The University of Texas at Austin
McKetta Department of Chemical Engineering
Cockrell School of Engineering

Manufacturing and the PSE Community: A Critical Linkage

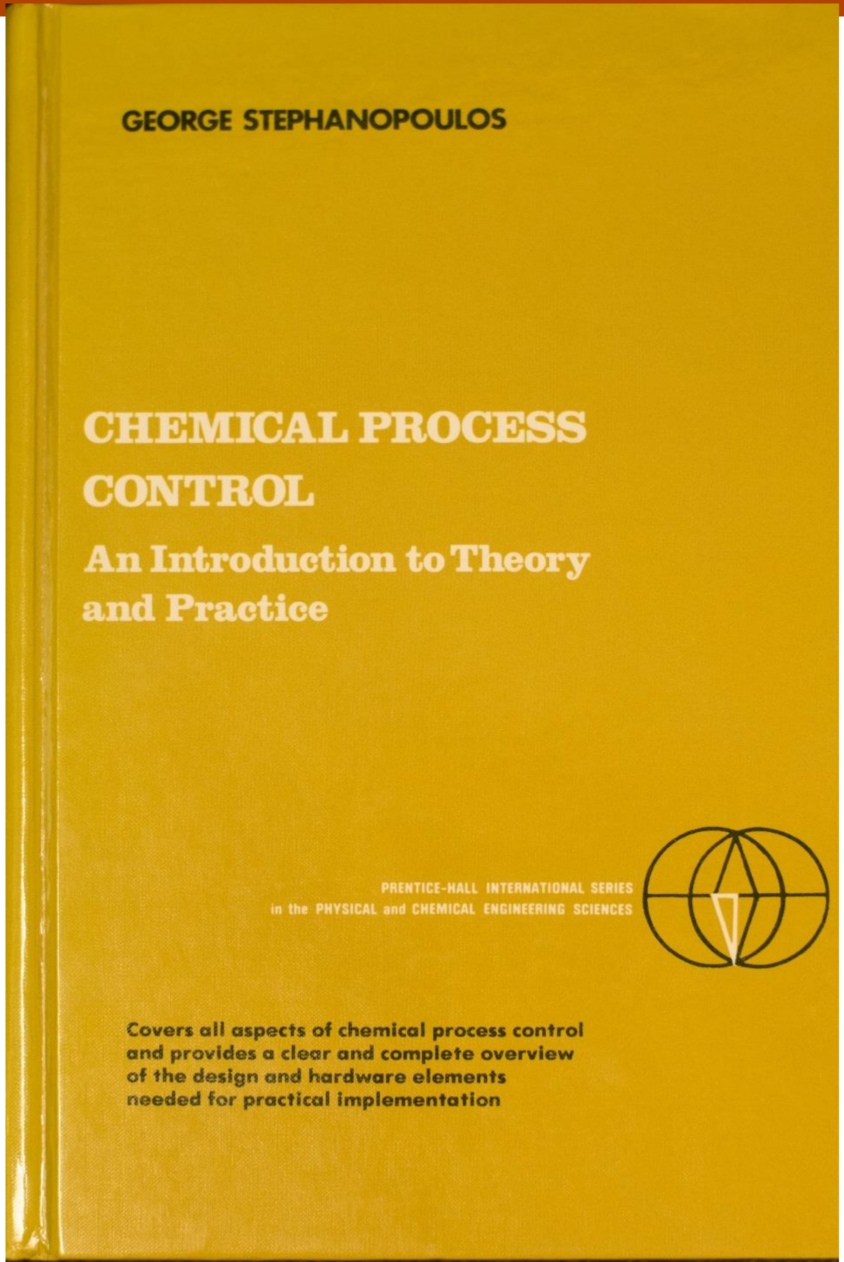
100 YEARS
education • discovery • leadership

Thomas F. Edgar
Director, UT Energy Institute
Professor, Chemical Engineering

MIT Symposium
June 1-2, 2017

George: On the Beaches Near Athens
ca. 1980

Process Control Opus (1984)



First Process Control Book to Discuss Plantwide Control

Preface

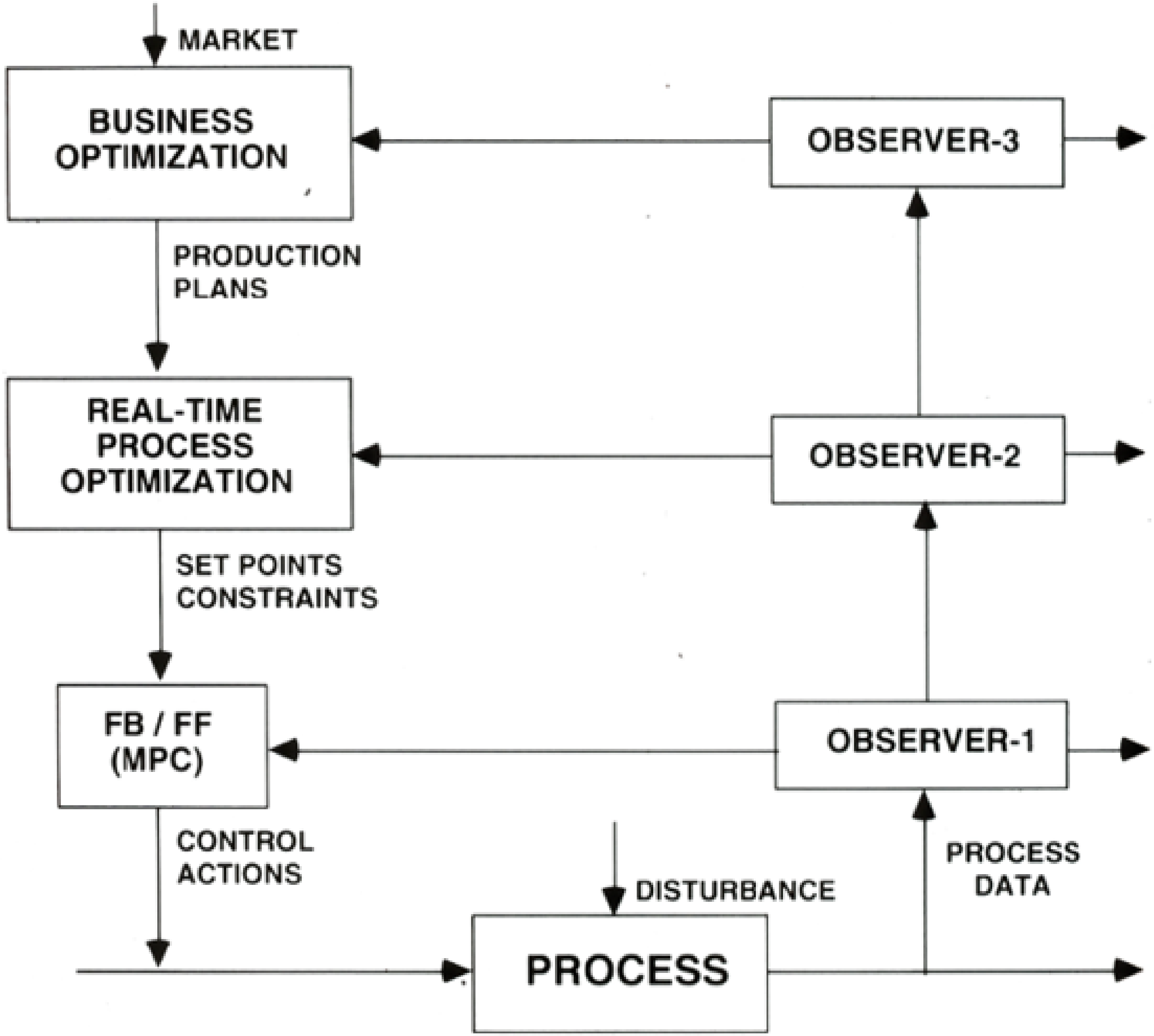
During the last ten years, academic research and industrial practice in chemical process control have ben shaped by the following important realizations:

1. The structure of chemical processes has become increasingly complex, due to better management of energy and raw materials. As a consequence, the design of control systems for complete plants now constitutes the focal point of engineering interest, rather than controller designs for single processing units. Furthermore, the design of a control system has become intimately related to the design of the process itself.

