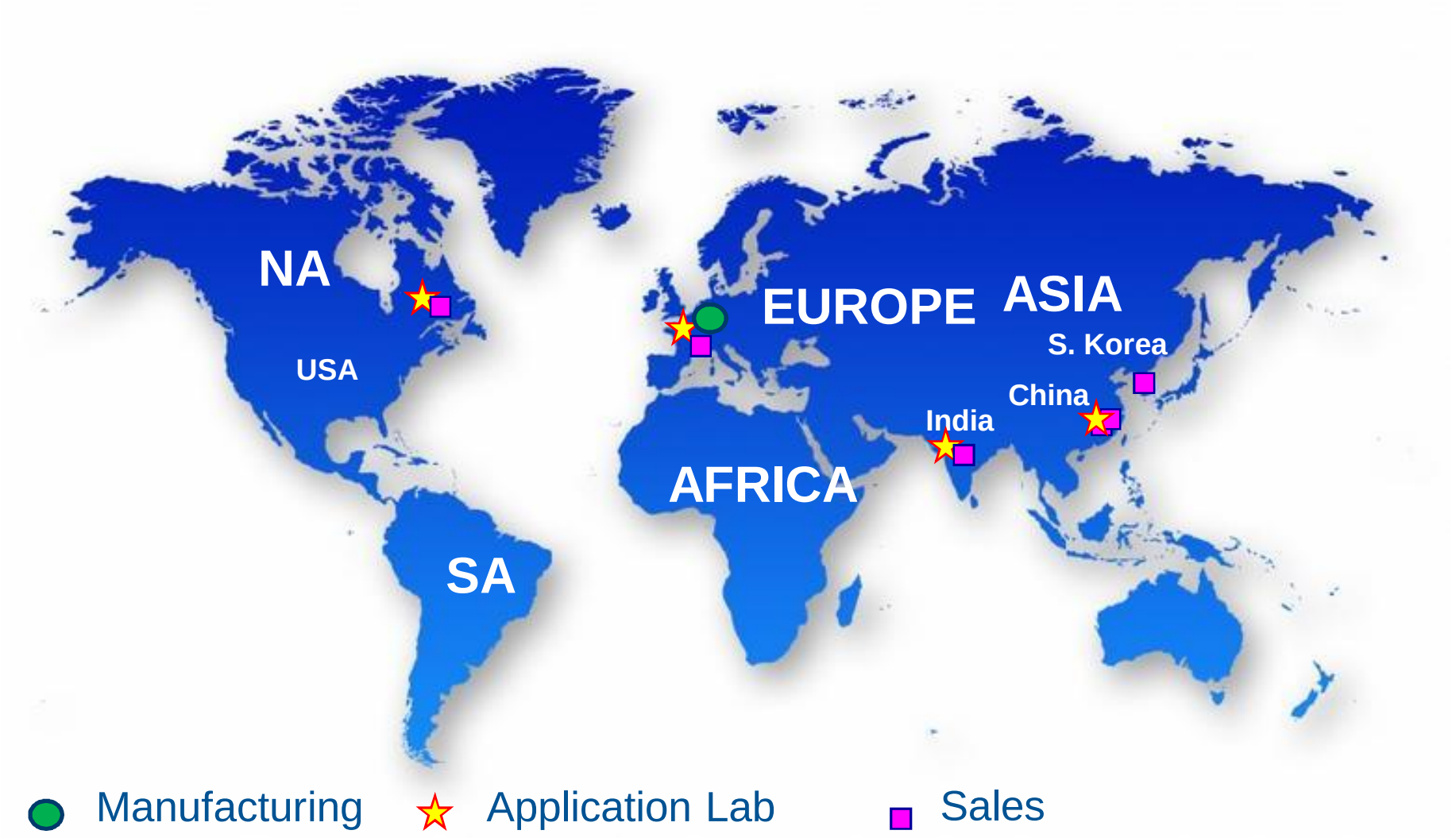
Collaborations with platforms in Europe

Low Flow lab system

G4
Ceramic reactor

- First introduced in 2002
- Technology leveraged for larger gen sizes with advanced materials to increase throughput:
  - Glass
  - Ceramic
- Worldwide established business operations

Corning® Advanced-Flow™ Reactors (AFR): worldwide presence

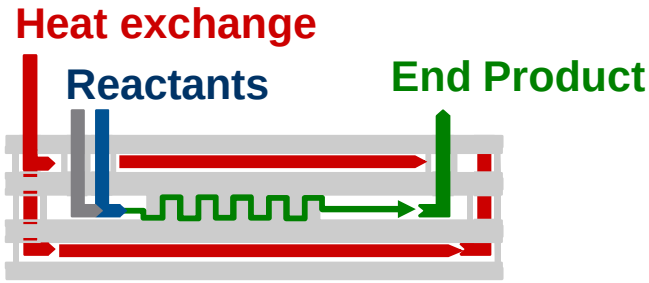


Corning ® Advanced-Flow™ Reactors

Offer broad capability from feasibility to production and enable the transition from batch to continuous processes

