Batch Model Predictive Control - Use of ExperTune to Develop Models

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Outline

- Model Predictive Control Intro. & Definitions
- Batch Bioprocess MPC Project Overview

What is Model Predictive Control?

Model Predictive Control (MPC)

- Most commercialized & economically successful form of model-based control
- Uses *linear* dynamic models to predict plant behavior (Feedforward)
- Combines Feedforward (primary) and Feedback (corrective) control with prediction to control plant based on models
- Solves control and optimization application mathematically online in real-time
- Relies heavily on matrix inversion and higher order math to solve control problem

What is Model Predictive Control (Cont'd)?

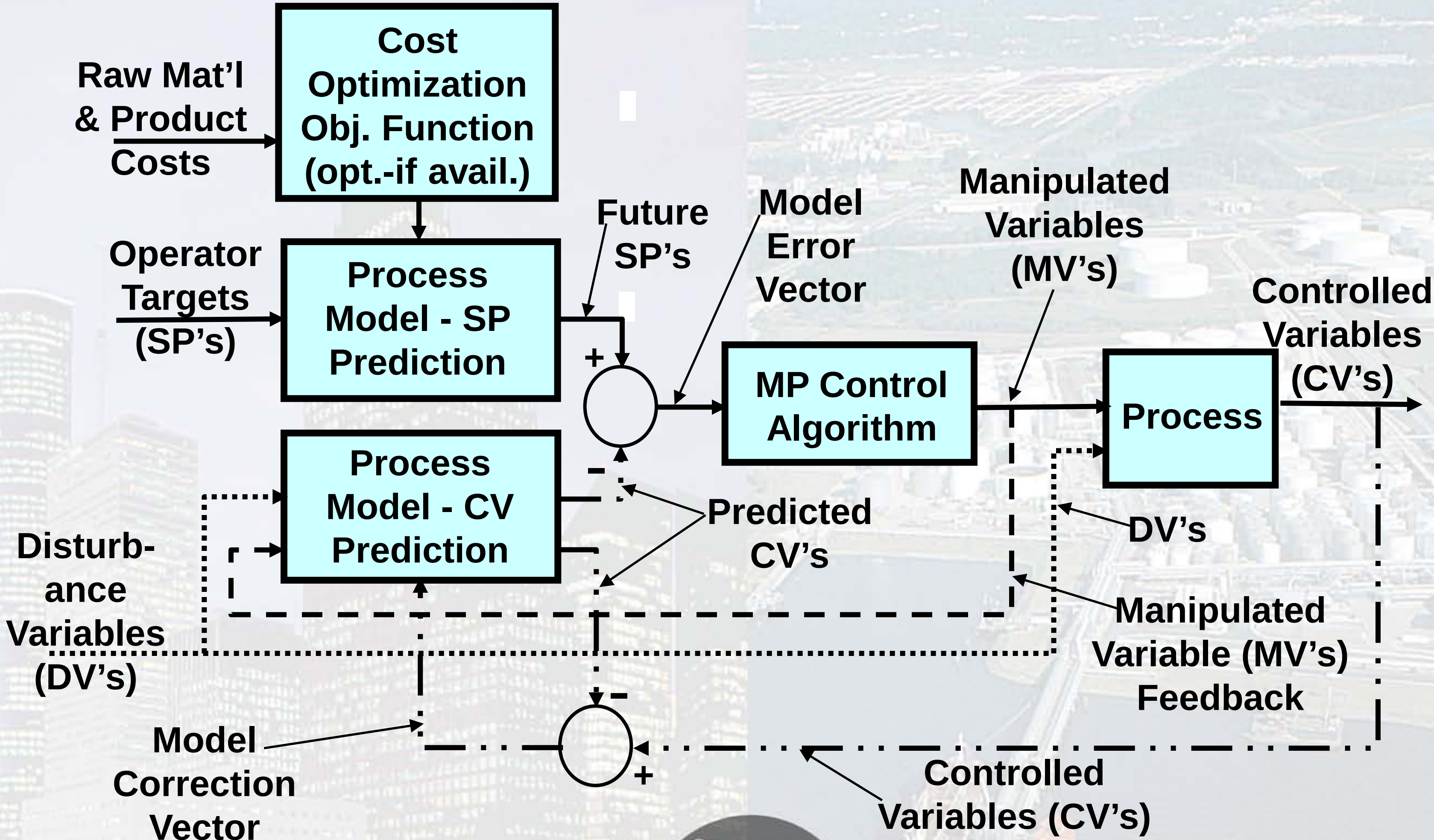
- Model Predictive Control (MPC)
  - Corrects for mismatch between actual plant behavior and model to varying degrees depending on ctlr design (Feedback aspect)
    - Real differences between comm. ctlrs
  - May include operating constraint control (constrained vs. unconstrained MPC)
  - May include one or more dynamic cost or economic optimization (objective) functions
    - Economic Optimization is most popular & money-making feature for many MPC apps.
  - May include offline ctlr simulation cap.