Other pioneers: Buckley, Douglas, Luyben, and Skogestad

Management of Process Operations

via GS ca. 2000



Five Levels of Process Control (2004)

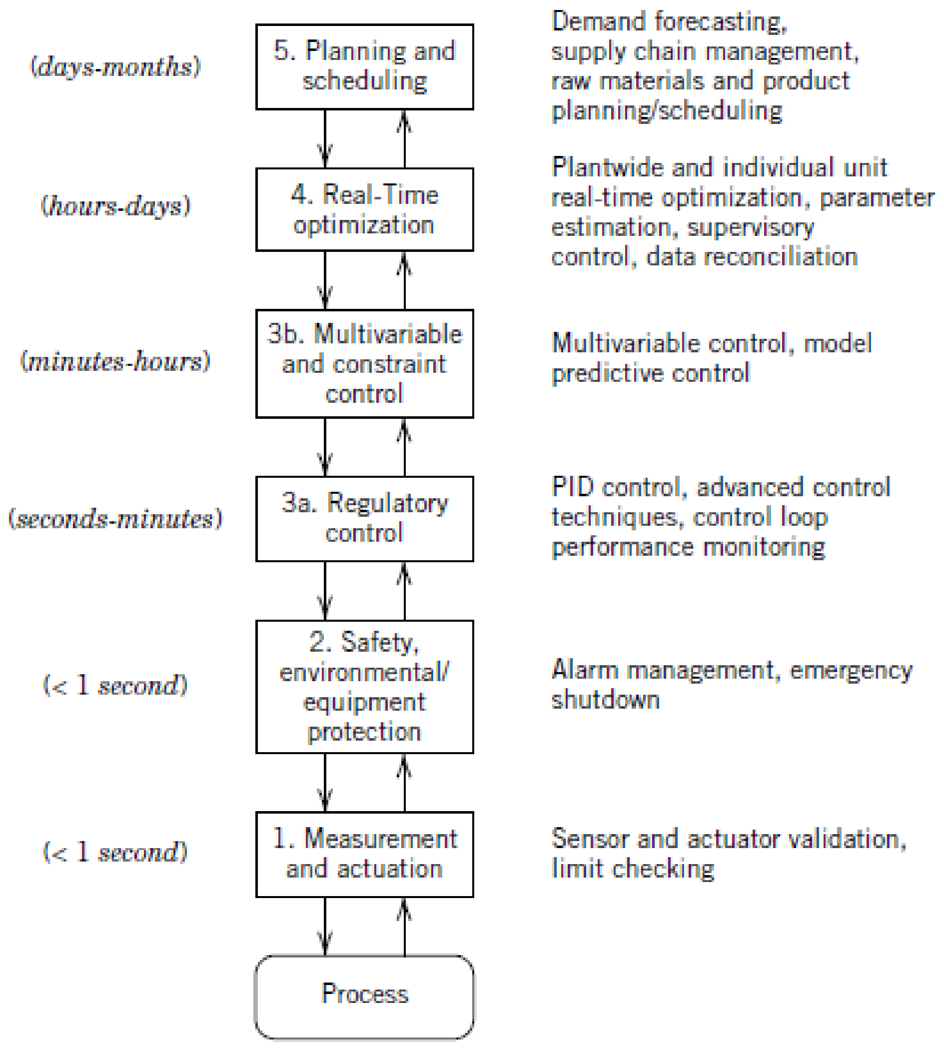
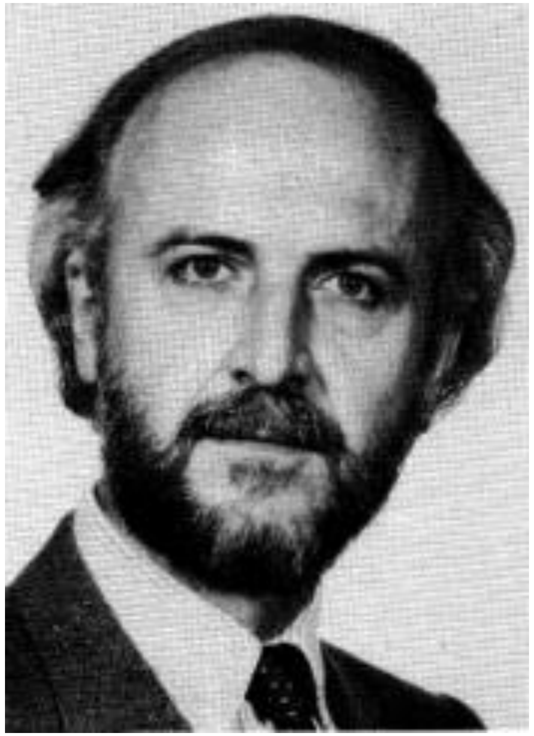
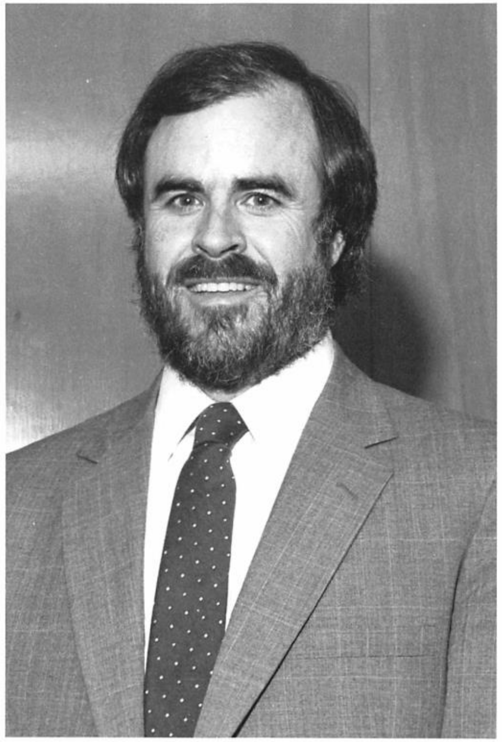