Corning® Advanced-Flow™ Reactors product design

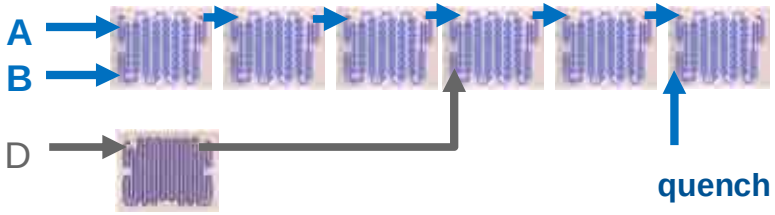
- **Engineered fluidic modules**:
  - glass or ceramic plates with integrated mass and heat transfer



- **Reactor design**: a modular assembly

A+B → C

C+D → E



- **Reactor:**

Corning® Advanced-Flow™ Reactor - Glass

Corning® Advanced-Flow™ Reactor - SiC

Fluidic modules

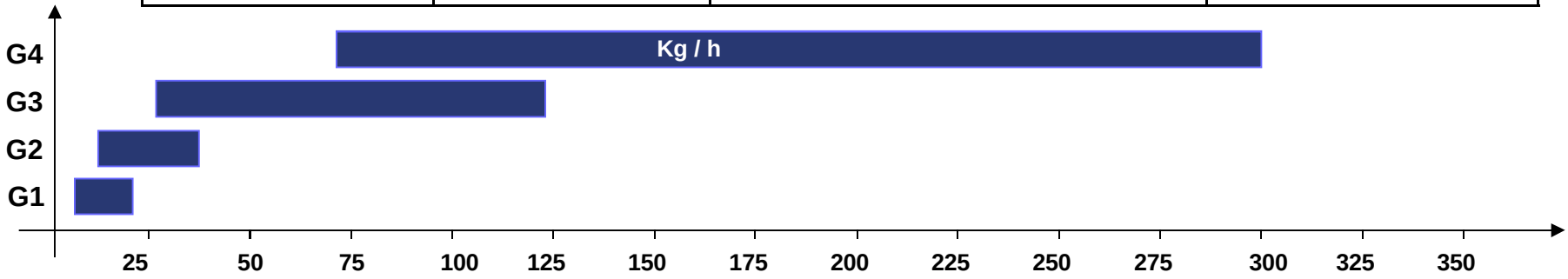
Increase throughput with similar:

- Mixing
- Residence time distribution
- Heat Exchange
- Mass transfer in heterogeneous systems

D. Lavric and P. Woehl, **Advanced-Flow™ glass reactors for seamless scale-up**, *Chemistry Today* 27, 45-48 (2009)

Large product portfolio enables seamless scalability from lab to production

	Low Flow	G1	G2	G3	G4
Single Plate volume (ml)	0.45	8 – 11	21 – 25	55 – 65	200 – 260
T -60 to 200 °C P up to 18 bar	High flexibility, metal-free reaction path From laboratory to production: a seamless scale-up				
	• Low internal volume • Use minimal number of reactants	• Small volume • Scalability from test to production • Process dev. and optimization tool	• Continuous production of large amount of chemicals • Several tons annually		• Large volume • small footprint • Processing > 300 kg/hr • Superior corrosion resistance of SiC



Glass & ceramic materials: Superior corrosion resistance

Flow reactor characteristics

Transfer
- Superior mixing & mass-transfer
- Excellent HE with reaction integration
- Appropriate residence time
- Narrow RTD

