



Engineered Learning Systems for Engineering and Education



G. W. Rubloff

www.isr.umd.edu/~rubloff/

Director, Institute for Systems Research and
Professor, Department of Materials and Nuclear Engineering



OUTLINE:

- Motivation - Simulation for Engineering and Education
- Features of Engineered Learning Systems
- Current R&D Directions for Learning Systems
- Application to Environmentally-Benign Semiconductor Manufacturing
- Conclusions



Acknowledgements



Rubloff group

Nayanee Gupta grad student, MNE, UMCP
Natasha Kositsyna undergrad, CS, UMCP
Ramaswamy Sreenivasan grad student, ChE, UMCP
Bill Levine EE/ISR faculty, UMCP
Yatin Sankholkar former MBA, UMCP
David Eckard former undergrad, ECE, NCSU
Mansour Oveissi former staff, UMCP
G. Brian Lu former postdoc, NCSU

Support
National Science Foundation
Visual Solutions, Inc. - software assistance, β -site
Institute for Systems Research
Institute for Advanced Computer Studies
University of Maryland

UMd Human-Computer Interactions Lab (HCIL)

Anne Rose HCIL/UMIACS, UMCP
Ben Shneiderman CS/ISR/UMIACS faculty, HCIL Director, UMCP
Catherine Plaisant HCIL/UMIACS, UMCP

Civil Engineering

Greg Baecher Chair, Civil Eng, UMCP
Ben Levy grad student, CE, UMCP
Phil Tarnoff Director, Ctr. Adv. Transp. Studies, UMCP

CEBSM, U. Arizona

Farhang Shadman Director, CEBSM, & Prof. ChE, U. Arizona



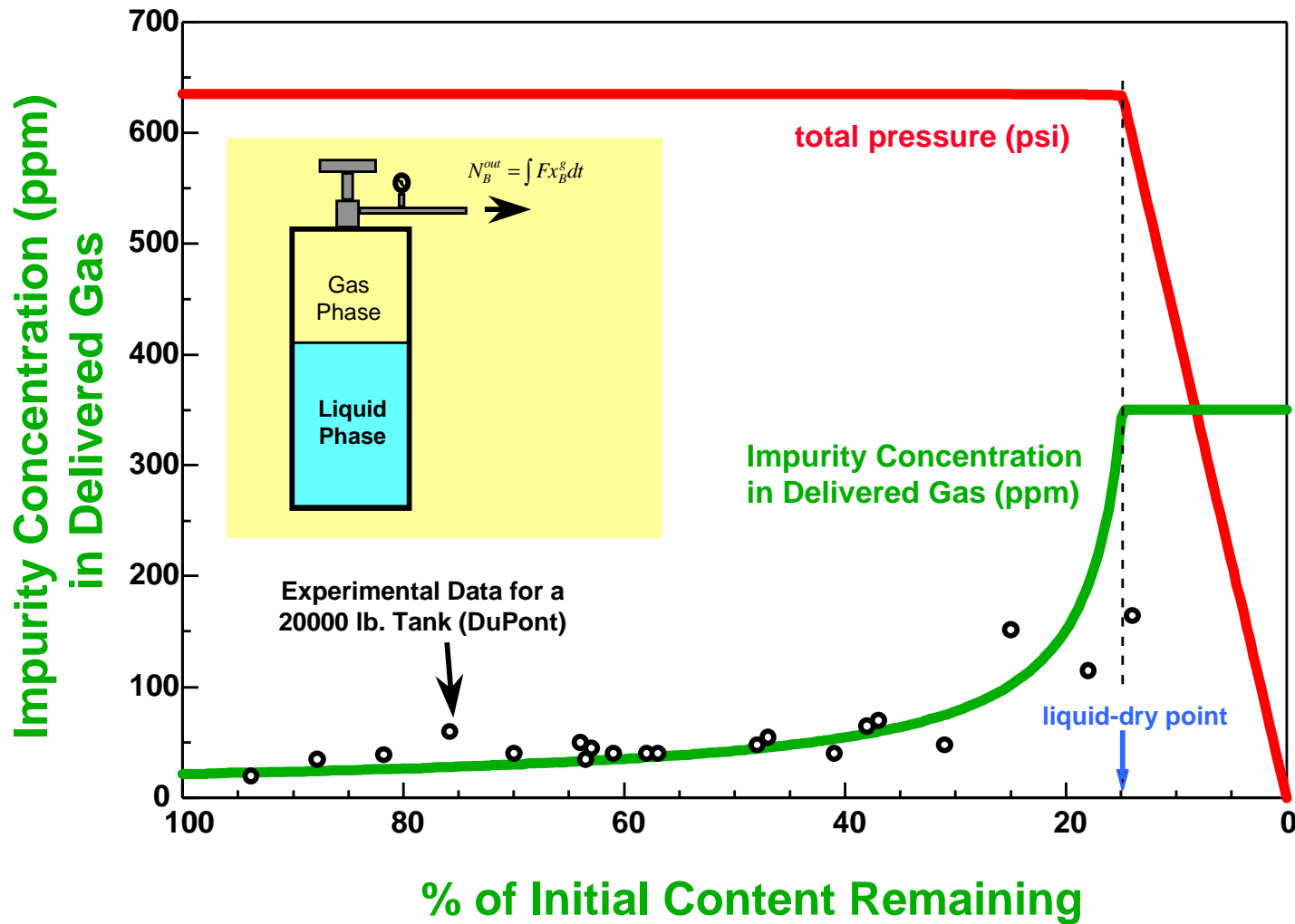
Physically-Based Dynamic Simulation for Engineering



- Physical and chemical models can be incorporated into dynamic simulators using commercial simulation platforms (Windows)
- Such simulators reveal time-dependent behavior critical to semiconductor manufacturing equipment, process, sensor, and control behavior
- Dynamic simulators have been validated against experiment
- Applications of dynamic simulators include design, control, optimization, and education/training

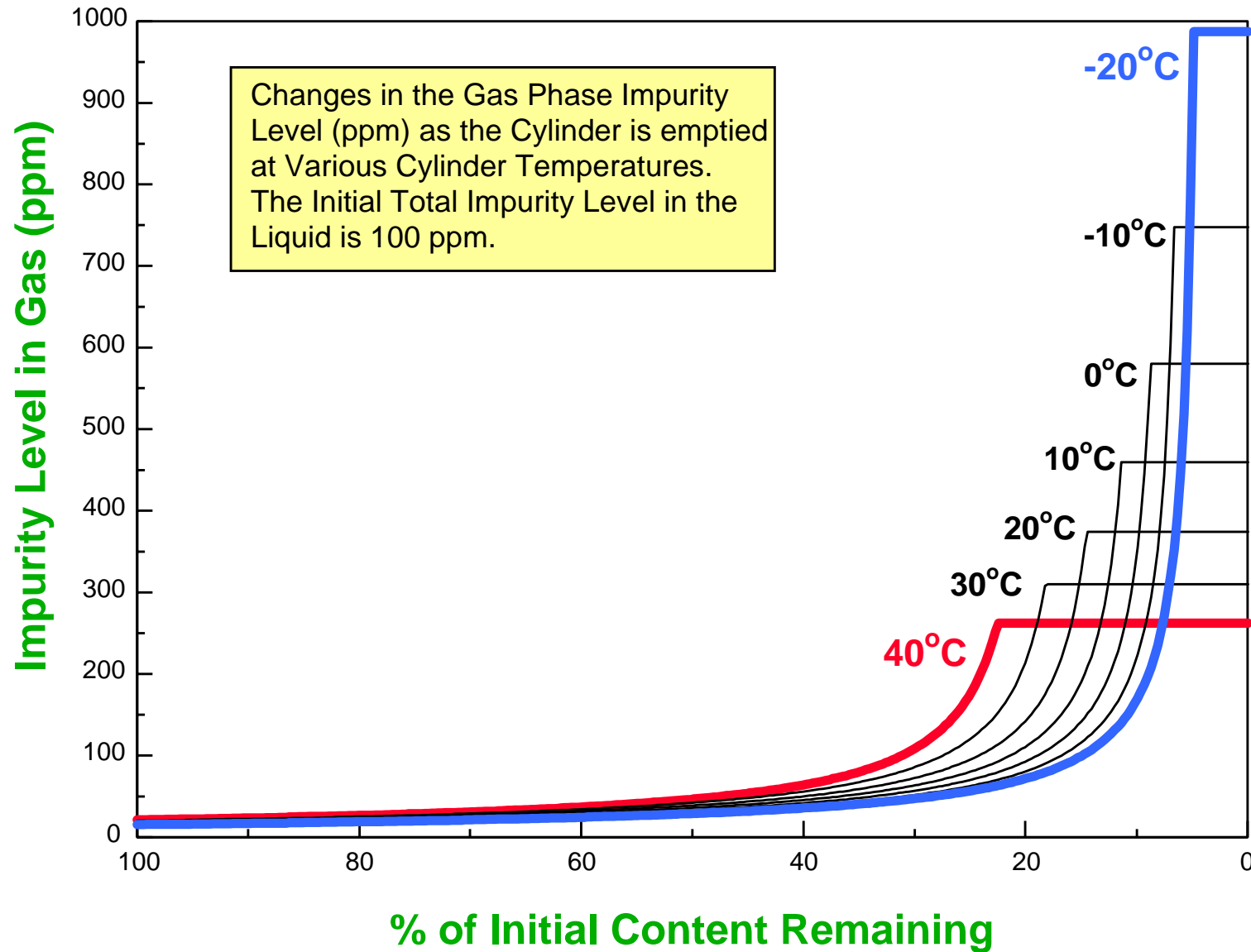


Impurity Concentrations in Liquid Source Delivery (w/ Motorola)