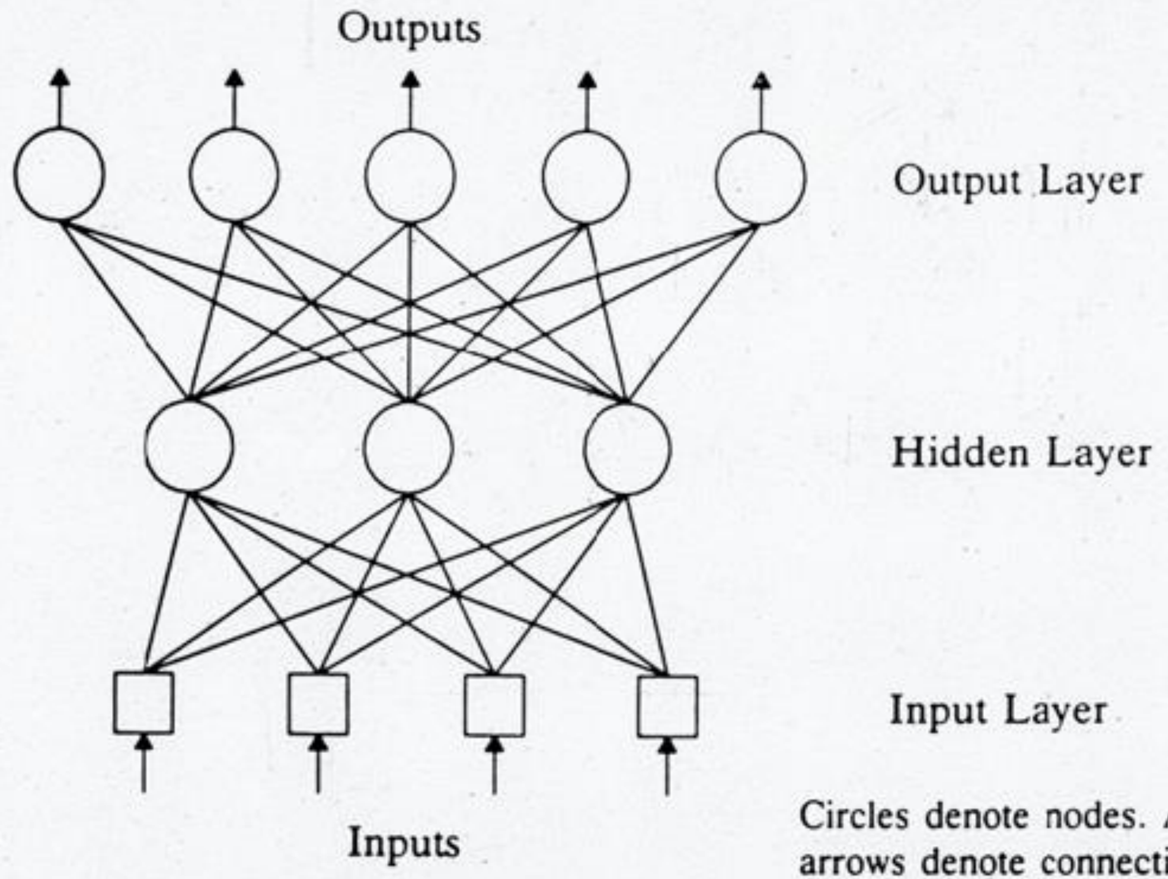
Figure 19.1 the five levels of process control and optimization in manufacturing. Time scales are shown for each level.
Process Dynamics and Control, Seborg, Edgar, Mellichamp, and Doyle)

PSE Doppelgangers (ca. 1986)





Artificial Neural Network Topology



Circles denote nodes. Arcs denote connections. The arrows denote connections to the outside world. The boxes represent preprocessing on the inputs.

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History Repeats Itself

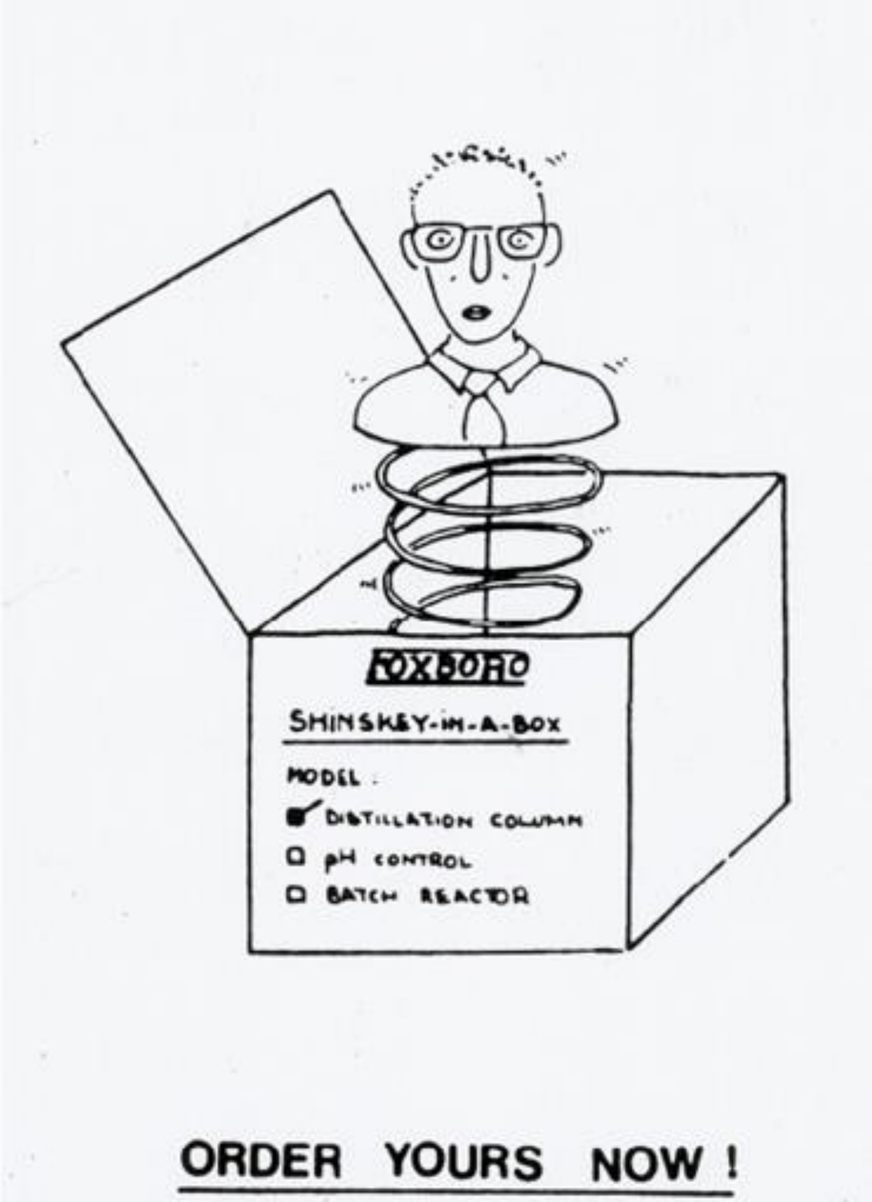
“Everything has been thought of before, but the problem is to **think of it again**”
-Johann Wolfgang von Goethe (via Jim Rawlings)

Artificial intelligence has phenomenal potential, and anything connected with that would be an exciting lifetime career. There is a huge growing demand in the energy sector to develop reliable, cheap, and clean energy. Developments in biotech are moving faster than ever, with a need for innovation to combat diseases such as cancer and obesity, and developing vaccines.

-Bill Gates: 2017 Graduation Speech at Columbia University

Bill was only 30 years behind George (LISPE at MIT)

Foxboro's "Shinskey-in-a-box" Expert System




TO ERR
IS HUMAN
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<u>CPC Acronym Evolution Award</u> (1996)

DMC

- CPC III – Dynamic Matrix Control
- CPC IV – Dynamic Maintenance Control
- CPC V – Dog Maintenance Control

<u>CPC Pooper Scoop Award</u> (1996)

George Birchfield

For suggesting that even a dog could control Shell's Deer Park refinery (operator just feeds the dog)

"It could be somebody sitting on their bed that weighs 400 pounds" -**Donald Trump** (2016)

"On the Internet, nobody knows you're a dog."

George’s Less Well-known Awards

Extended Horizon Award (CPC IV, 1991)

- For asking the longest questions at CPC (and sometimes providing long answers as well). No acceptance speech was permitted.

Olympic Games Award (CPC-FOCAPO, 2012)

- For suggesting a new approach to ChE education like “The Beer Game taught in Business schools.” Could have application to an experimental component of the process control class

What is Smart Manufacturing?

Right Data, Right Time, Right Form Wherever Needed for the Business of Enterprise

“Internet of Things” Deception

- Connect your smartphone to your digital scale
- Then you will lose weight
- You have to do something *else*?