Controls
- Reduced process fluid hold-up
- Accurate T,P, & RT control

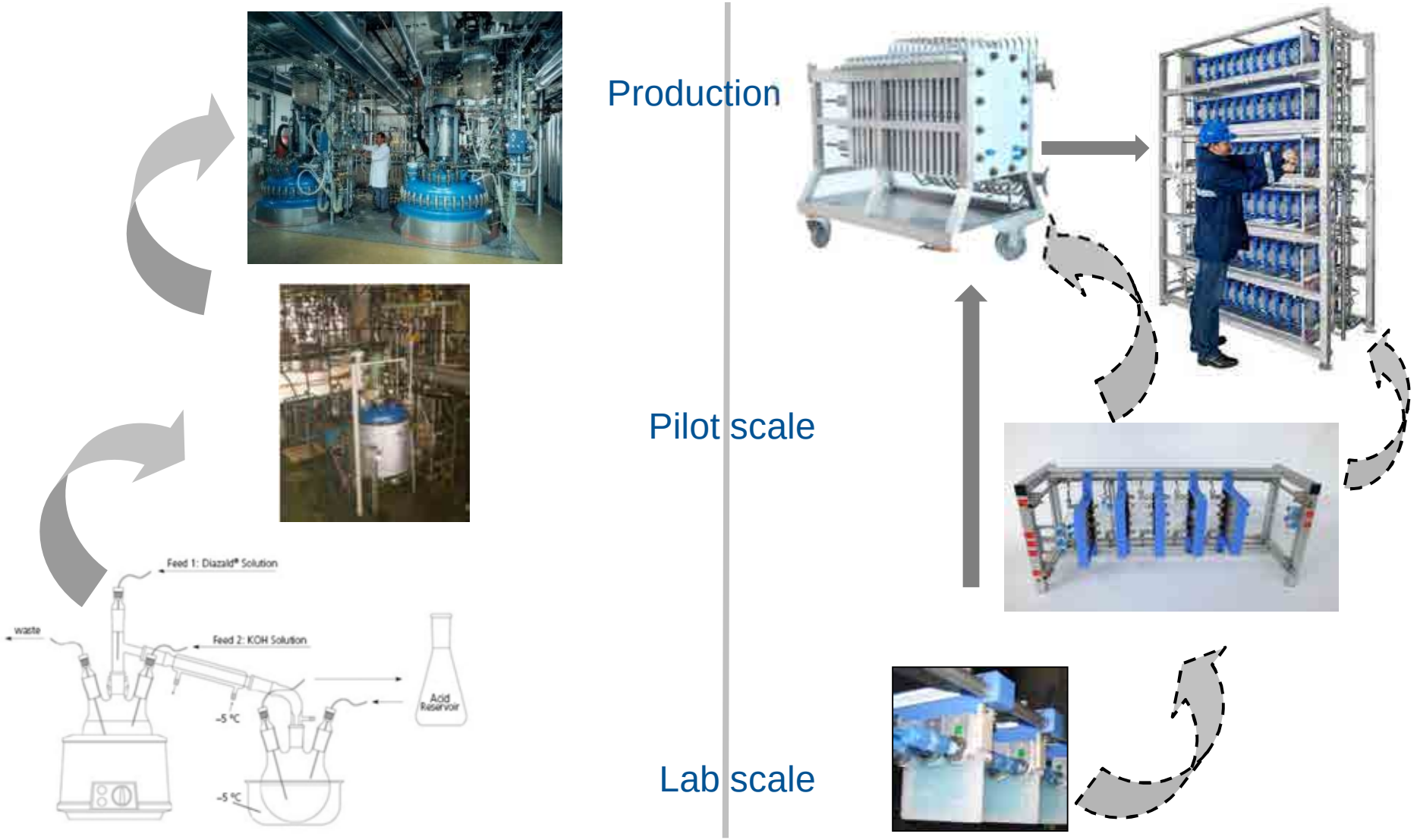
Production
- Numbering-up to meet capacity
- Flexible to fit chemistry & market needs

Weight loss ($mg/cm^2.year$)*	316L SS	Glass	S-SiC
H_2SO_4-96%	destroyed	good	good
HNO_3-65%	destroyed	good	good
NaOH-10% low T°	good	good	good
NaOH30% High T°	good	destroyed	good
HCl-32%	destroyed	good	good