Impurity Concentration Delivery Profile vs. Source Temperature

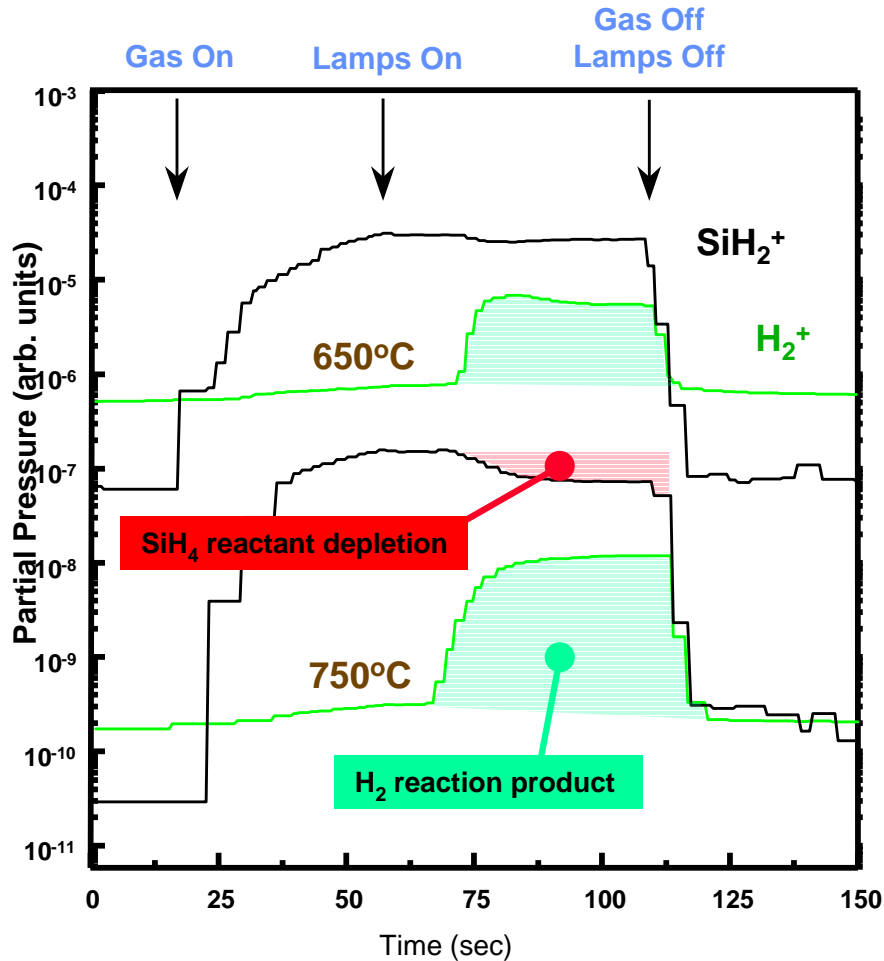




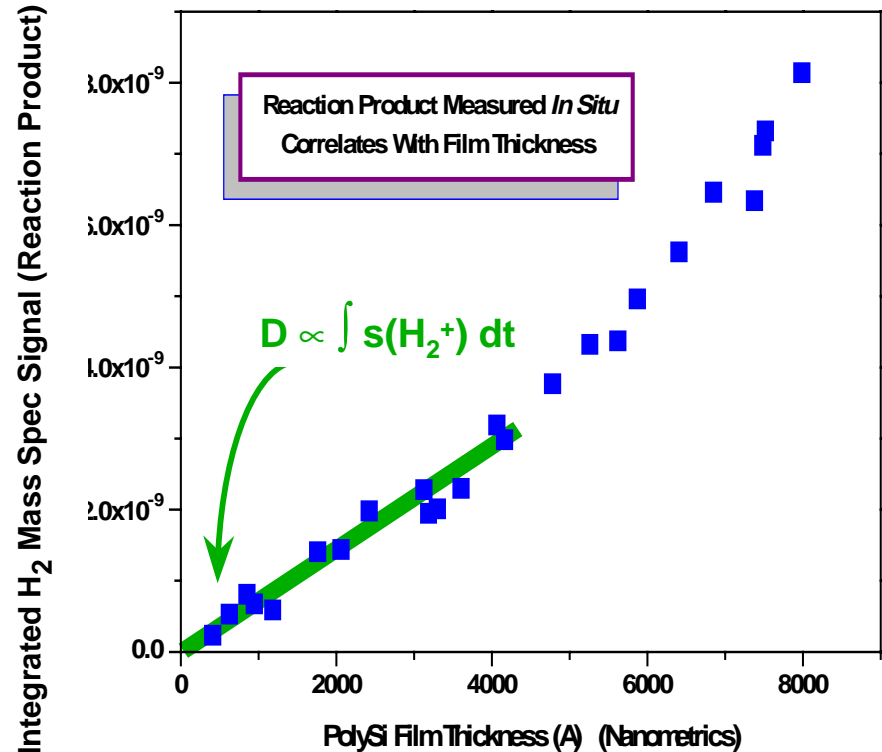
Real-Time Mass Spectrometry for Thickness Metrology in RTCVD polySi from SiH₄



Real-time mass spectrometry through process cycle

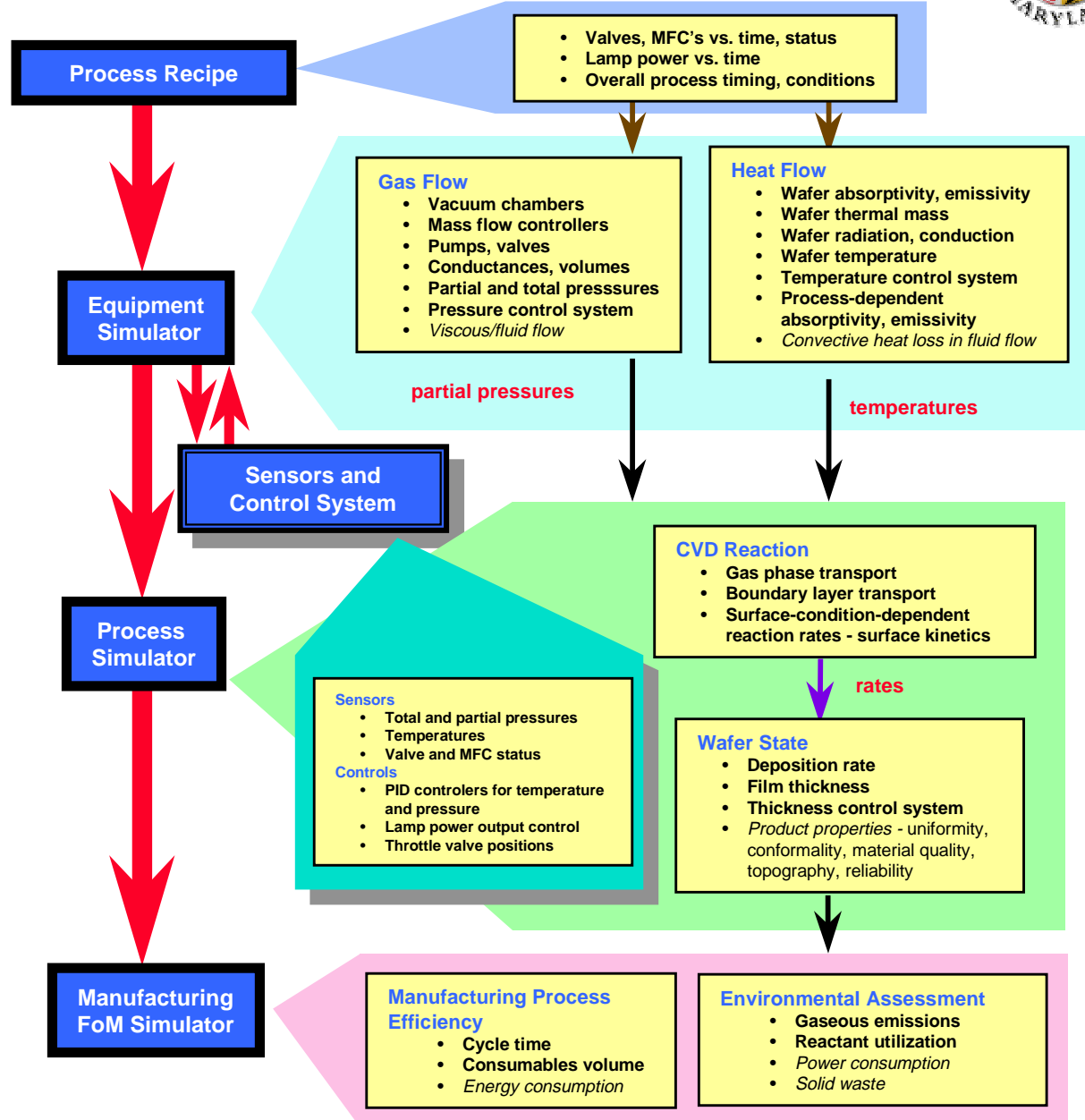


Integrated H₂ product signal used for real-time, in-line thickness metrology



Dynamic RTCVD PolySi Simulator

- **Dynamic simulation can realistically represent complex systems, including**
 - *equipment*
 - *process*
 - *sensors*
 - *control*
- **Results validated against experiment**
 - *timing/dynamics*
 - *subtle systematics*
- **Numerous applications**
 - *systems analysis*
 - *optimization*
 - *sensor-in-tool models*
 - *control system design*
 - *training ==> learning*
- **Platforms commercially available (Windows)**
- **Exploit rapidly growing software base**



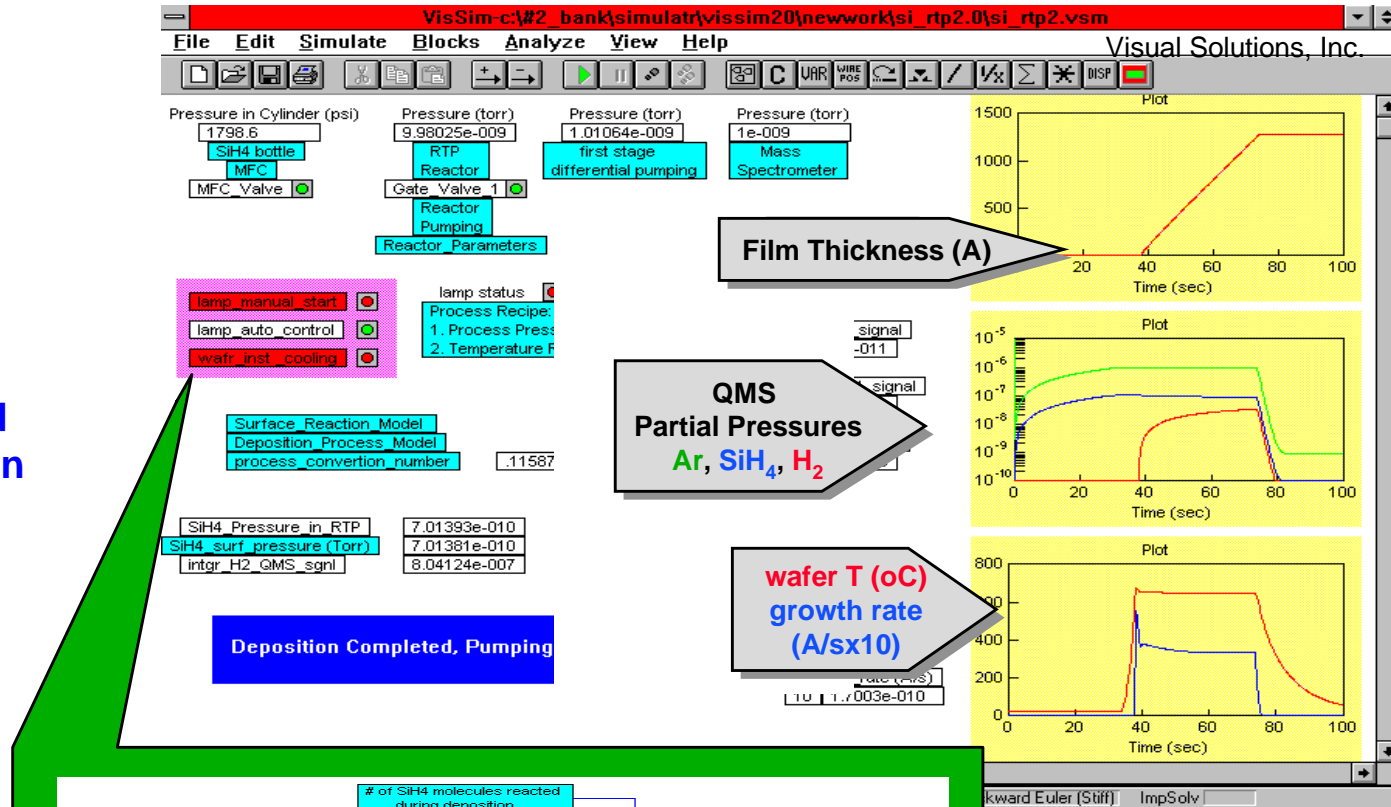


Dynamic RTCVD PolySi Simulator



Understand dynamic system behavior

Build basis for control and optimization

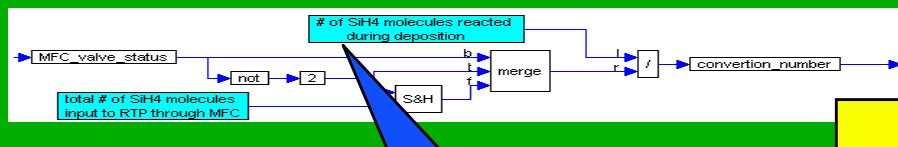


Deposition Completed, Pumping

Film Thickness (A)