Internet of Things

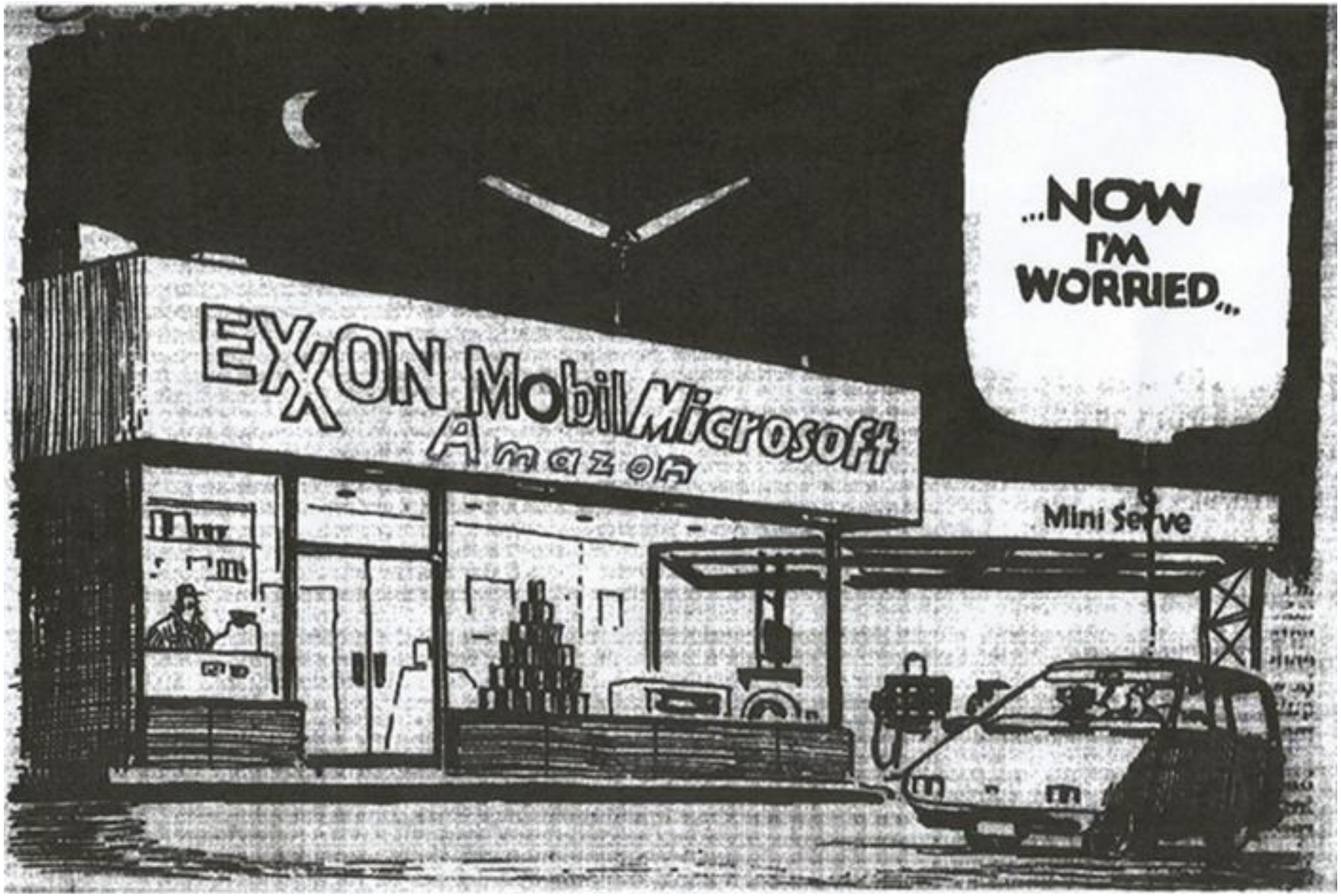
Shifts in automation are changing the way we work

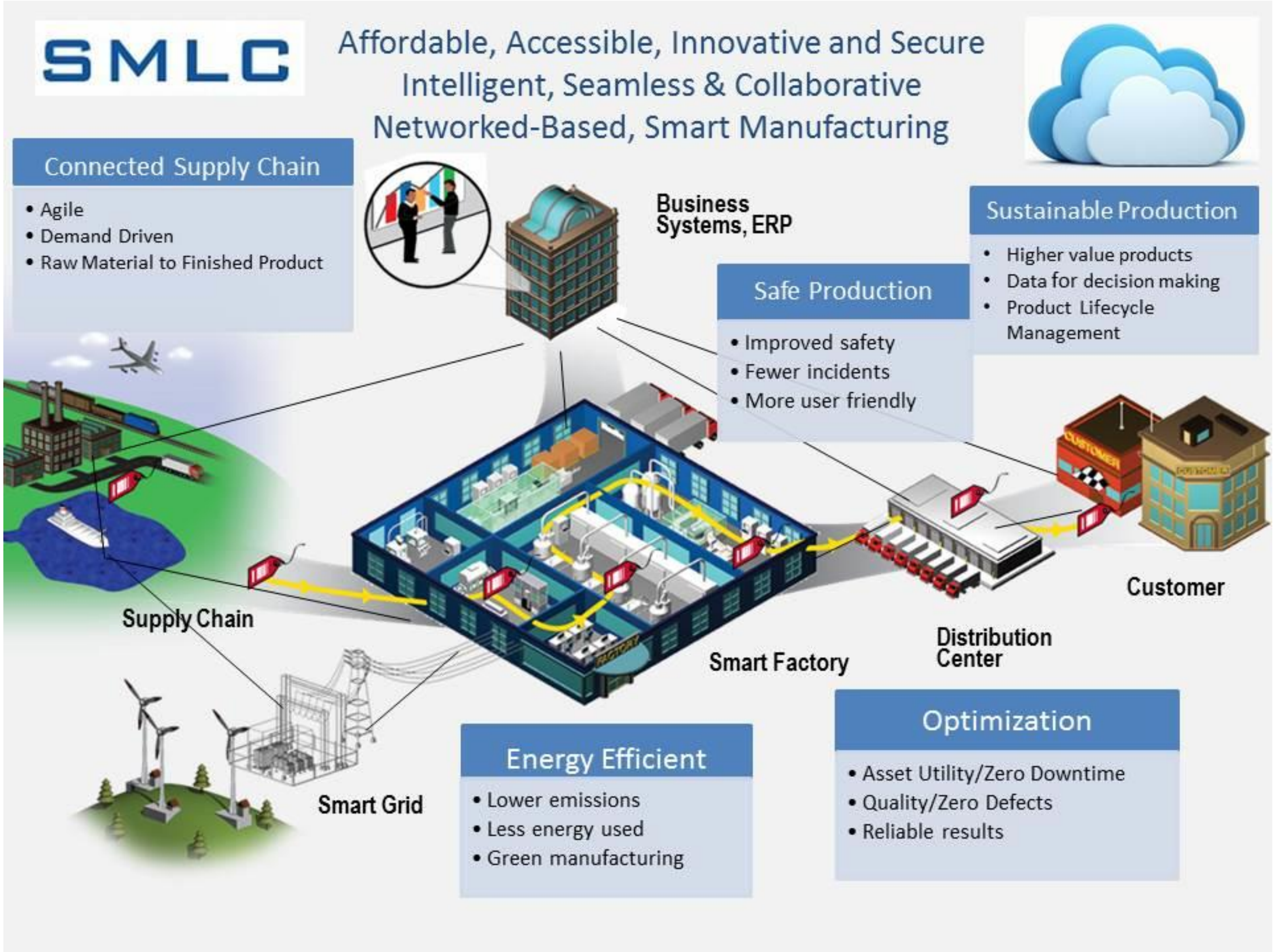
Increasing connectivity continues to provide more data

Things and connectivity

- **6.4 billion** connected “things” in 2016
- More than 20 billion by 2020
- **5.5 million new things** every day
- A single plant can have tens of thousands of I/O points
- Traffic growing at 23% per year
- We have more data than we know what to do with

Convergence of Information Technology and Operations Technology




SMLC
Affordable, Accessible, Innovative and Secure
Intelligent, Seamless & Collaborative
Networked-Based, Smart Manufacturing
Connected Supply Chain
• Agile
• Demand Driven
• Raw Material to Finished Product
Business Systems, ERP
Sustainable Production
• Higher value products
• Data for decision making
• Product Lifecycle Management
Safe Production
• Improved safety
• Fewer incidents
• More user friendly
Supply Chain
Smart Factory
Distribution Center
Customer
Smart Grid
Energy Efficient
• Lower emissions
• Less energy used
• Green manufacturing
Optimization
• Asset Utility/Zero Downtime
• Quality/Zero Defects
• Reliable results