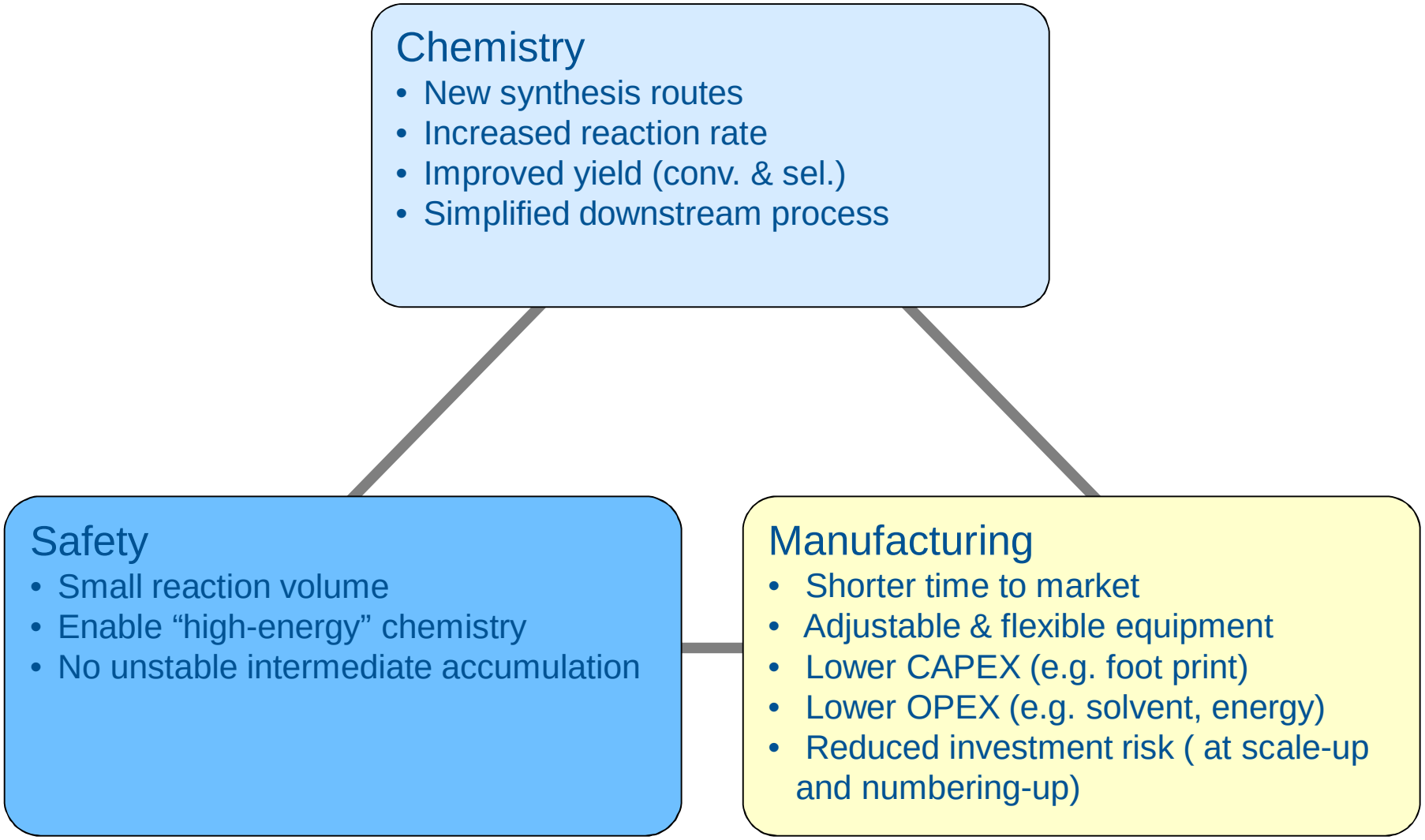
Glass transparency
- For development in the lab
- For photochemistry

For production: scale-up combined with internal and external numbering-up

Source: Chemistry Today, vol. 27 (3), 45-48, 2009
Chemistry Today, 26 (5), 1-4, Sept~Oct (2008)



Corning Advanced-Flow™ Reactors Benefits Sources



Corning ® Advanced-Flow™ Reactors

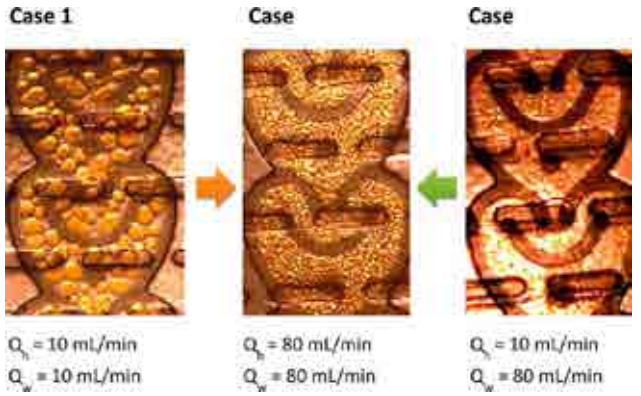
Ensure superior mass & heat transfer, enabling excellent process intensification

Corning Advanced-Flow™ Reactors
Experimental Data

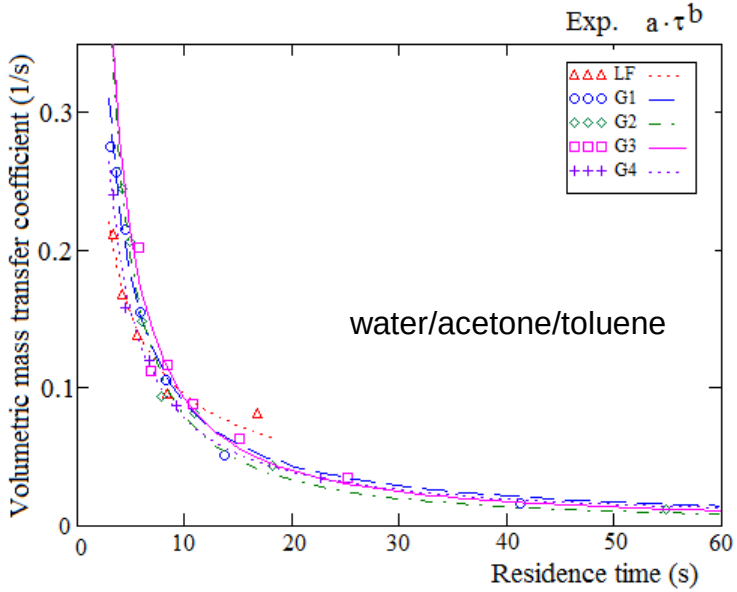
Never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgment than what was presented to my mind so clearly and distinctly as to exclude all ground of doubt. (Discourse on the method René DESCARTES (1596-1650;first principle)