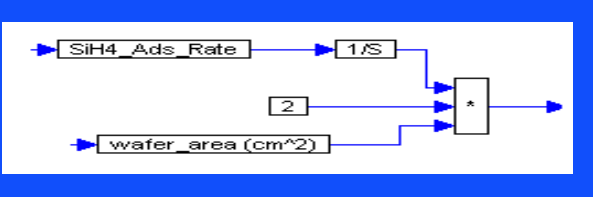
QMS Partial Pressures
Ar, SiH₄, H₂

wafer T (oC) growth rate (A/sx10)



Multi-level Structure

Second Level Compound Block





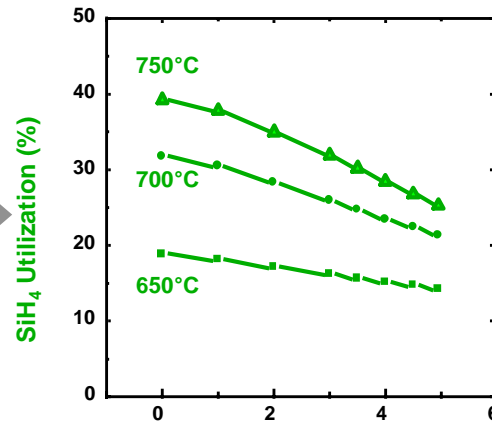
Optimizing for Manufacturing & Environment



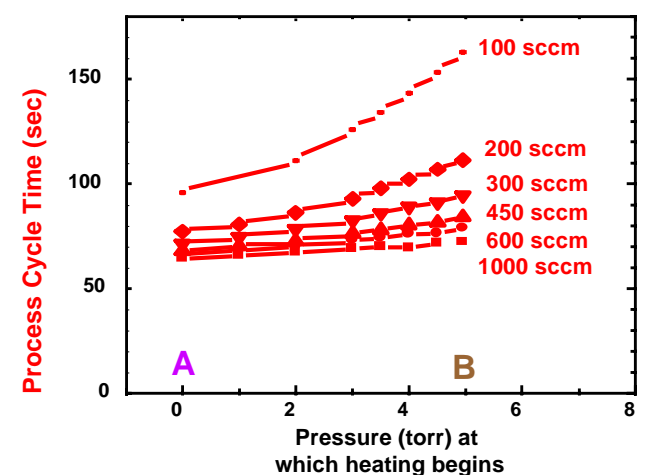
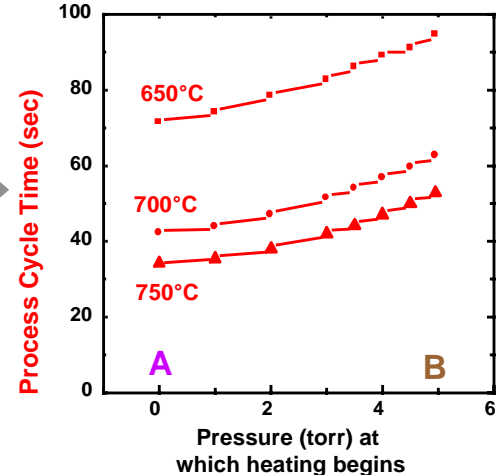
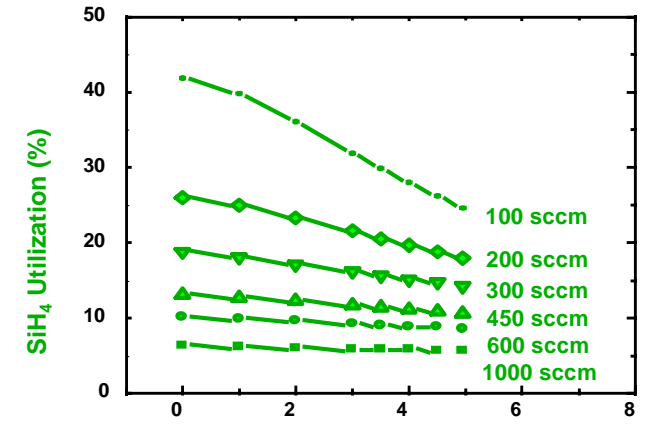
SiH₄ Utilization
Environment
Manufacturing

Process Cycle Time
Manufacturing

Constant flow rate
300 sccm

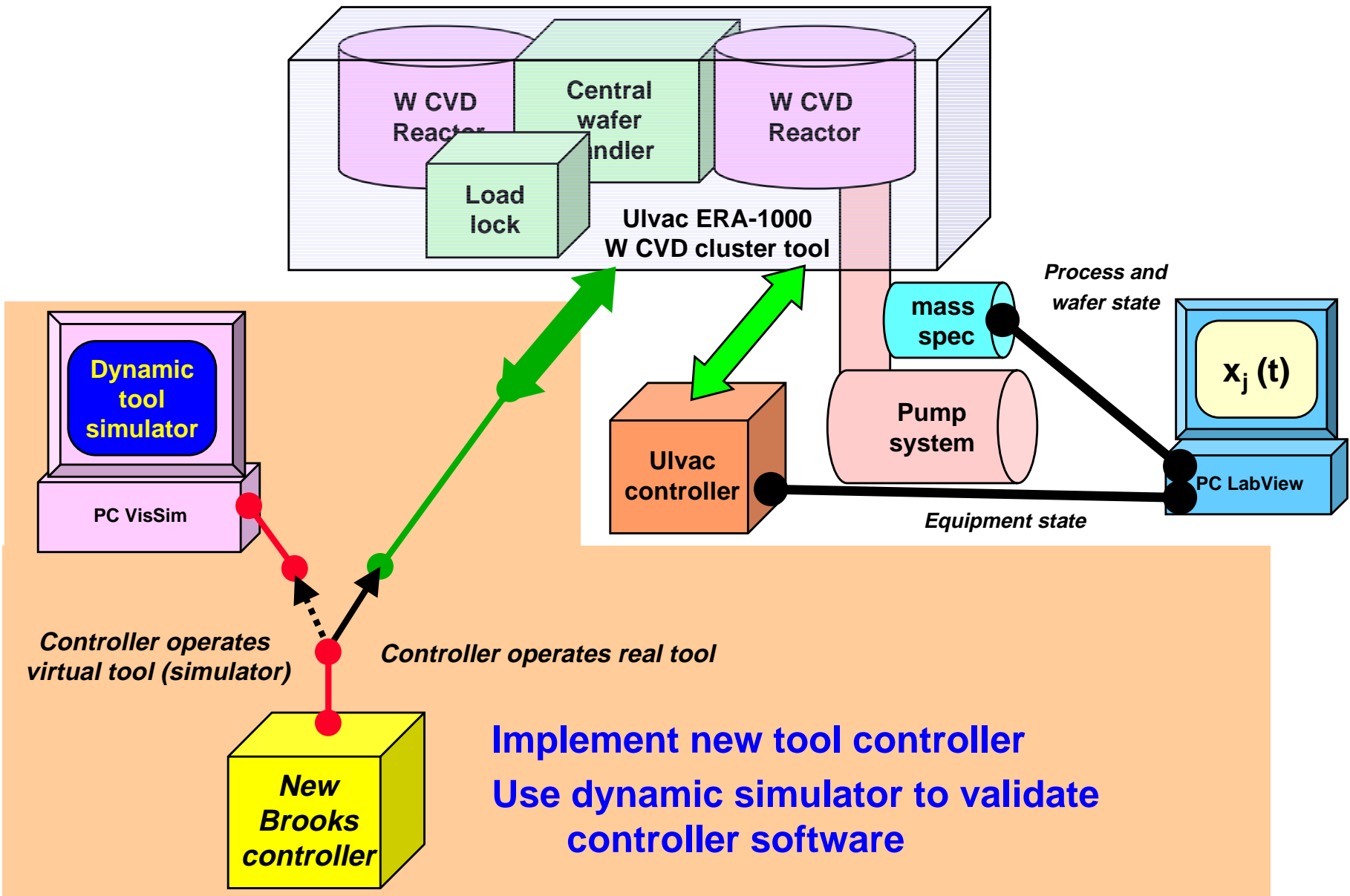


Constant temperature
650°C



A: start gas flow and heating simultaneously
B: start heating after gas flow established

Multi-Sensor Integration and Control



Motivation

Simulation is a powerful engineering tool, but usability is increasingly limited as complexity and validity increases

User interface design is crucial to usability and effectiveness

Simulation could provide active learning experiences which enhance education and training