Model Predictive Control Definitions

Definitions

- Controlled Var. = **CV**
  - Example = Bioreactor Temperature
- Manipulated Var. = **MV**
  - Example = Bioreactor Cooling Media Flow
- Disturbance Var. = **DV**
  - Example = Bioreactor Agitator Speed
- Constraint Var. = **AV**
  - Example = Bioreactor Temperature Limits
- Setpoint Var. = **SP**
  - Example = Bioreactor Temperature Setpoint

Generic Unconstrained Model Predictive Control Block Diagram



Acknowledgement: the above diagram was extracted from Advanced Control Unleashed, G. K. McMillan et al ©2003 ISA, and was modified by the presenter.

Model Predictive Control - Indications

- Complex multivariable process
  - Irrespective of controller-related variable set size
- Large plant controller-related variable set
  - Typical example: >50 CV's >10 MV's >5 DV's >10 AV's
- >High degree of interaction between controlled and manipulated variables
- >Multiple disturbance inputs that affect final product spec. or quality

> = Drivers to use MPC for this project

Model Predictive Control - Indications (Cont'd)

- >High value or high $ impact of
  - – Products or Incremental production increase
  - – Raw materials or utilities
  - – Environmental constraint excursions
- >Difficult process dynamics
  - – Long dead time and/or time constant processes
  - – Integrating (non self-regulating) processes

> = Drivers to use MPC for this project

Model Predictive Control - Contraindications

Contraindications

- >>Rapidly changing or unstable or *nonlinear* process dynamics
- Changing/evolving process or equipment or instrumentation
- Poorly understood process or dynamics
- Inadequate resources available for plant testing and controller design & maintenance

>> = Drivers to NOT use MPC for this project

Batch Bioprocess MPC Project - Introduction

What is It?

- Fundamentally changes Batch Bioprocess nutrient addition control strategy
- Optimizes Bioprocess production

Why Do It?