SMLC
Smart Manufacturing
Leadership Coalition
www.smartmanufacturingcoalition.org

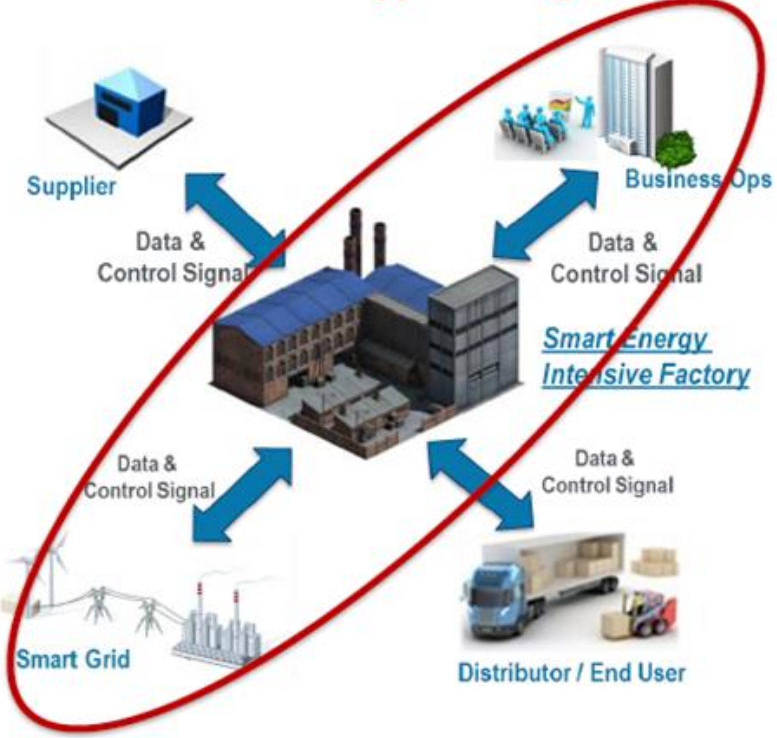
Clean Energy Smart Manufacturing Innovation Institute

- $140+ Million in Public-Private Investment
- 9th Manufacturing Institute established 2017

SMLC
Smart Manufacturing Leadership Coalition
www.smartmanufacturingcoalition.org

SMART Manufacturing: Advanced Controls, Sensors, Models & Platforms for Energy Applications

Focus on Real-Time For Energy Management

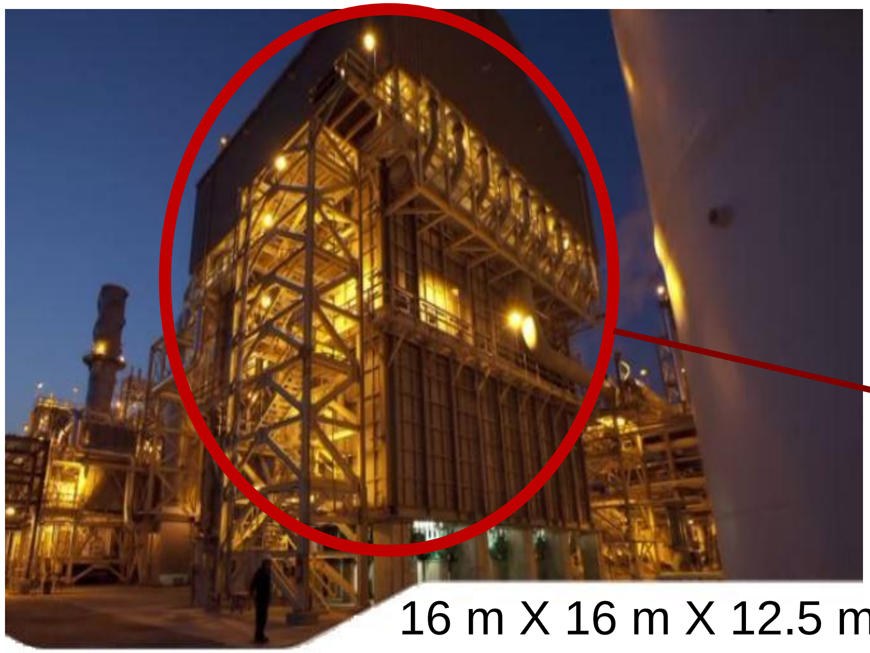


- Encompass machine-to-plant-to-enterprise real time sensing, instrumentation, monitoring, control, and optimization of energy
- Enable hardware, protocols and models for advanced industrial automation: requires a holistic view of data, information and models in manufacturing
- Leverage High Performance Computing for High Fidelity Process Models
- Significantly reduce energy consumption and GHG emissions & improve operating efficiency – **20% to 30% potential**
- Increase productivity and competitiveness across all manufacturing sectors:
  Special Focus on Energy Intensive & Energy Dependent Manufacturing Processes

Leverages AMP 2.0

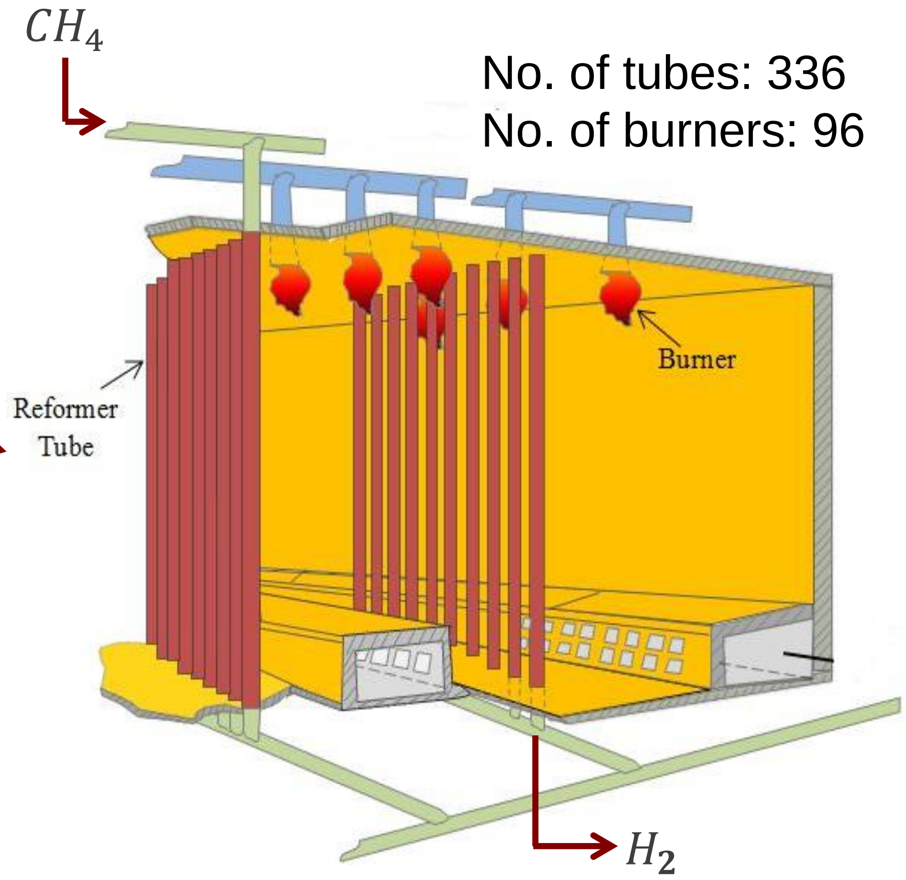
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Test Bed
H_2 Plant: Steam-Methane Reformer (SMR)