Volumetric mass transfer coefficient: A seamless scale-up

- Patented HEART-shape design:
  - Superior mixing performance in multiphase systems[1]
  - higher performances in L/L mass transfer coefficient ($k_L a$)[2]
    - Up to 10^3 compared to packed column
    - 2x-4x better than other “micro-channel” devices



[1] M. José Nieves-Remacha, A.l A. Kulkarni, K. F. Jensen, **Hydrodynamics of Liquid−Liquid Dispersion in an Advanced-Flow Reactor**, *Ind. Eng. Chem. Res*. 51,16251 – 16262 (2012)

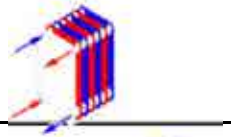
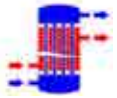
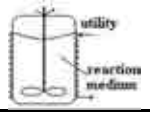
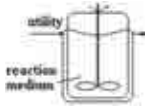


Similar mass transfer performances from lab to production

[2] D. Lavric, C. Cerato-Noyerie, P. Woehl, F. Zhang, **Multiphase systems: Enhanced Mass fluxes in Corning®-advanced-flow™ reactors**, IMRET 12, Lyon, France (2012)

Heat transfer coefficient ~100x-1000x higher than batch

- Seamless scale-up: similar heat transfer coefficient from G1 to G4

Method		Volumetric heat transfer coefficient (MW/m^3K)
Ceramic SiC fluidic modules		1.5
*Corning glass fluidic modules (water/water, ~ 0.7 m/s)		1.6
*Plate (*metallic*, 4 mm spaced; water/water, 1 m/s)		1.25
*Shell and tubes (*metallic*; water/water; 1 m/s)		0.2
*Batch with external heat exchanger		10^{-2}
*Jacketed batch		10^{-3}

*D. Lavric, **Thermal performance of Corning glass microstructures**, Proceedings of the *Heat Transfer and Fluid Flow in Microscale III* Conference, Hilton Whistler, BC, Canada, ECI international, 2008

Corning ® Advanced-Flow™ Reactors

Minimize scale-up failures and drastically reduce the time from laboratory to production

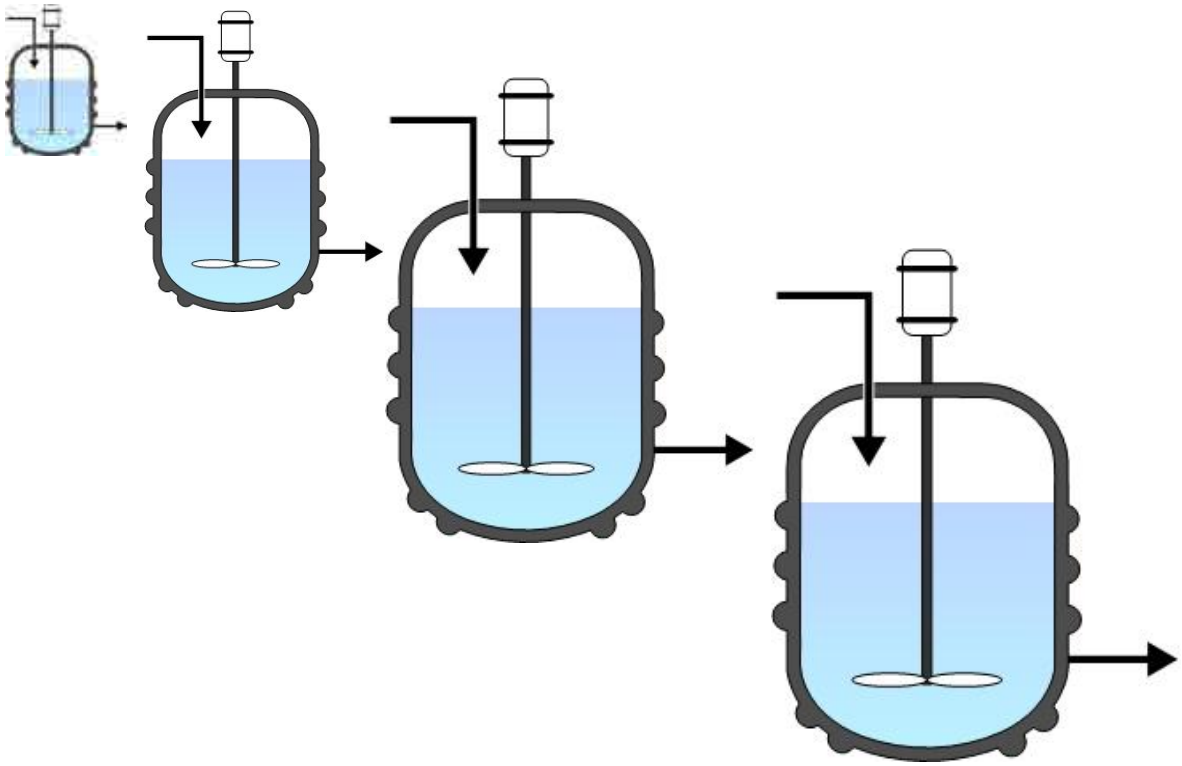
What is really a seamless scale-up?