- Reduce raw material consumption
- Increase product yield

Batch Bioprocess MPC Project - Introduction

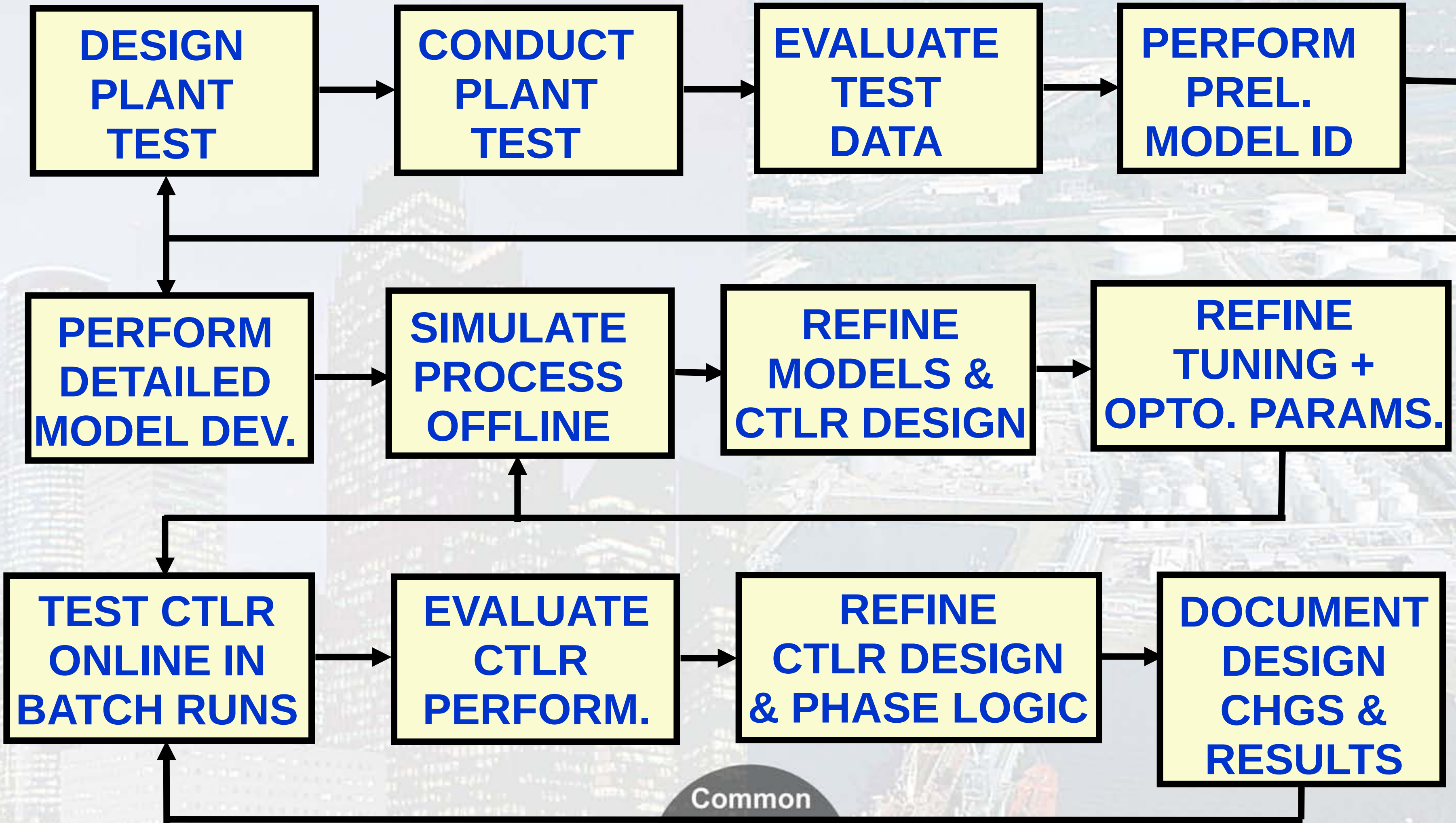
Challenges

- Few published commercial Pharma Batch MPC applications
- Commercially available Process Identification Tools are not designed for Batch or Pharma applications
- Many Batch process variable input/output relationships are nonlinear and time-variant