16 m X 16 m X 12.5 m

No. of tubes: 336
No. of burners: 96



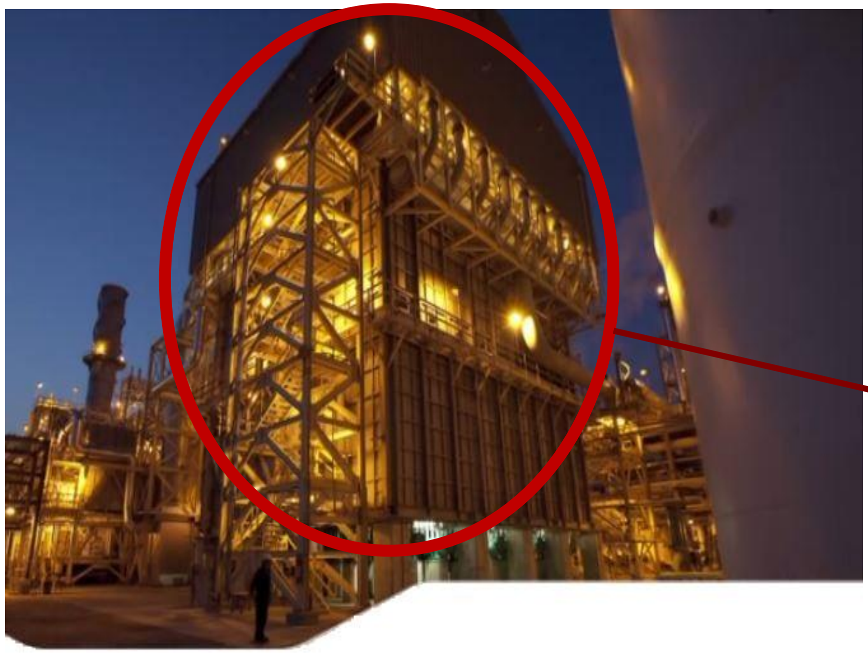
(Furnace Subsection)

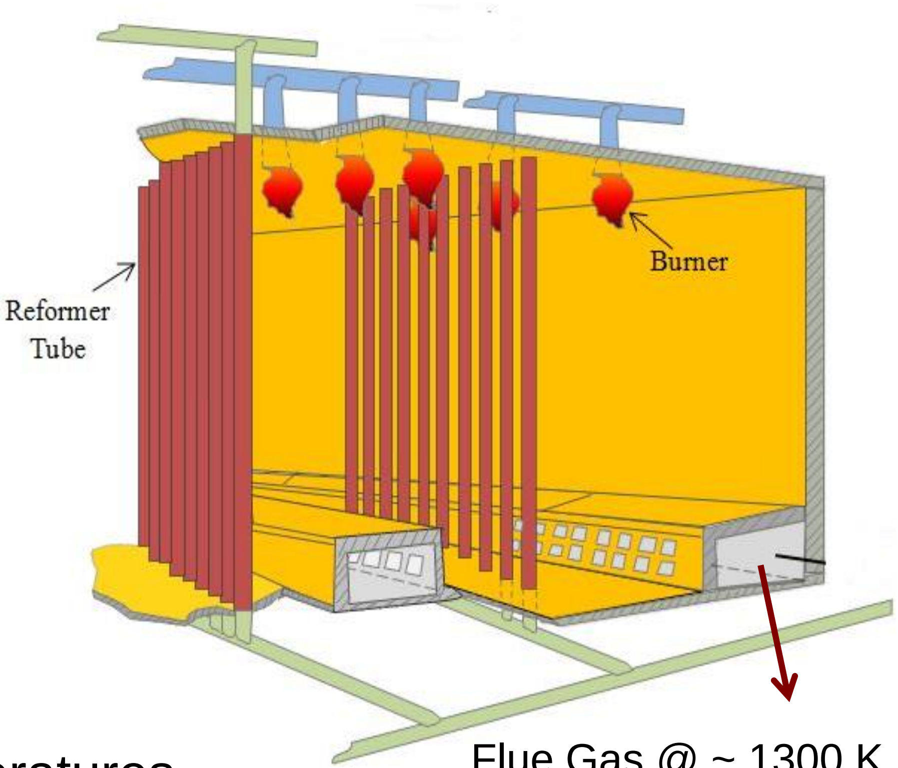
Endothermic Reforming reactions

$$CH_4(g) + 2H_2O(g) \leftrightarrow 4H_2(g) + CO_2(g)$$
$$CH_4(g) + H_2O(g) \leftrightarrow 3H_2(g) + CO(g)$$

[1] Praxair Inc. YouTube Channel

H_2 Plant: Reformer Furnace





Ideal Scenario: Uniform tube-wall temperatures

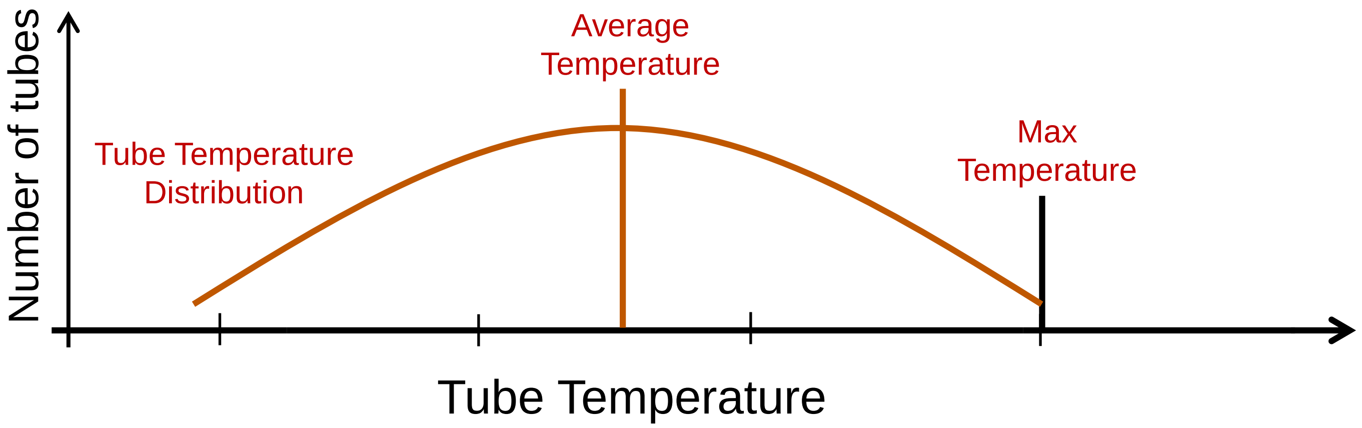
⇒ Each molecule undergoes same processing experience

⇒ Maximum efficiency

[1] Van Gerven, T., Stankiewicz, A. (2009). Structure, energy, synergy, time. The fundamentals of process intensification. *Industrial & engineering chemistry research*,

Furnace Balancing

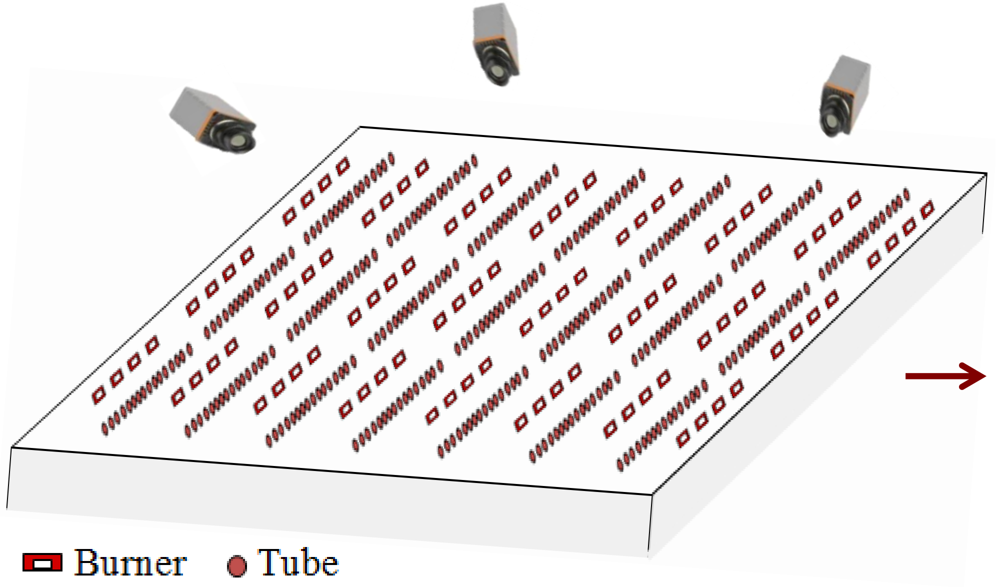
- With reduced non-uniformity, can increase average temperature without violating temperature constraints
  - ⇒ greater methane conversion
  - ⇒ overall lower energy consumption per unit hydrogen produced