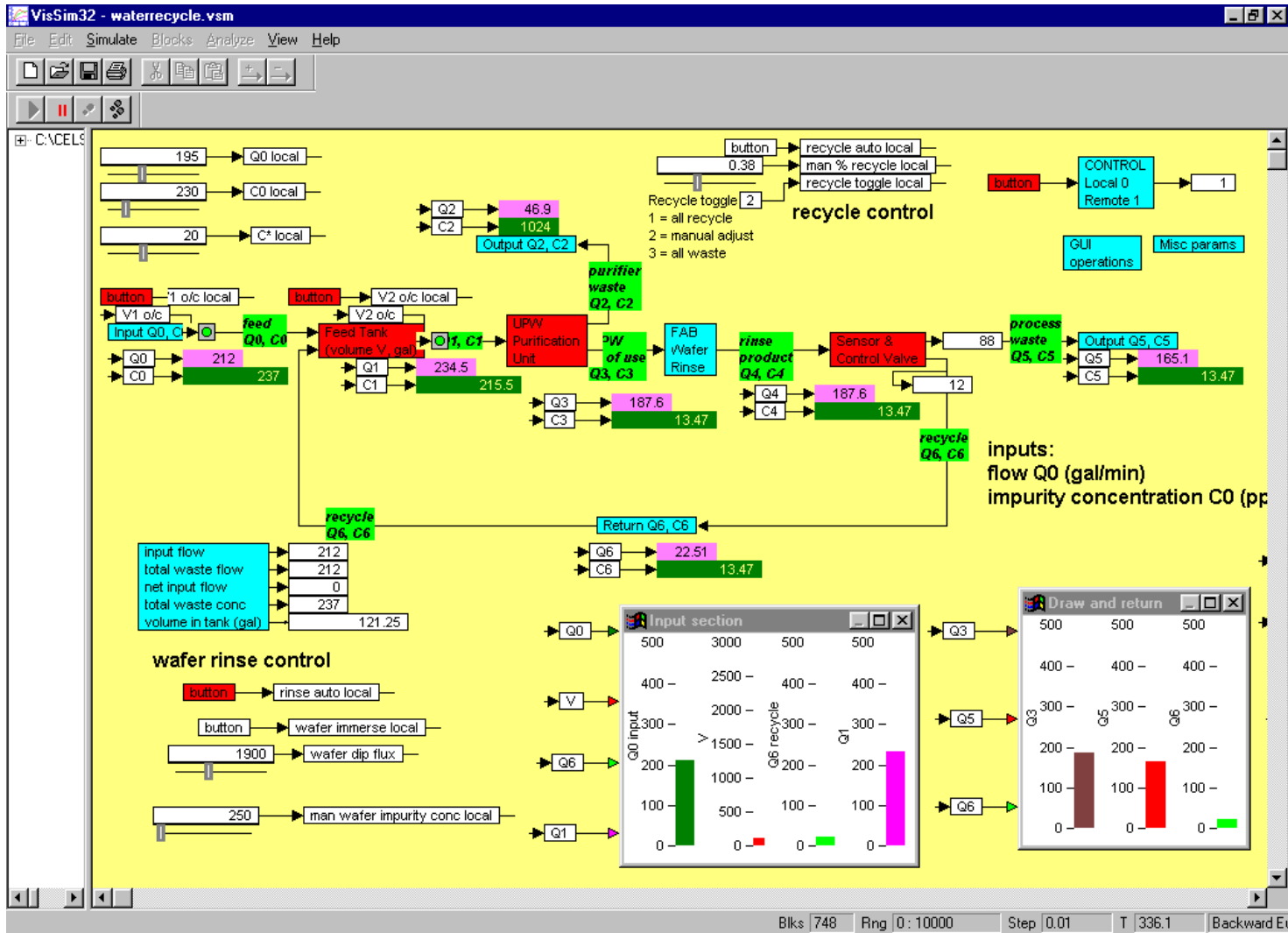
Simulation must be encapsulated in a rich exploratory environment for effective learning at any/all levels

Engineered Learning Systems

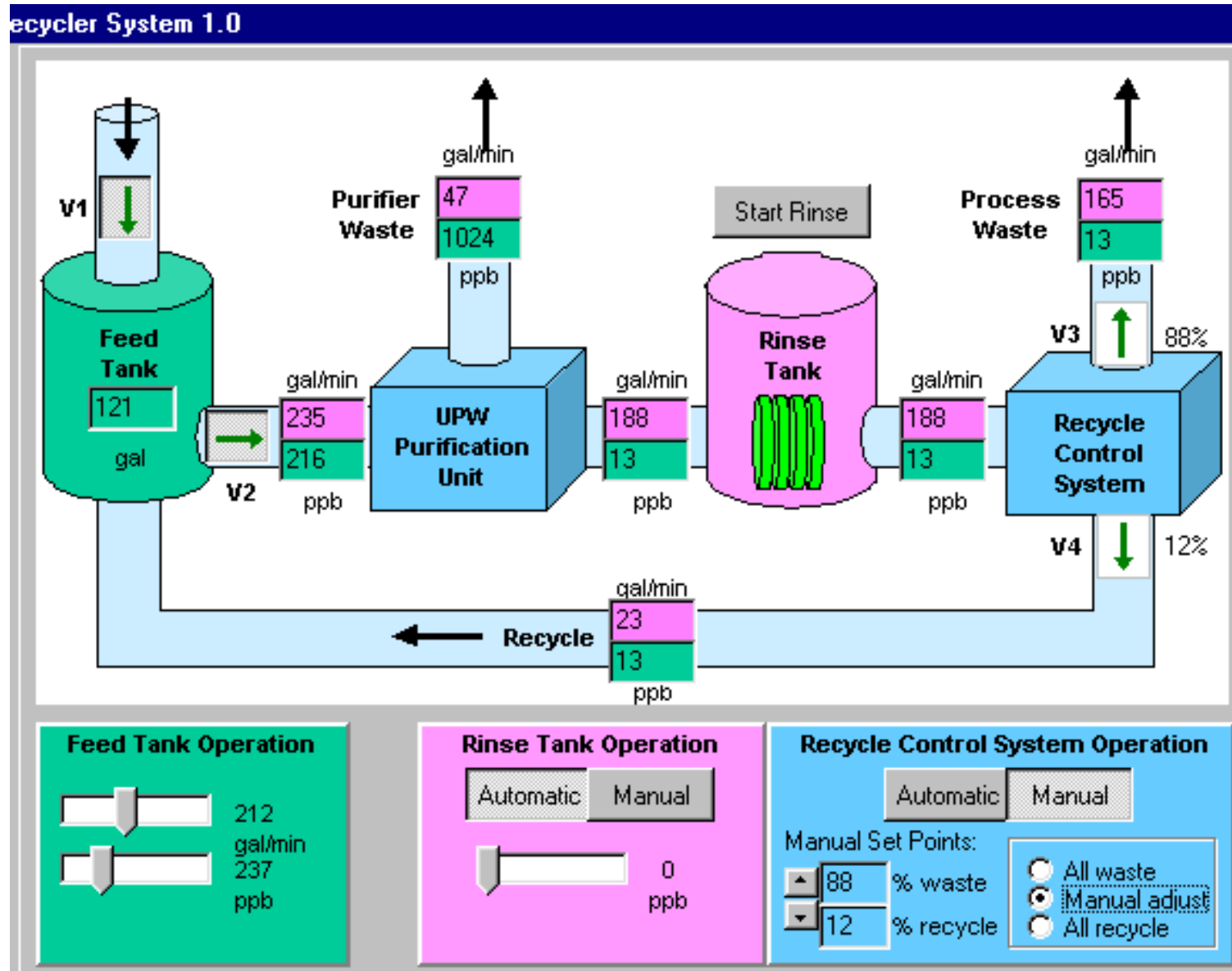
- effective user interface designs
- simulation experiences for active learning
- closely coupled guidance material
- software tools as learning aides
- easy authoring
- educational continuum
 - *novice to expert*
 - *classroom to on-the-job*