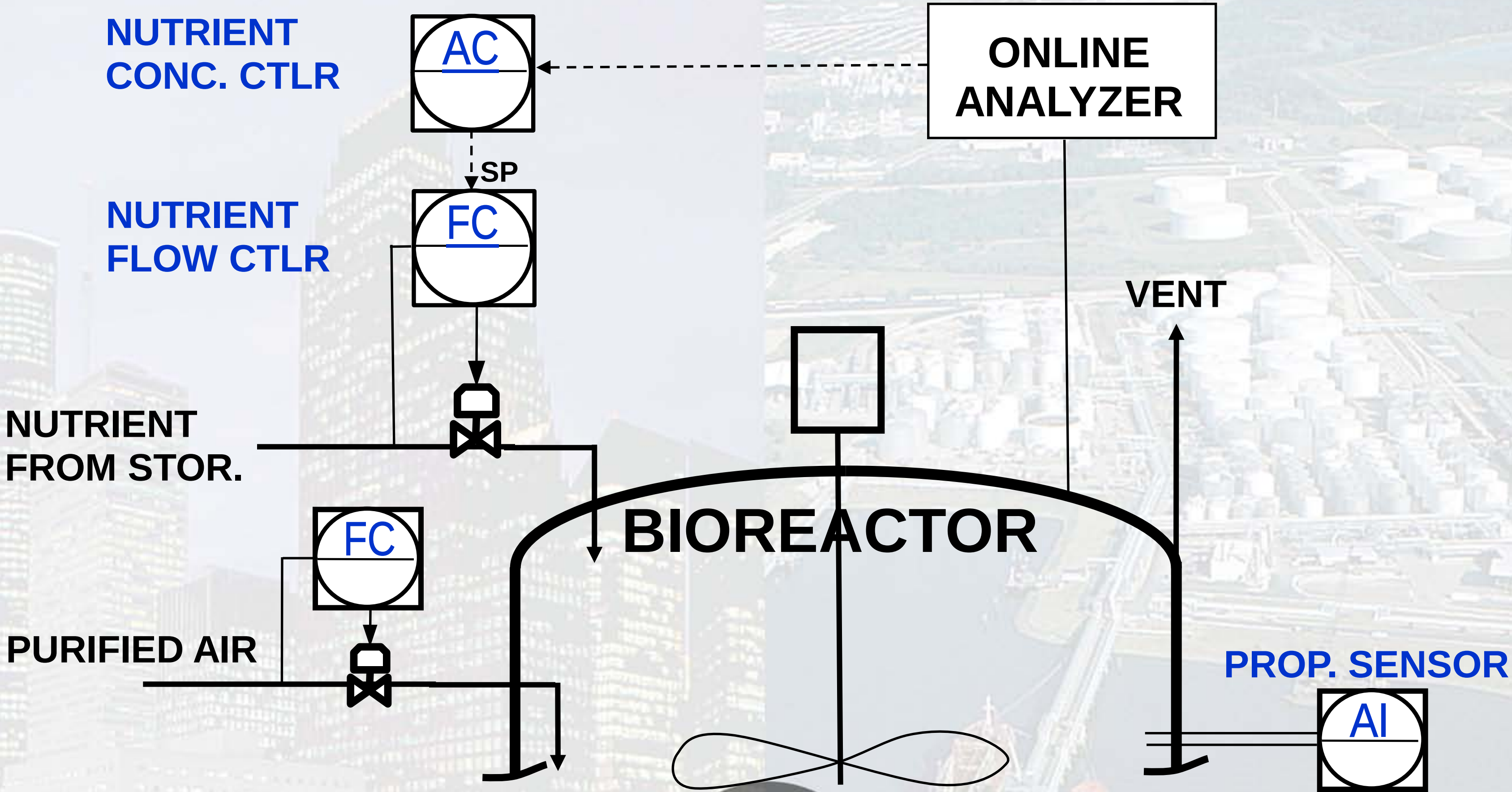
Batch Bioprocess MPC Project - Summary Objectives and Results

OBJECTIVES	RESULTS
Optimize media growth conditions	Achieved with Batch Product Profiles
Increase product yield	Partially Achieved
Reduce raw material usage	Fully Achieved
Reduce/eliminate dependency on online analytical instrumentation	Mostly Achieved