A seamless scale-up will be achieved when keeping the same parameters (temperature, residence time, concentration, stoichiometric ratio), the same results will be obtained in the lab and in production (conversion, yield, impurity profile…).

A seamless scale-up allows a straightforward process that does not require much time from the lab to the production.

What a seamless scale-up is not

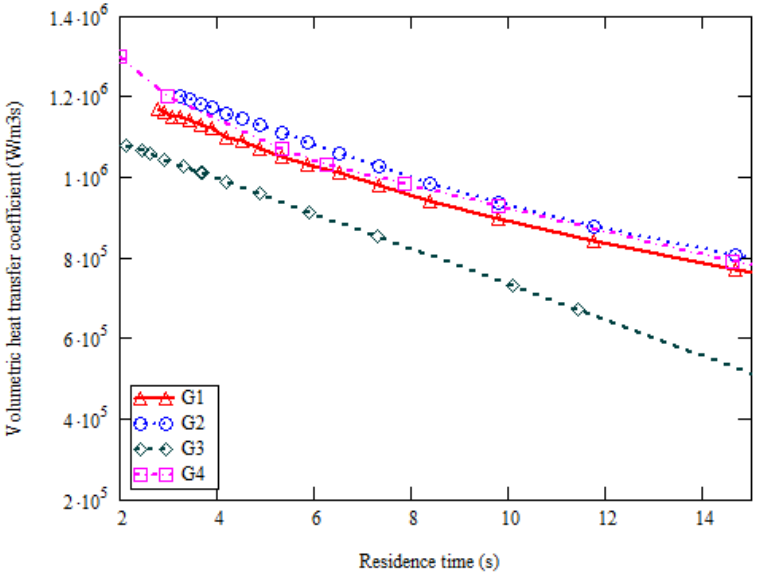
A seamless scale-up does not mean simply a size increase

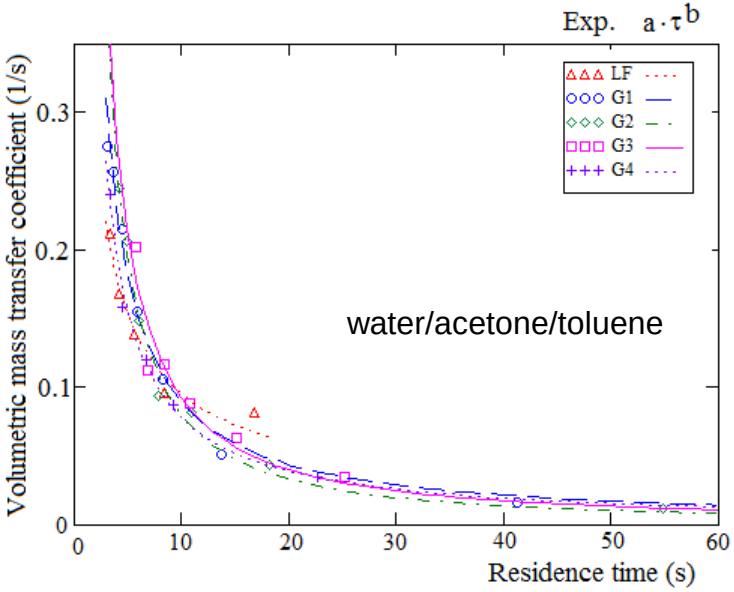


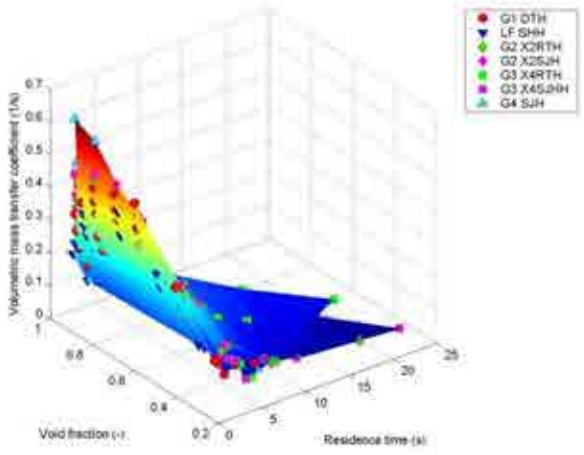
“to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution”. (Discourse on the method René DESCARTES (1596-1650; second principle)