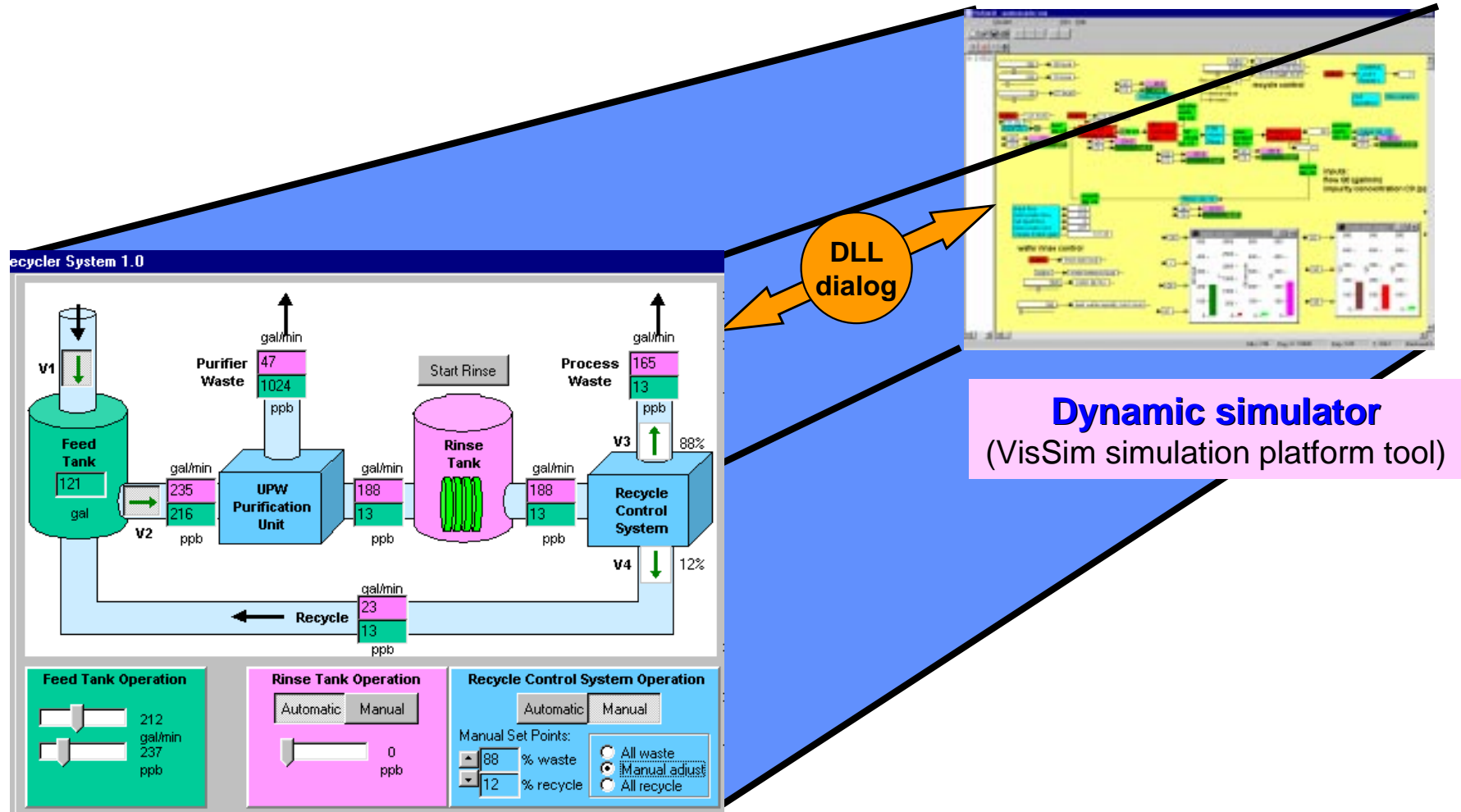


Dynamic Simulator

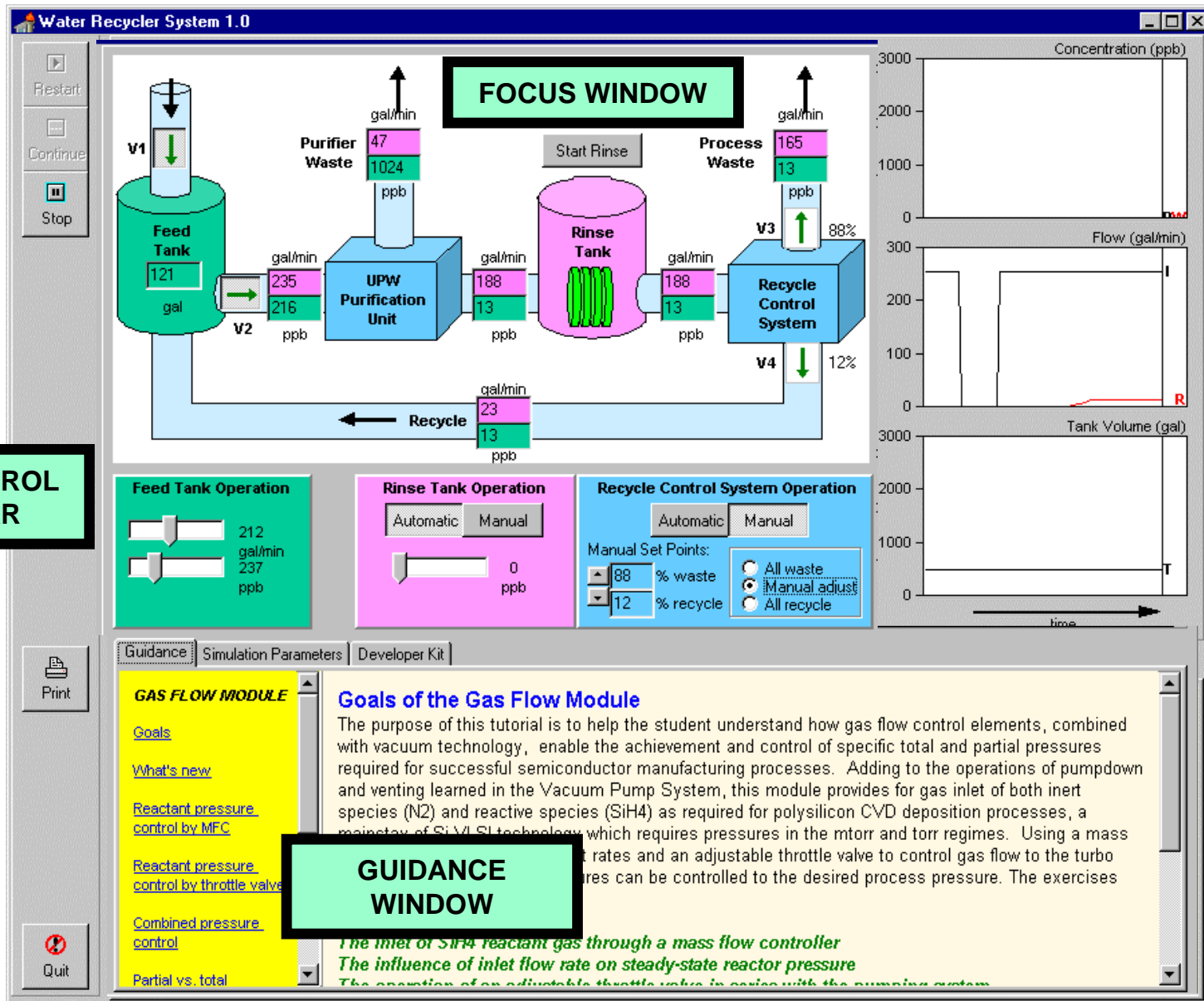


Commercial VisSim PC simulation platform (Visual Solutions Inc)





Enhanced user interface
(Delphi visual development platform)



The screenshot displays the 'Water Recycler System 1.0' interface. At the top left, there are control buttons: 'Restart', 'Continue', and 'Stop'. The main area features a process flow diagram with a 'FOCUS WINDOW' highlighting the 'Rinse Tank'. The diagram includes a 'Feed Tank' (121 gal), 'UPW Purification Unit', 'Rinse Tank', and 'Recycle Control System'. Data points for flow rates (gal/min) and concentrations (ppb) are shown at various stages. A 'CONTROL BAR' is overlaid on the left side of the diagram.

Below the diagram are three operational panels:

- Feed Tank Operation:** Includes sliders for flow rate (212 gal/min, 237 ppb).
- Rinse Tank Operation:** Includes 'Automatic' and 'Manual' modes and a concentration slider (0 ppb).
- Recycle Control System Operation:** Includes 'Automatic' and 'Manual' modes, manual set points for % waste (88%) and % recycle (12%), and radio buttons for 'All waste', 'Manual adjust', and 'All recycle'.

On the right side, there are three graphs: 'Concentration (ppb)', 'Flow (gal/min)', and 'Tank Volume (gal)'. The bottom section contains a 'GUIDANCE WINDOW' with a 'GAS FLOW MODULE' section, including 'Goals', 'What's new', and a list of topics like 'Reactant pressure control by MFC' and 'Reactant pressure control by throttle valve'.



Current R&D Directions for Learning Systems



- **Tools for experimentation and collaborative design**
 - *Free and guided exploration, annotation, simulation experience sharing*
 - *Models and simulations of system architecture, hardware elements, control systems*
- **Increasing ability for system alteration and redesign by user**
 - *Lab notebook, annotation, and collaboration*
 - *User-choice in functional elements*
 - *Network reconfiguration*
- **Incorporation of different modeling/simulation tools, including legacy codes**
 - *Excel, Java, Fortran, C/C++, ...*
- **Broad applications set on common, commercial software base**
 - *Manufacturing, control, optimization, equipment, ...*
 - *Environment, hydrology, geopolitics, ...*
 - *Commercial platforms for modeling/simulation and user interface design*
 - *Commercialization of learning systems products*

Heater Transfer Simulation 1.0
✕

Restart

Continue

Stop

Watch

Options

Help

Print

Quit

Pressure History (torr)

| | |
|----------------------|------------|
| Wafer Heating | ON OFF |
| Heating Mode | Lamp Power |
| 10000 w | More |

| | |
|-------------------------------|------------|
| Chemical Reaction | |
| Wafer Temperature (C): | 838 |
| SiH4 Partial Pressure (torr): | 2.5E+1 |
| Film Thickness (nm): | Reset 1285 |
| Deposition Rate (nm/s): | 5.1E+2 |

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EquipSim Vacuum Gas Flow Heat Transfer Chemical Reaction CELS new one Lab Notebook Developer Kit

HEAT TRANSFER MODULE

What's new ...

[In the heat transfer module](#)

[Wafer heating panel!](#)

[Wafer heating monitor](#)

Heating methods

[Lamp heating of wafer](#)

[Substrate heating of wafer](#)

[Setting wafer temperature directly](#)

Lamp heating of wafer

Wafer heating can be accomplished by using high power [heating lamps](#) to direct light (optical radiation) onto the wafer through a transparent [window](#) on the process chamber. Lamp heating is particularly important for use in rapid thermal processing (RTP), in which the high radiative power of the lamps (kilowatts) can cause the wafer to heat rapidly (in a few seconds) to temperatures as high as 900-1000C. Typically, quartz halogen lamps are used to illuminate the wafer.

To achieve rapid wafer heating for RTP, the wafer must essentially be thermally isolated from its surroundings (e.g., held in just a few points, or by a ring). This produces an advantage in thermal cycling of the wafer, since less time is required to establish elevated temperature process conditions. However, with the wafer thermally isolated, the primary mechanism for wafer cooling after the process is radiative heat loss, followed by slow conductive or convective heat loss at lower

Graphical elements associated with technical term are highlighted in focus window

Focus Window

Pressure History (torr)

1 atm

CT

approx. 12 seconds

Restart Continue Stop **SIMULATION IS RUNNING** Display Options Print Guidance QUIT

Guidance Simulation Parameters Developer Kit

GAS FLOW MODULE

Goals

What's new

Reactant pressure control by MFC

Reaction pressure control by throttle valve

Using MFC and throttle valve for pressure control

What's new in the Gas Flow Module

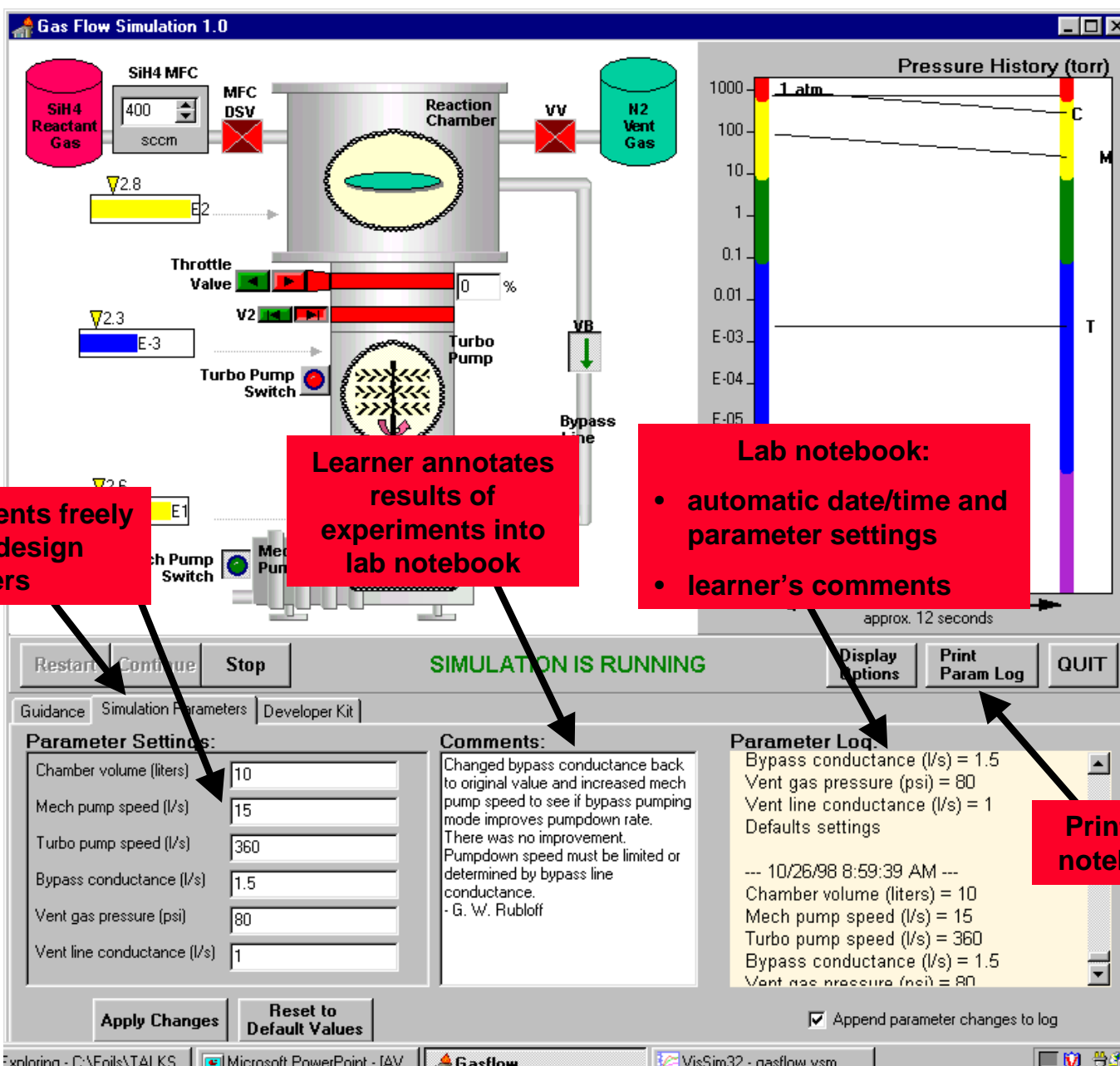
The Gas Flow Module contains two new components, the [reactant throttle valve](#), which are described here. For information on vacuum Vacuum System Module, see its What's New section or the overall [Glossary](#) pages.