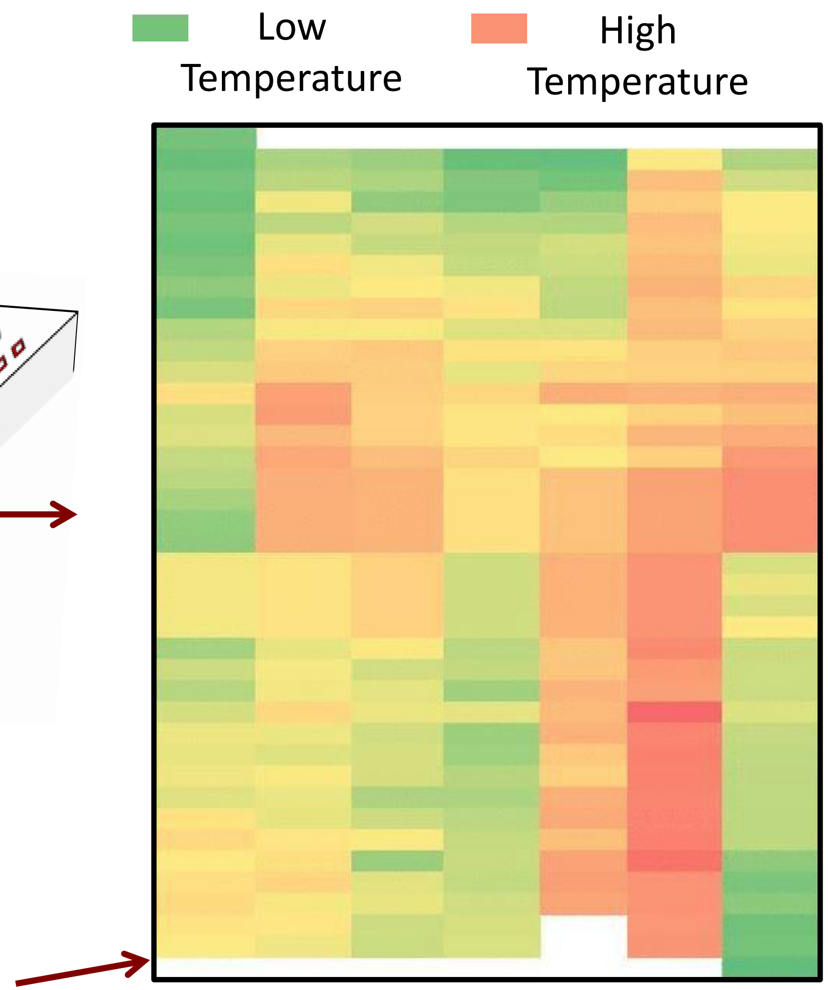
Large Temperature Non-uniformity Leads to Sub-optimal Plant Operation

Distributed Temperature Sensing

- Allowed furnace-wide tube temperature measurements



Top view of reformer



Temperature contour

Metals Processing

- Temperature, esp. the core, cannot be sensed and controlled directly
- In practice, operators tend to overheat
- Insufficient heating in only some portions adversely affects the product quality - waste

High energy demand combined with sensing limitations – steel production and processing a primary target for advanced model based analysis and control

Min energy usage of furnaces – *modeling and optimization* - directly impact overall consumption & related CO_2 emissions

Stones, E.J. *et al*. (2007) Technical Report, NPC Global Oil and Gas Study; Vishwanathan, V et. al. (2005) Pacific Northwest National Laboratory; https://www.worldsteel.org/statistics/

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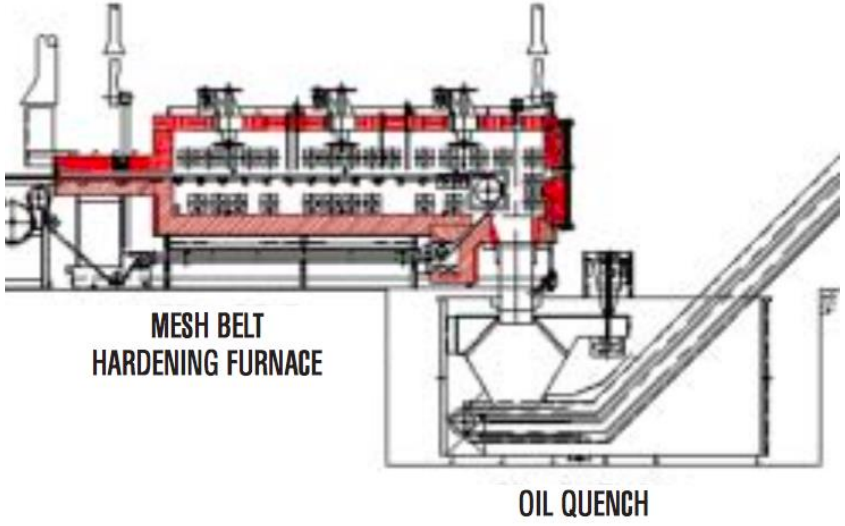
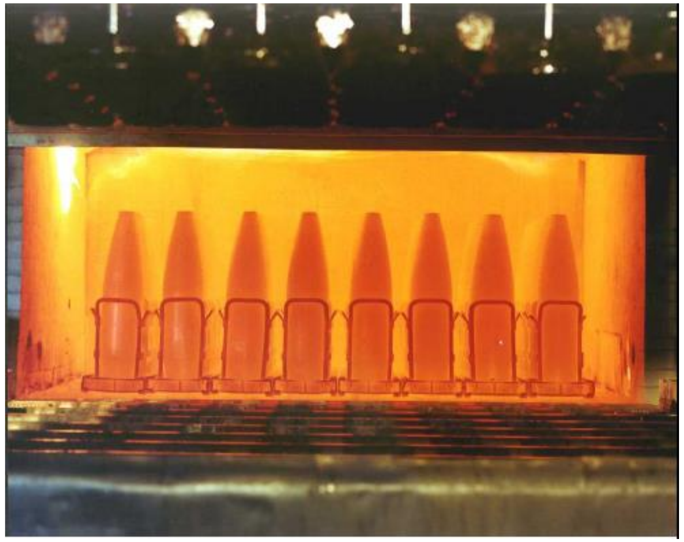
System Description

- Heat treating (austenitization)
- Operated in a continuous manner under T feedback control
- Parts loaded on to trays placed on a conveyor belt – through the furnace
- Natural gas fired radiant tubes in ceiling and floor



System Description



- After exiting the furnace, parts are quenched to induce desired mechanical properties
  - Hardness, toughness, shear strength, etc.
- Nitrogen (inert gas) flows counter current to the direction of movement of conveyor belt

Image Source: General Dynamics, Scranton, PA; *Operation Energy Demonstration Project*

Microstructural Evolution

- Steel polycrystalline material
  - Crystallinity affects physical properties
- Grain boundary
  - Single phase interface with identical grains on both sides, except in orientation
  - Crystal structure defect – region of high energy
- Austenite grain grows to lower free energy – higher thermodynamic stability
  - Artillery shells must be tough
  - Large grain sizes make the product brittle or less tough