REQUIREMENTS FOR CHEMICAL REACTIONS	REACTOR CAPABILITIES
Contact between the molecules of the reactants	MIXING / MASS TRANSFER
Keep the molecules in contact during a sufficient time to allow the completion of the reaction	RT
Enable the same history of the molecules in the reactor	RTD
Provide isothermal condition	HEAT TRANSFER

Advanced Flow Reactors seamless scale-up:







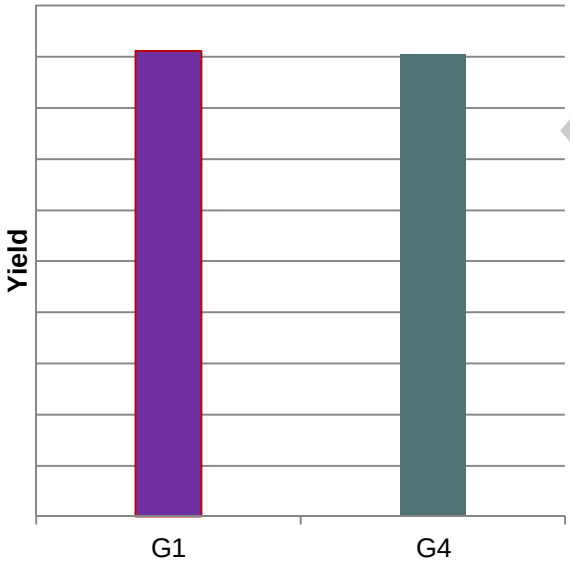
CO_2 absorption in $NaHCO_3/Na_2CO_3$ buffer solutions

Moving from G1 to G4 by keeping the same residence time per fluidic module will keep the heat and mass transfer characteristics at the same levels.

Then, the rest is easy…

"to conduct my thoughts in such order that, by commencing with objects the simplest and easiest to know, I might ascend by little and little, and, as it were, step by step, to the knowledge of the more complex" *(Discourse on the method René DESCARTES (1596-1650; third principle)*