Reactant gas inlet control system

The [reactant gas inlet control system](#) comprises three parts. First, the supply of reactant gas, in this case silane (or SiH₄), is generated by a red [reactant gas inlet control system](#) which SiH₄ can be introduced into the reaction chamber. MFC's are critical in such systems and pressures of reactive gases are critical to the reaction rate. The flow rate may be adjusted either by clicking on the up and down arrows on the MFC, or by directly editing the value of the flow rate, which is given in units of sccm (standard cubic centimeters per minute).

Guidance/Tutorial window

Cursor placed over technical term in guidance window



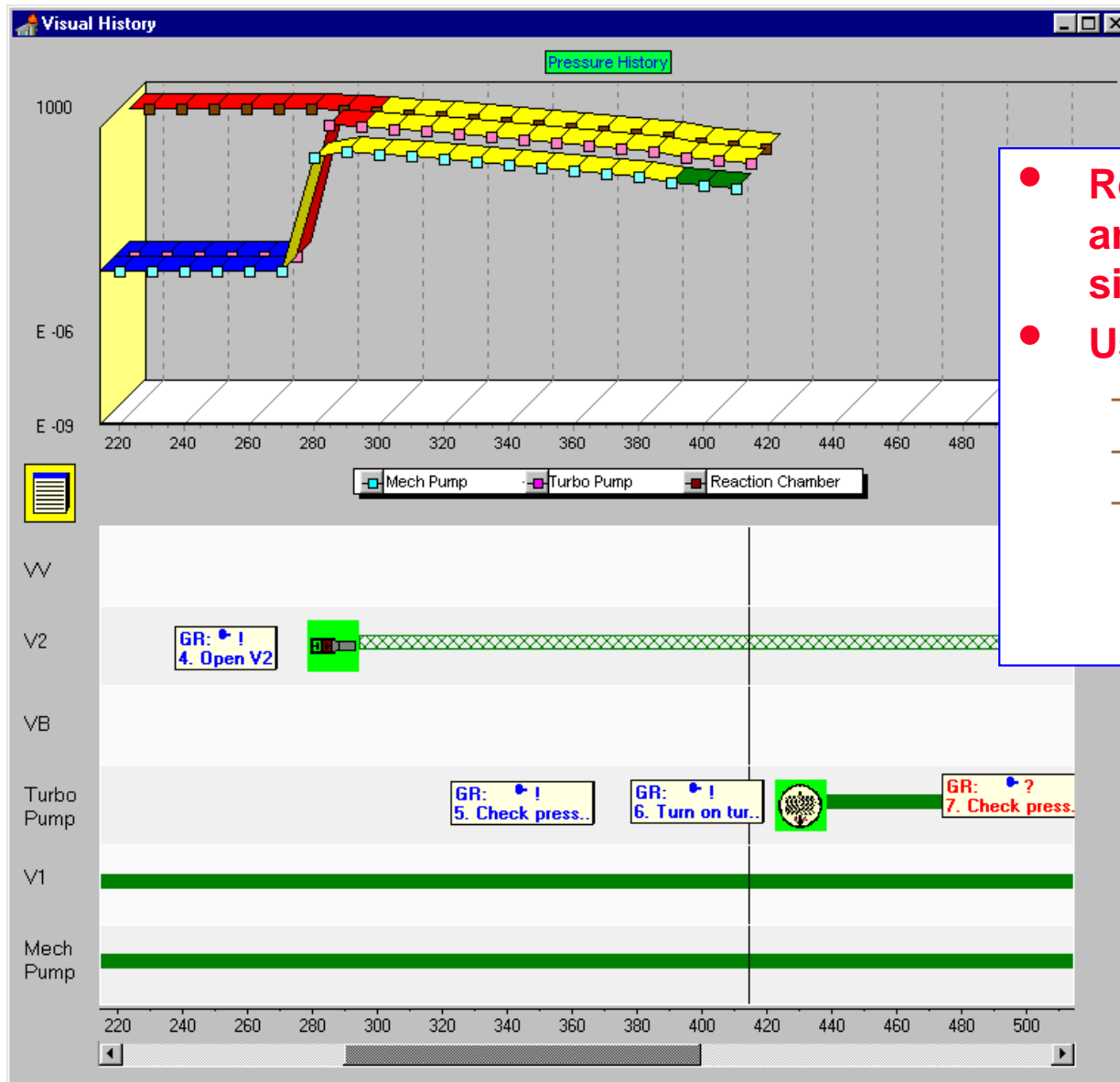
Learner experiments freely with system design parameters

Learner annotates results of experiments into lab notebook

Lab notebook:

- automatic date/time and parameter settings
- learner's comments

Print lab notebook



- Record, revise, replay, and annotate event histories in simulation experiments
- Use for
 - *tutorial generation*
 - *questions to teacher/expert*
 - *peer collaboration*

History Editor - C:\CELSA\Learning Historian\fullpump.his
✕

Action

Restart

Continue

Stop

History

Replay

Load

Save

Clear

Hide

Comment

Misc

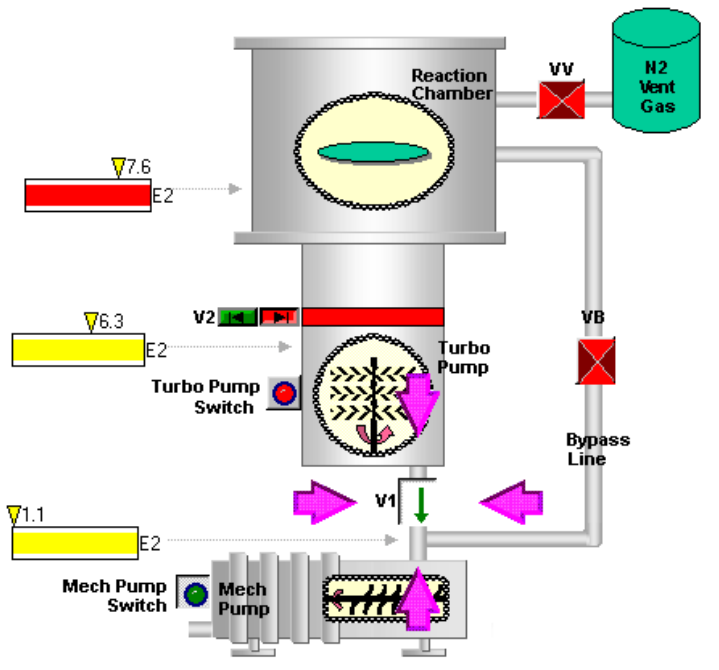
Timer

Options

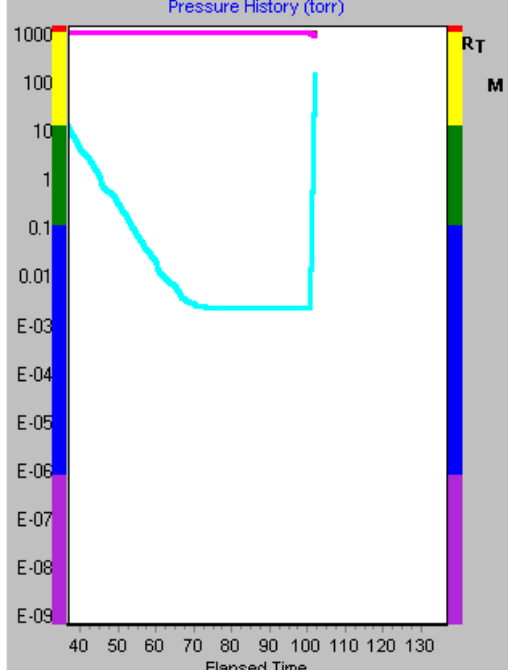
Email

Print

Quit



Pressure History (torr)



Guidance Historian Lab Notebook Developer Kit

Goals

[Using the system](#)

[Pump system introduction](#)

Pumpdown using:

- * [mech pump through bypass](#)
- ** [Demo 1: Mech only](#)
- * [mech pump through turbo](#)
- * [mech and turbo pumps](#)
- ** [Demo 2: Mech & Turbo](#)
- [Visual Historian Exercise](#)

Pumpdown

[Turbo pump](#) [Turbo pump sys](#)

In Pumpdown 1, you use
This has two limitations:

- Typically the bypass
- long time to approx
- reactive contaminant species (e.g., water or hydrocarbons from previous air exposure).
- The base pressure achievable with only the mechanical pump is not low enough to remove sufficient reactive species and achieve low enough base pressure in the reaction chamber to

From: GR

2. Open V1

Here we opened valve V1 so that the mechanical pump operates to pump down the turbo pump volume.

OK



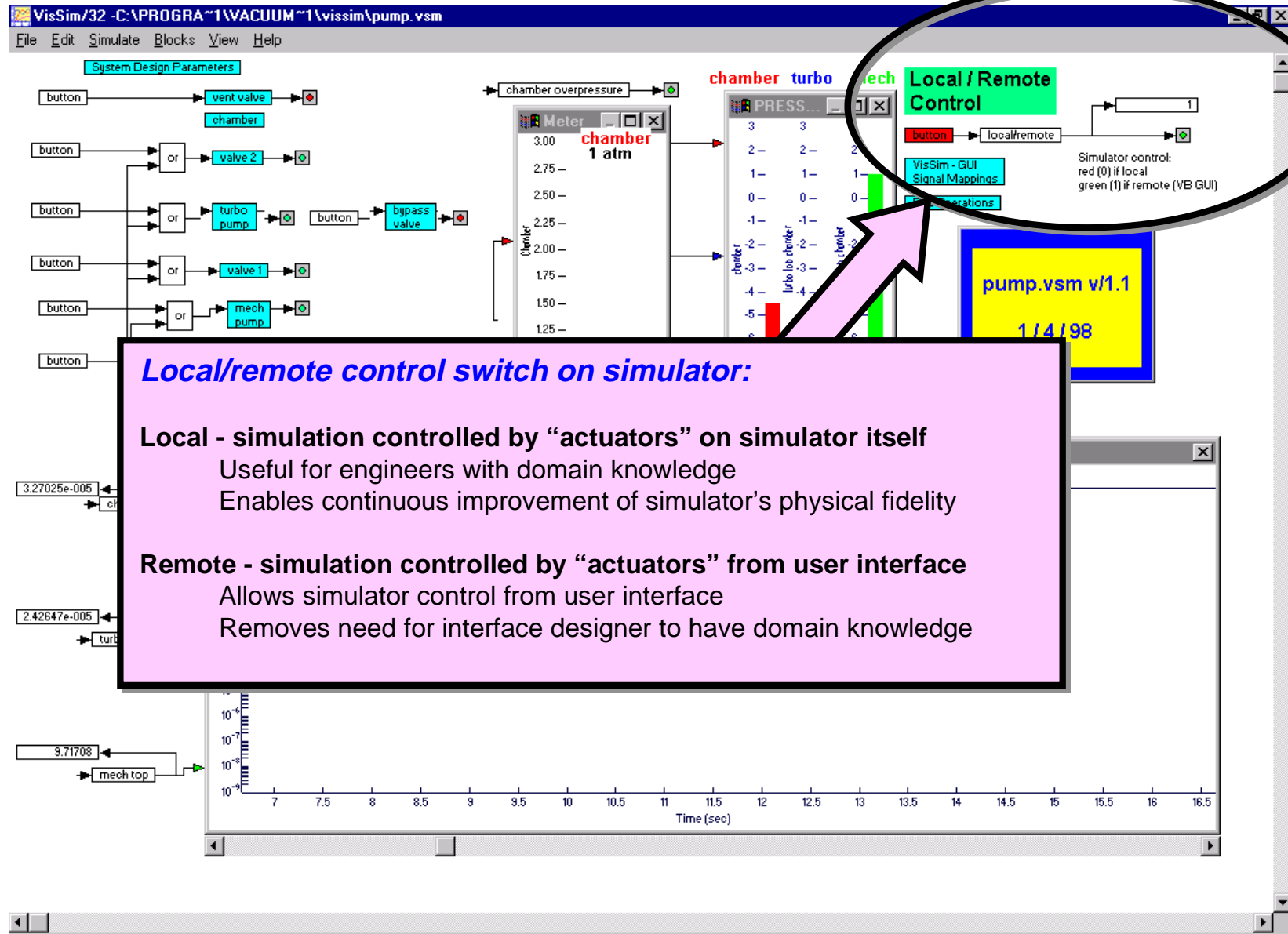
Design for Authoring



- **Enable independent authoring of**
 - *engineering/technical material vs.*
 - *user interface and software design*
- **Provide effective authoring tools to *engineering expert***
 - *minimal if any software knowledge required*
 - *reusable library of simulator objects*
- **Provide effective authoring tools to *software/interface designer***
 - *minimal if any engineering knowledge required*
 - *reusable library of user interface and software objects*
- **Anticipate sequence of learning modules which can bring learner from novice to knowledgeable practitioner status**
 - *learning tool becomes on-the-job assistant*
- **Assess authoring efficiency from diverse set of application experiences**