Image Source: https://vacaero.com/images/; accessed on: 10/04/2016

- To achieve defect-free and structurally sound product, control:
  - macroscopic properties like T
  - microscopic properties like grain size

Anelli, E., ISIJ, Vol 32, 1993, pp 440-449

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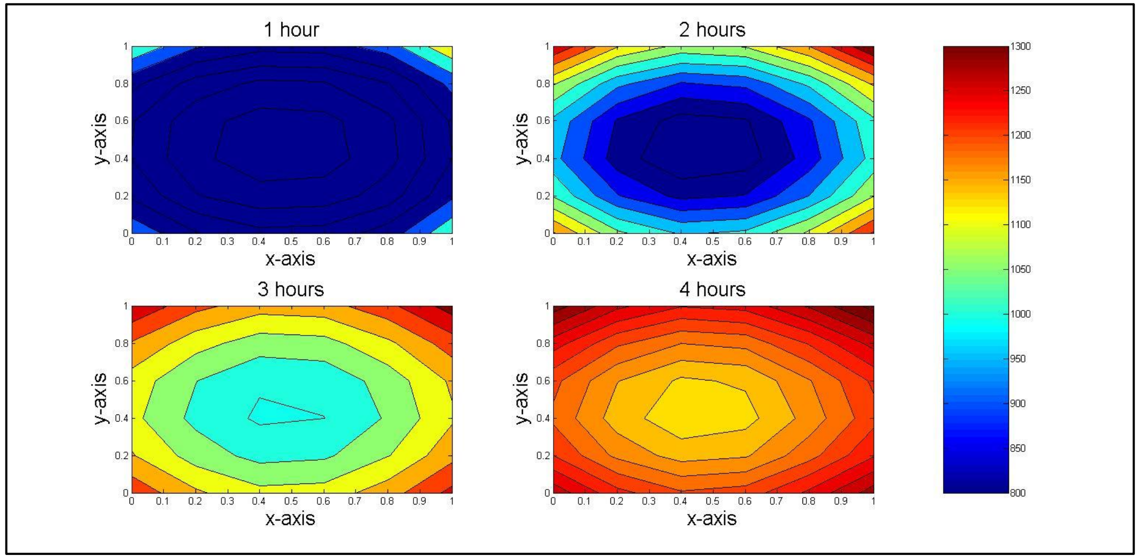
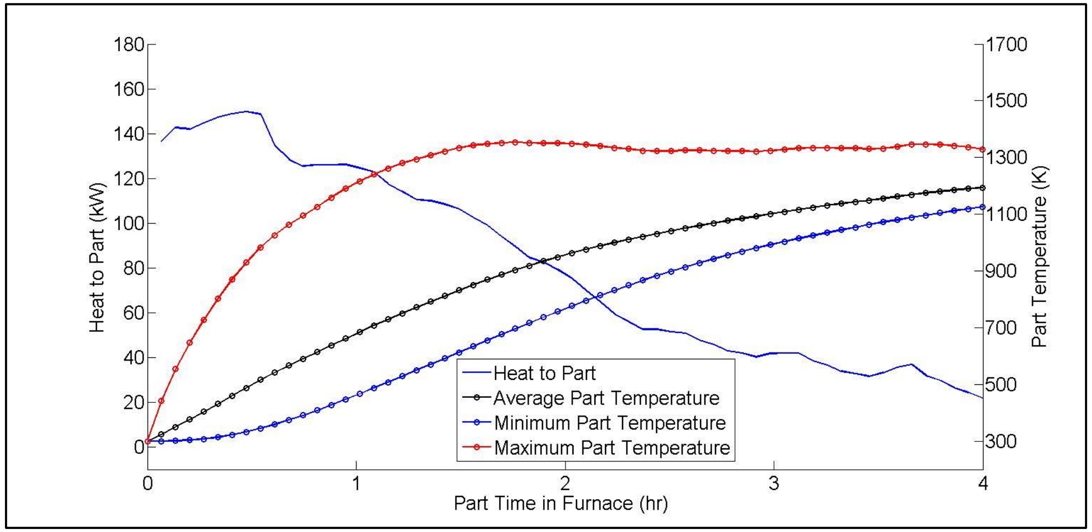
Heuristic Set Points - Temperature Profiles

Temperature distribution of part no. 20



Heat transferred to part no. 20



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Optimization Formulation

$$\min_{T_{sp,i}} Energy\ Usage$$

$$s.t.$$

$$1000\,K \leq T_{sp,i} \leq 1300\,K$$ *Min/Max zone temperatures*

$$T_{sp,i} + T_{diff} \leq T_{sp,i+1}$$ *Increasing zone temperatures*

$$T_{\text{part, exit}} \geq 1100\,K$$ *Min part temperature*

$$\frac{\sigma_{\text{part, exit}}}{\overline{T}_{\text{part, exit}}} \leq 0.05$$ *Temperature spread*

$$d_{part,exit} \leq 90\,\mu m$$ *Grain growth restriction for ensuring product toughness*

Process model

How does the U.S. bring back manufacturing jobs?

Manufacturing and Jobs

- Between 2000 and 2016, the United States lost 29 percent of its manufacturing jobs, while total U.S. employment grew almost 10 percent.
- The biggest reason President Trump can't bring back jobs is because there is nowhere to bring them back from. They have been lost in large part to the success of efficiency. Manufacturing output in the U.S. was at an all-time high in 2015, driven by technology and a skilled workforce.
- We should try to bring back the kinds of manufacturing that is complex and high-value-added and recognize what production is better performed in other nations (e.g., Germany has a trade surplus with China).

Ref: Atkinson and Ezell, ITIF (2017)

Three Components of Smart Manufacturing

- Factory and enterprise integration and plant-wide optimization,
- Exploiting manufacturing intelligence, and
- Creating disruptive business models.

Over the past 50 years, PSE researchers have developed methodologies to optimize whole systems, whether at the unit, plant, or enterprise level.

Smart Manufacturing in the Future

- Plant-wide optimization is at the heart of PSE thinking. Simulation tools with embedded optimization capability have led to plants optimized for profitability and minimal environmental impact and abnormal events, while seeking sustainable production.
- In order to become more responsive and agile, the process industries can incorporate information technology (IT)-enabled manufacturing intelligence, with communication occurring between all parts of the supply chain.
- Computational methods that can handle multiple dynamic stages within the supply chain, taking into account technical constraints on flexible manufacturing at each stage, and handling uncertainty in demand and production, supply, and quality.

The Model-based Approach

- Decides on a course of action based on the information received, and the ability to achieve that outcome. Can these outcomes be achieved according to the model, and how can this be carried out?
- Along with speed and agility, customers also want certainty: of supply, of quality, and of safety.
- The process industries formerly focused on producing molecules that were required for further processing (e.g., methanol and ethylene). Now there is predictive capability to design polymer blends, solvent mixtures, and electrolytes.
- Molecular characterization of the whole supply chain, from primary manufacture, through intermediates, to the final product, is next.

Future PSE Model Requirements

- Model accuracy is important, and strongly relies on the ability to predict the properties and functional performance of complex mixtures.
- High-performance computing and communications have been crucial for PSE developments. However, mathematics has been the key enabler for PSE tools and techniques and will continue to be so for smart manufacturing.
- Modeling tools are still the domain of experts so must become more pervasive in industrial applications.

Conclusions

- The Smart Manufacturing paradigm encompasses process modeling, data analytics, control, optimization, and the enterprise view of manufacturing, and thus strongly aligns with PSE.
- The main challenge for maximal impact of SM is to make PSE and ICT tools pervasive in small, medium, and large enterprises.
- George Stephanopoulos was an early thought leader for plantwide control and plant operations from the enterprise perspective.

After a long distinguished career, what's left?

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George's Travel Plans?