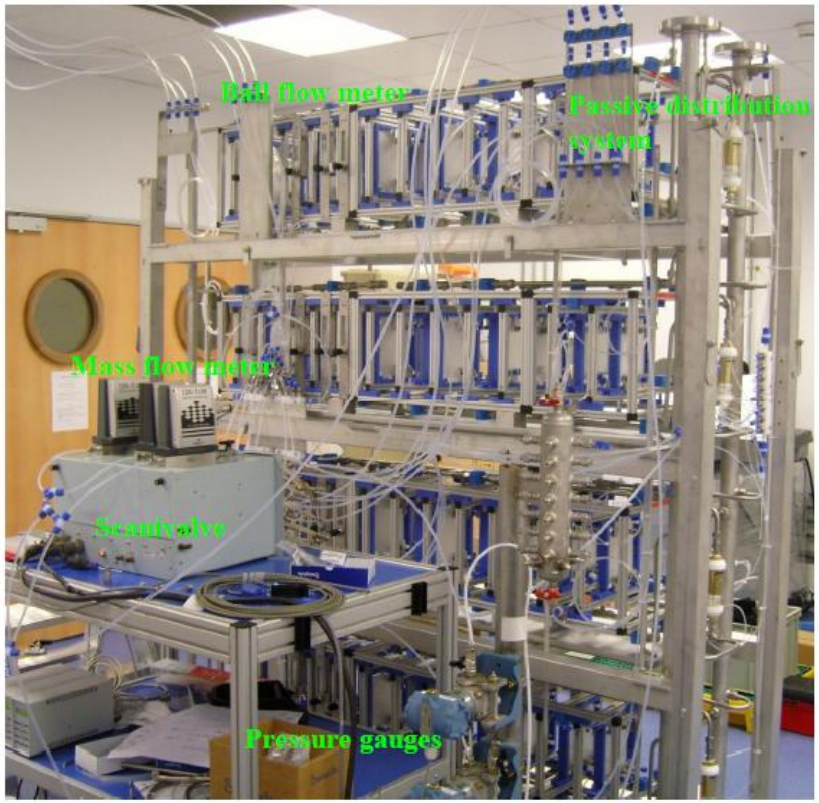
Lab G1
3.7t/y



Production, G4
110 t/y

Multiphase application: L/L/G

Scale-up and numbering-up as well



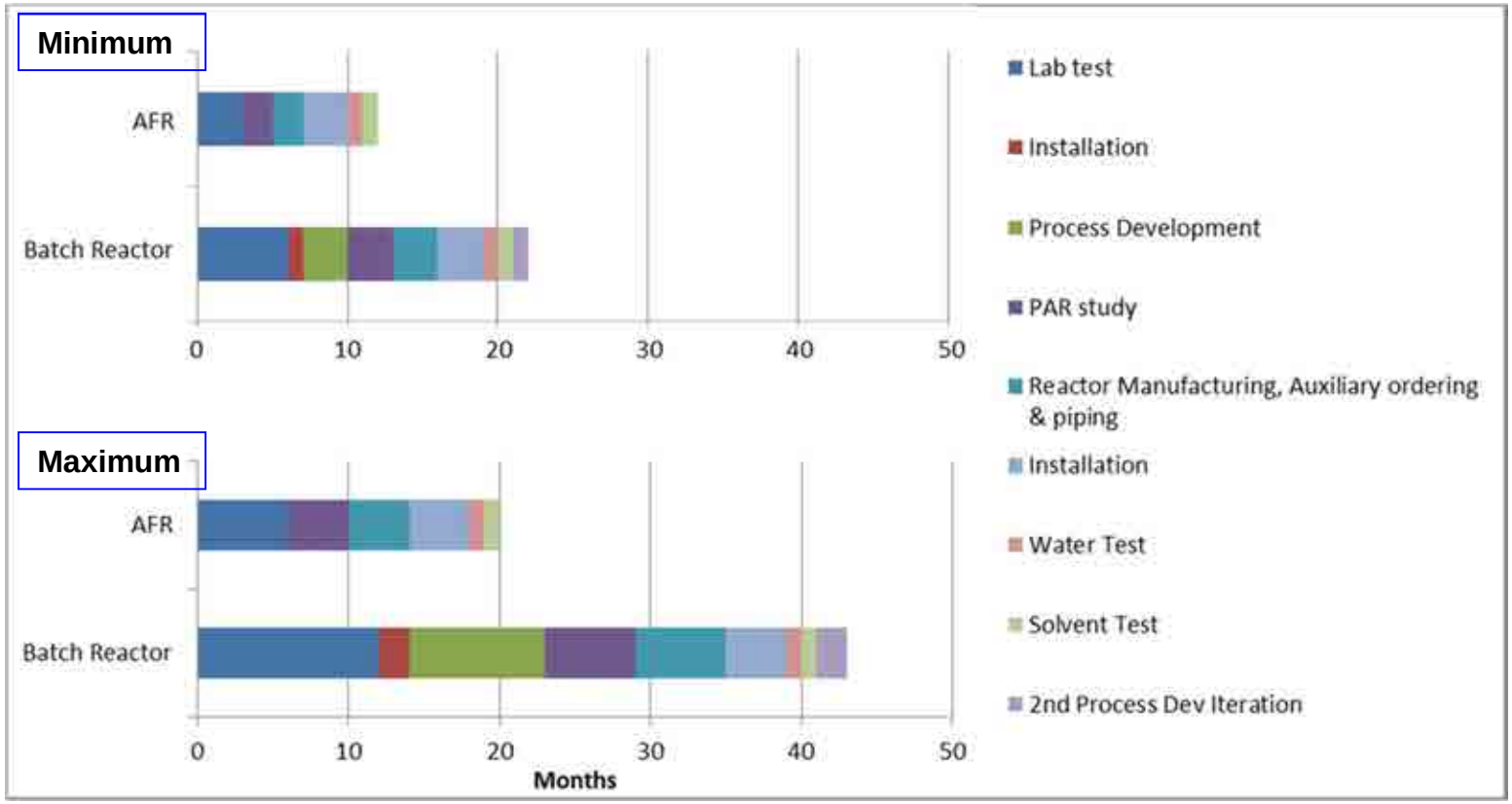
From concept validation in the lab…

…to the industrial production.

Braune, S. *et al.*, **Selective nitration in a microreactor for pharmaceutical production under cGMP conditions**,*Chemistry Today*, 26 (5), 1-4, (2008)
R. Guidat, D. Lavric, 2010, **Uniform flow distribution through combined numbering-up**, CHISA 2010, 28 August-1 September, Prague, Czech Republic

Development time reduced by ~50% vs. batch

- Faster knowledge generation => kilo-lab test phases shortened
- Seamless scale-up => process development phase avoided



In every case to make enumerations so complete, and reviews so general, that I might be assured that nothing was omitted. (Discourse on the method René DESCARTES (1596-1650;fourth principle)

Corning ® Advanced-Flow™ Reactors

CORNING