Simulator: Local and Remote Control



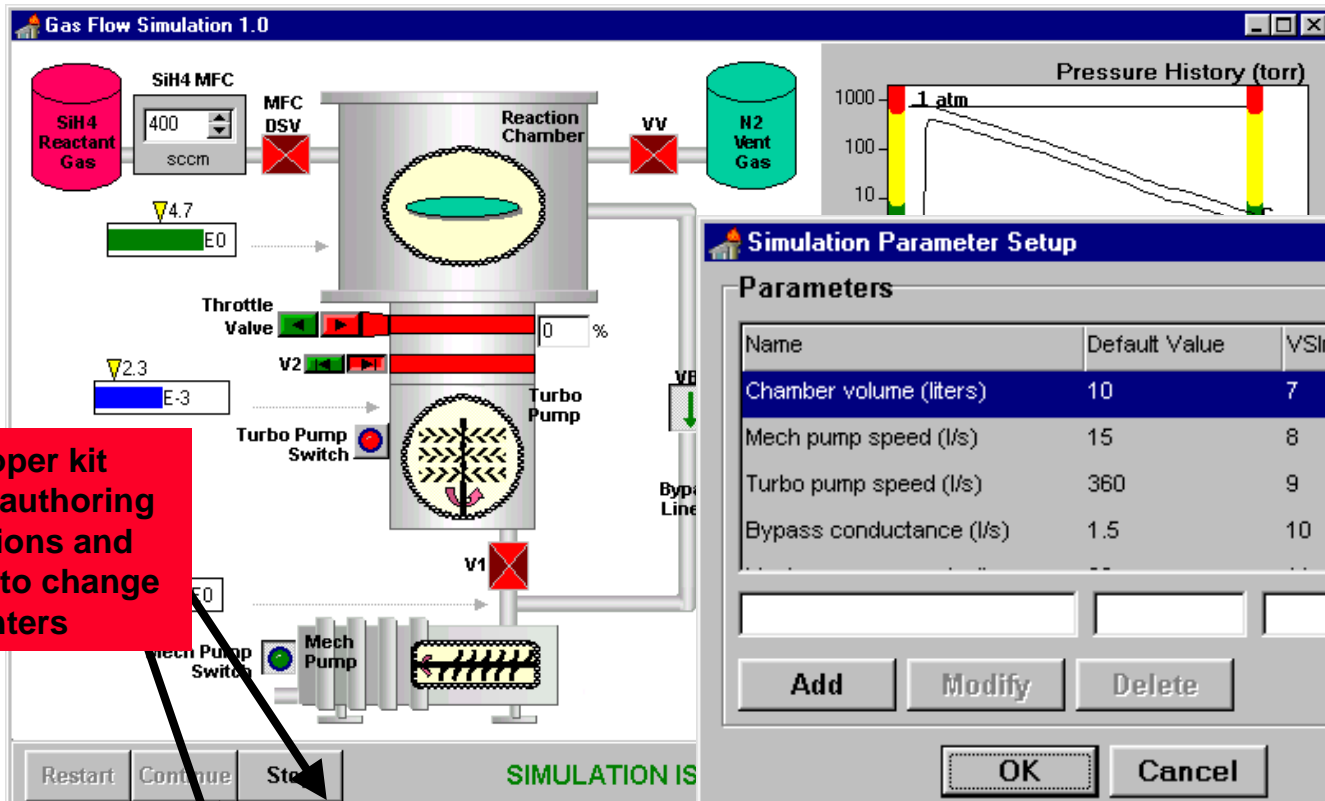
Local/remote control switch on simulator:

Local - simulation controlled by “actuators” on simulator itself
 Useful for engineers with domain knowledge
 Enables continuous improvement of simulator’s physical fidelity

Remote - simulation controlled by “actuators” from user interface
 Allows simulator control from user interface
 Removes need for interface designer to have domain knowledge



Authoring - User Interface



Developer kit provides authoring instructions and flexibility to change pointers

Simulation Parameter Setup

Parameters

| Name | Default Value | V\$in # |
|--------------------------|---------------|---------|
| Chamber volume (liters) | 10 | 7 |
| Mech pump speed (l/s) | 15 | 8 |
| Turbo pump speed (l/s) | 360 | 9 |
| Bypass conductance (l/s) | 1.5 | 10 |

Buttons: Add, Modify, Delete, OK, Cancel

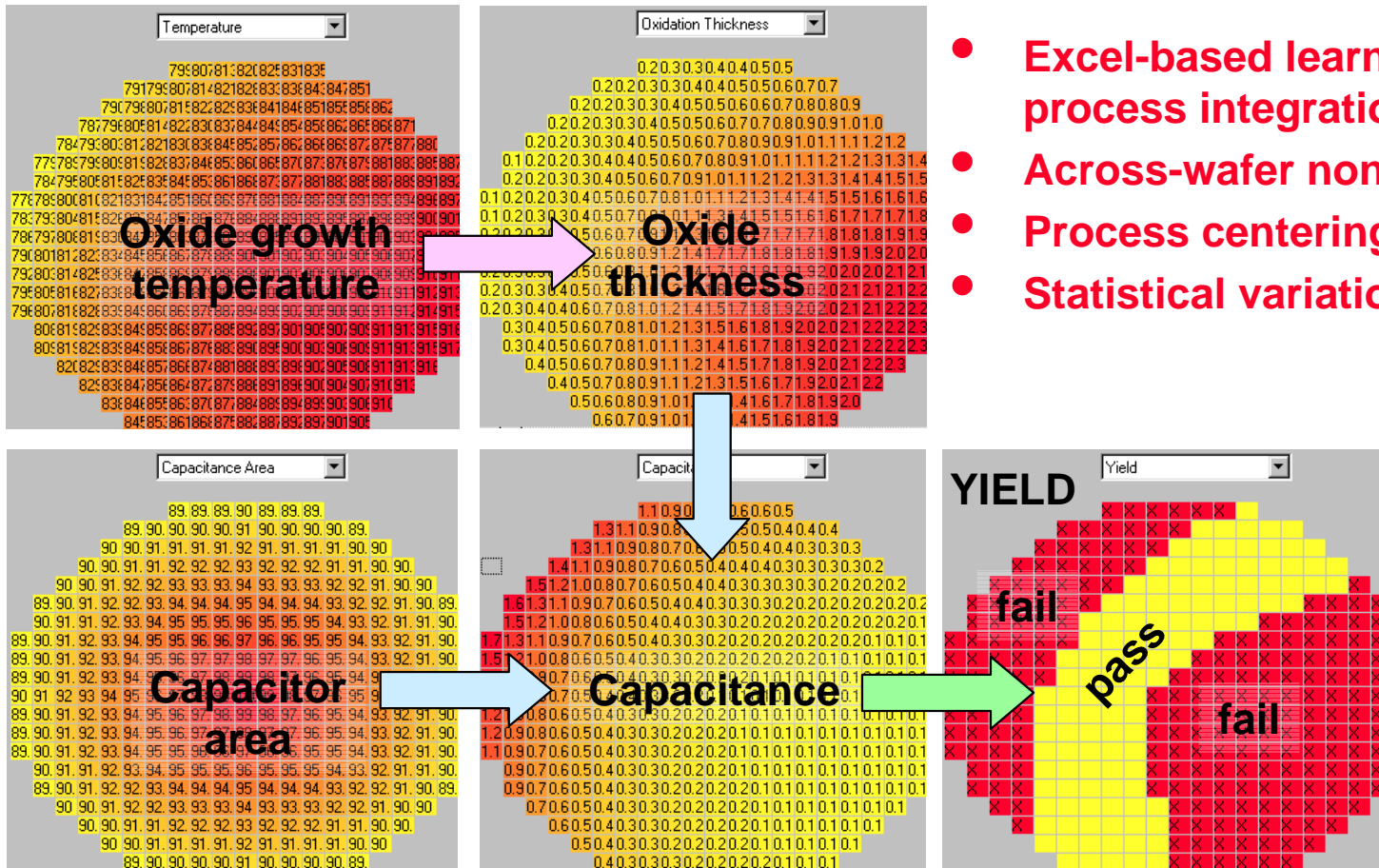
Developer's pop-up facilitates definition of system parameters to be integrated on simulator and user interface sides

Guidance URL: C:\CELS\GasFlow\pl\html\start_gasflow.htm
 Hit return to update material show on guidance page

Simulation Viewer: C:\Program Files\VisSim\VisSim30a\VisSim30a Program\VisSim32.exe

Simulation File: C:\CELS\GasFlow\pl\VisSim\gasflow.vsm
 Changes to simulation viewer and/or file take affect when simulation is started/restarted

Buttons: Simulation Parameters Setup, Email Setup



- Excel-based learning system for process integration and yield
- Across-wafer nonuniformity
- Process centering
- Statistical variation