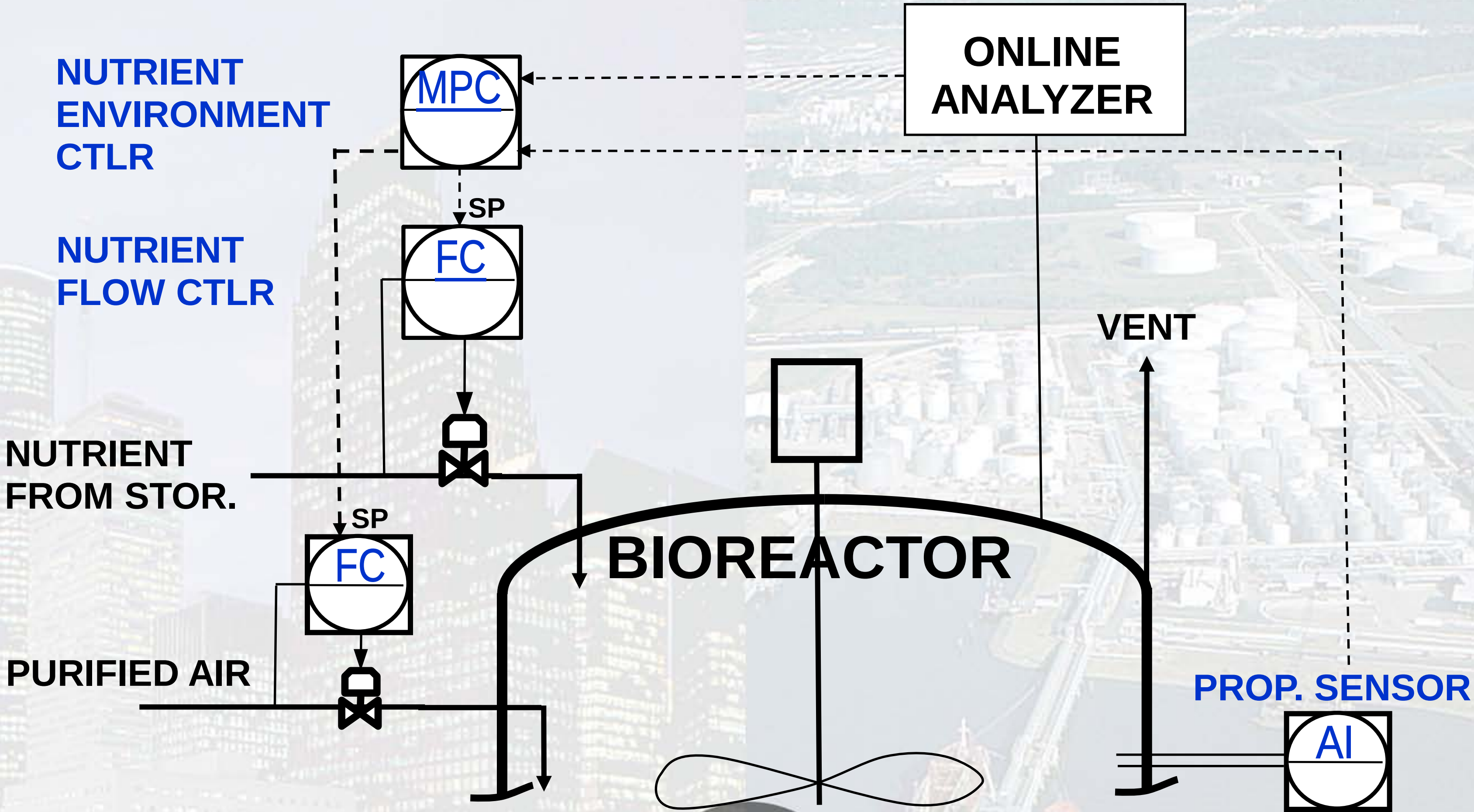
Batch Bioprocess MPC Project – MPC Controller Development



Batch Bioprocess Pre-Existing Nutrient Control Control Strategy



Batch Bioprocess MPC Nutrient Control Control Strategy



Batch Bioprocess MPC Project - Plant Test Considerations

Plant (Process Response) Testing

- Plant Testing Built into Recipe Phase Logic
  - Purified Air and Nutrient Flow Controllers set to Auto mode at Recipe-specified Plant Test Mode Initiation Time
  - Automated (PRBS) Testing Performed Using DCS MPC Identification Software
    - Repeated at various key batch times after property transitions
    - Multiple simul. MV testing used to determine overall Time-to-Steady State (TSS)