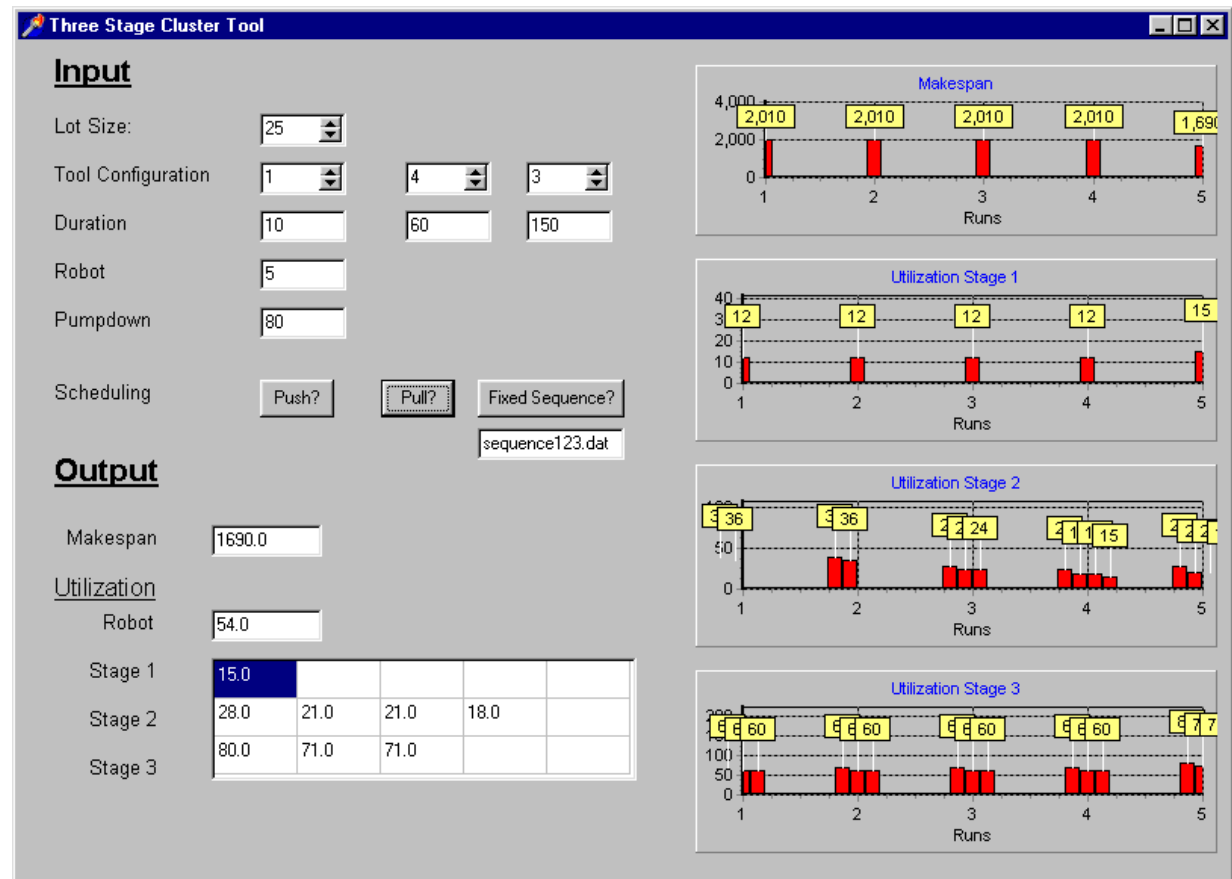


Discrete Event Simulation and Factory Operations



- Expand learning systems to support legacy code (Fortran, C/C++, ...)
- Cluster tool simulator (logistics, scheduling) - implemented in Java, now incorporated into engineered learning system

- Factory operations simulator (Factory Explorer), consisting of Excel front end which drives simulation engine, now incorporated into engineered learning system





Simulator-Based Manufacturing Education and Training for Microelectronics Processing



- NSF grant EEC - 9526147, 9/15/95 - 8/31/00, PI G. W. Rubloff, \$600K
- **Goal**
 - *Develop and assess methodologies in which physically-realistic simulation tools can be incorporated into broader software-based learning environments which are available anytime, anywhere, and which can provide value not only for experienced engineers, but also for manufacturing operators or technicians with little relevant technical background*
- **Manufacturing Training Modules - for operators, technicians, and students with little technical background**
 - *Vacuum-Based Process Equipment*
 - *Heat Transfer*
 - *Chemical Processes*
- **Engineering Design Modules - for practicing engineers and graduate students**
 - *Statistics and Design Optimization*
 - *Process Control*



Center for Engineered Learning Systems



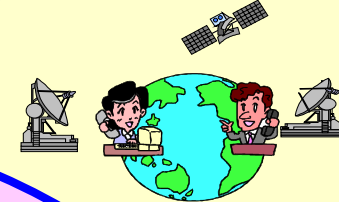
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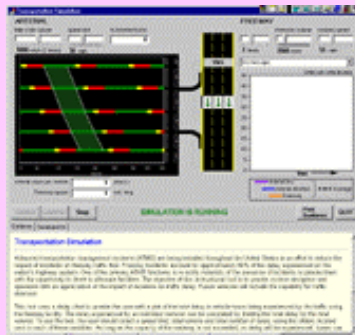
Portable, standalone



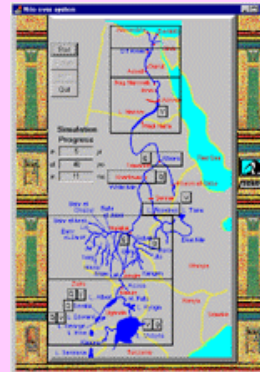
Internet-connected



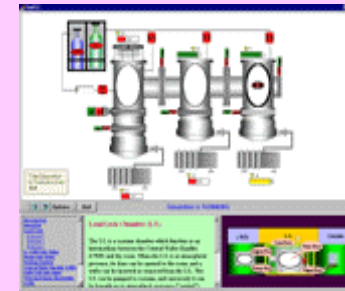
APPLICATIONS



Systems management



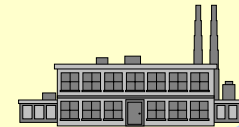
Politics, history, economics, and society



Science and technology

Individual and group active learning experiences

Real-time and asynchronous collaboration and counsel



At work, in school, and at home

CELS is administered as a Center within the Institute for Systems Research, an entity of the A. James Clark School of Engineering at the University of Maryland.



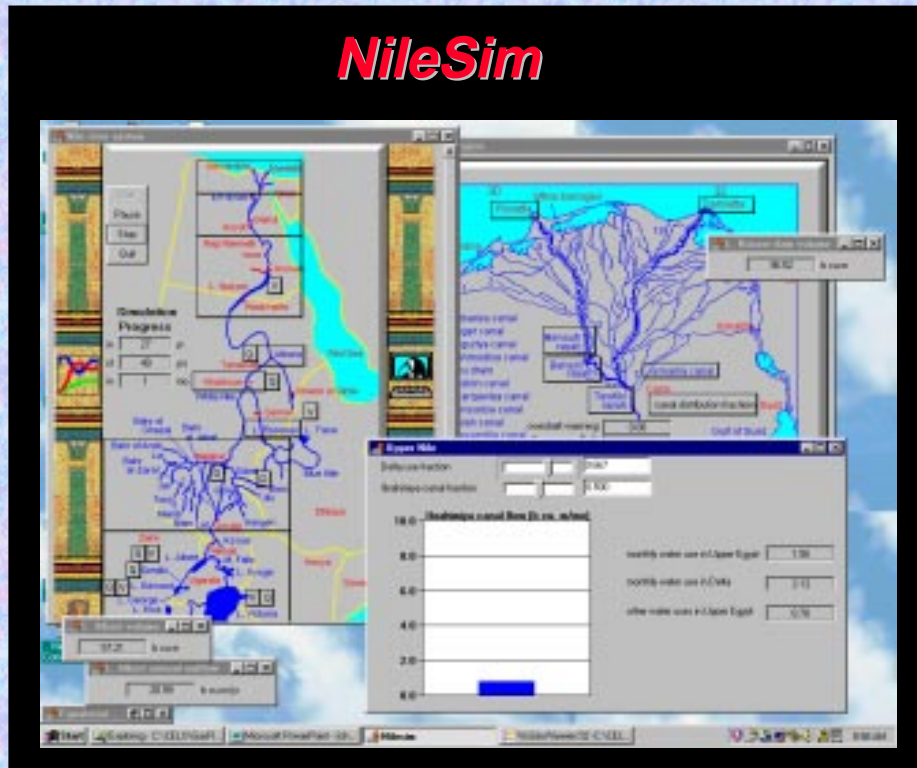
Other Simulator-Based Learning Systems



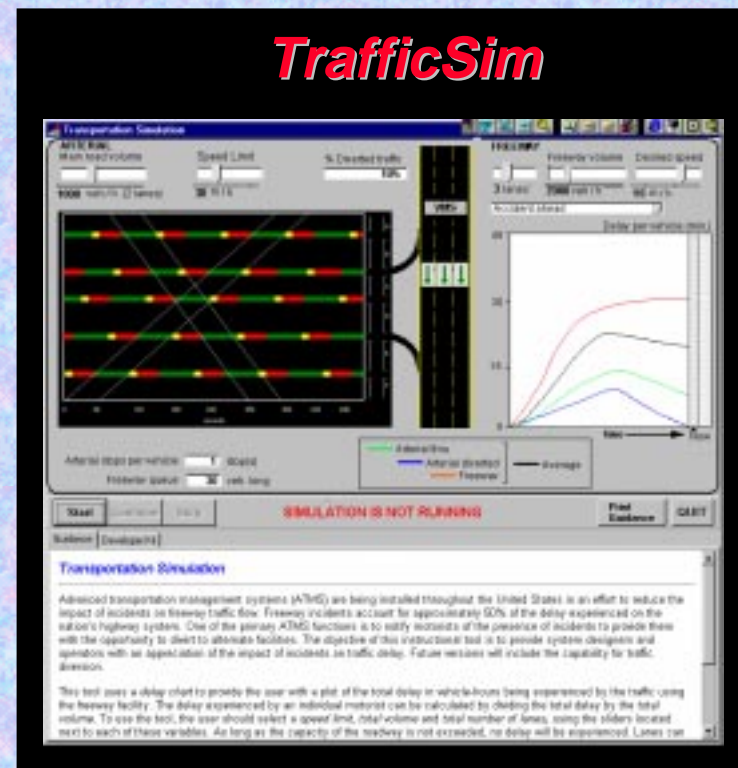
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NileSim



TrafficSim





Simulation-Based Learning Systems for Environmentally-Benign Semiconductor Manufacturing



- NSF grant EEC (recommended), 10/1/99-9/30/02, \$400K
- PI G. W. Rubloff (U. Maryland ISR), Co-PI F. Shadman (U. Arizona CEBSM)
- **Goals**
 - *Education modules at 3 levels: undergraduate, graduate, practitioners*
 - *Incorporation of legacy simulators*
 - *Simulation explorer*
 - *Educational assessment*



Wish List for ESH Learning Systems



- **User-driven system design**
 - *Choose individual system components*
 - *Expand and reconfigure network*
- **Exploit existing models and simulations**
 - *Utilize existing codes directly (Fortran, ...)*
 - *Generate compact models in simple, systematic fashion*
- **Facilitate design and optimization of control system**
 - *Incorporate various control systems elements*
 - *Experiment with optimization and fault management algorithms*

- **Build the basis for systems design and optimization**
 - *Educate new practitioners*
 - *Support systems engineering for current practitioners*



Conclusions



- **High quality user interface design** expands value of simulation to engineering and education
- **Effective engineered learning systems combine**
 - Simulation with good user interfaces*
 - Tightly coupled guidance materials*
 - Software learning aides*
 - Tools to facilitate experimentation and collaboration*
 - Easy authoring for both domain knowledge and software environment*
- **Learning system enhancements in progress**
 - Tools for experimentation and collaborative design*
 - Increasing ability for system alteration and redesign by user*
 - Incorporation of different modeling/simulation tools, including legacy codes*
 - Broad applications set on common, commercial software base*