Batch Bioprocess MPC Project - Plant Test Considerations

- Plant (Process Response) Testing (Cont'd)
  - Purified Air and Nutrient Flow Controllers Manipulated
    - Manually-initiated Step and Pulse Testing used to develop I/O Response Models
      - ExperTune Advanced vers. OPC Tuner Collected Data in Parallel with DCS Historian (Redundancy desired)
      - Uncompressed Historian data collected by DCS was exported to ExperTune ASCII Tuner
      - ExperTune ASCII Tuner used to determine individual I/O pair process model constants

Batch Bioprocess MPC Project Overview - Plant Test Plan

Determined from Plant Testing

- Process type for each input-output relationship (i.e., integrating or self-regulating)*&**
- Time-to-Steady State (TSS) for slowest input-output relationship*
- MV + DV > CV Input-Output relationships and non-linearity as batch progresses assessment**
- Input-output relationship anomalies and model discontinuities***
  - No insurmountable "MPC Killers"
  - Verified by offline simulation testing

*DCS Model ID Pkg.

**ExperTune ASCII Tuner

***DCS MPC Simulator

Batch Bioprocess MPC Project - Plant Testing Techniques

Plant Testing & Model ID Techniques

- PRBS (Pseudo-Random Binary Sequencing)
  - Advantages
    - Most Widely Accepted Automated MPC Testing Technique for Continuous Processes
    - Integral feature of DCS MPC Testing & Identification Software
  - Disadvantages
    - DCS requires estimate of Time-to-Steady State (TSS) upfront before beginning testing
    - DCS MP Controller must be fully configured for plant testing incl. all controller var. types (CV's, MV's, DV's, AV's)

Batch Bioprocess MPC Project - Plant Testing Techniques

Plant Testing & Model ID Techniques (Cont'd)

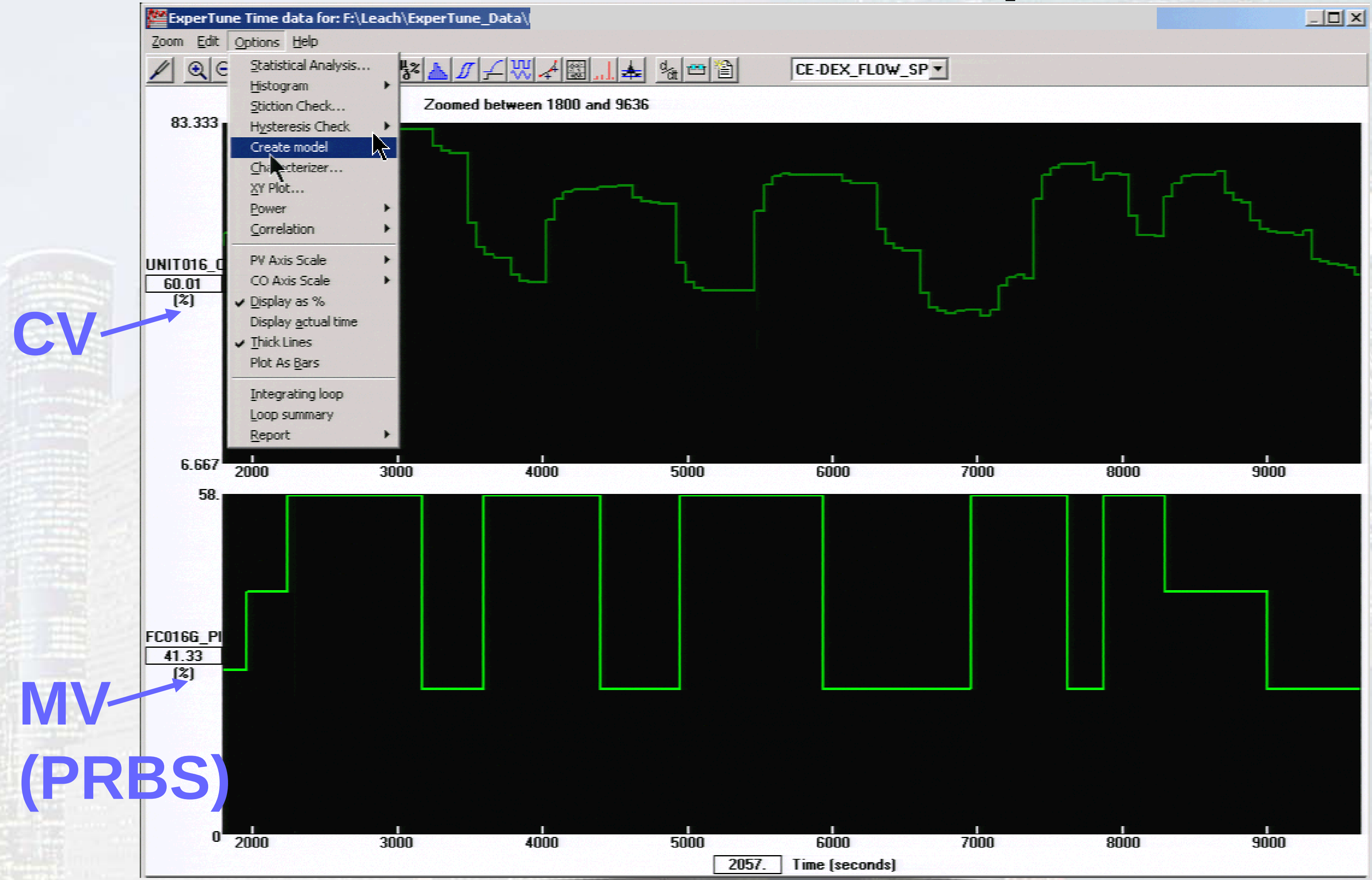
- PRBS (Pseudo-Random Binary Sequencing)
  - PRBS testing simultaneously moving multiple MV's used to determine Time-to-Steady State (TSS)
  - DCS MPC ID Pkg. could not properly identify individual process models from PRBS testing
  - ExperTune ASCII Tuner Adv. Vers. used to identify process models from testing

Batch Bioprocess MPC Project - Plant Testing Techniques

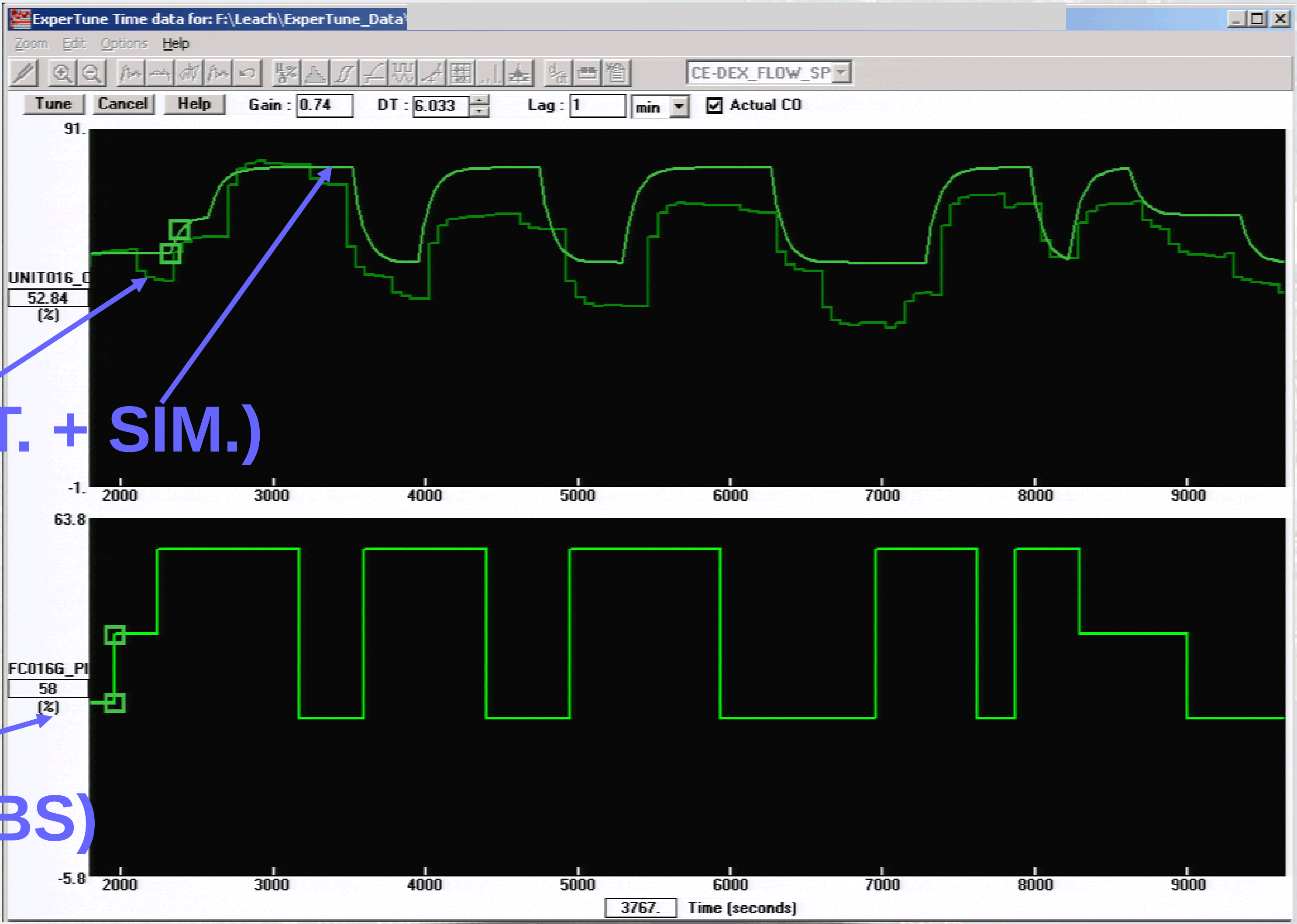
Plant Testing & Model ID Techniques (Cont’d)

- Manually-Actuated Asymmetrical Sequential Doublet Pulses
  - DCS MPC ID Pkg. could not identify most individual process models
  - ExperTune ASCII Tuner Adv. Vers. used to identify process models from testing

Batch Bioprocess MPC Project - Process Model Identification Techniques



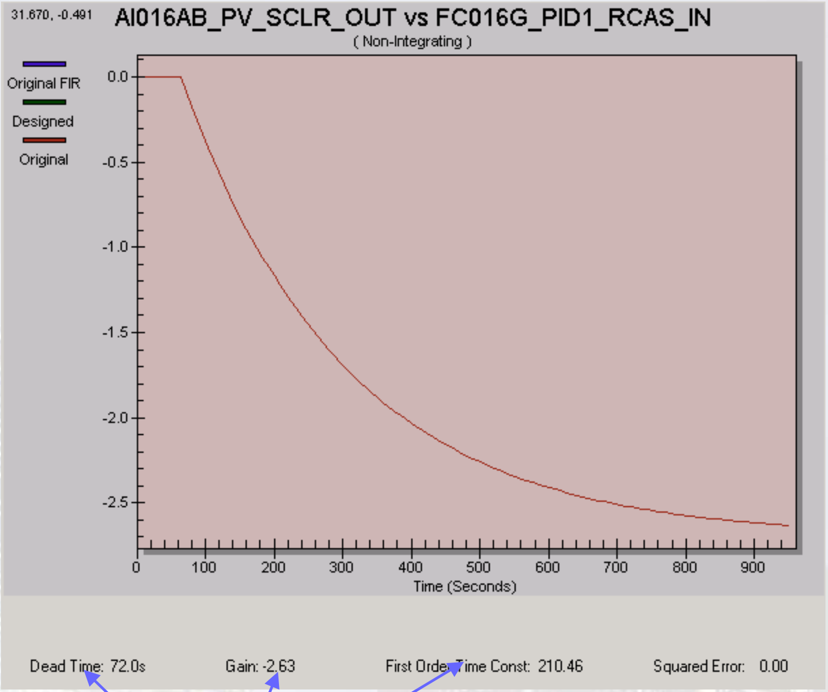
Batch Bioprocess MPC Project - Process Model Identification Techniques (Cont'd)

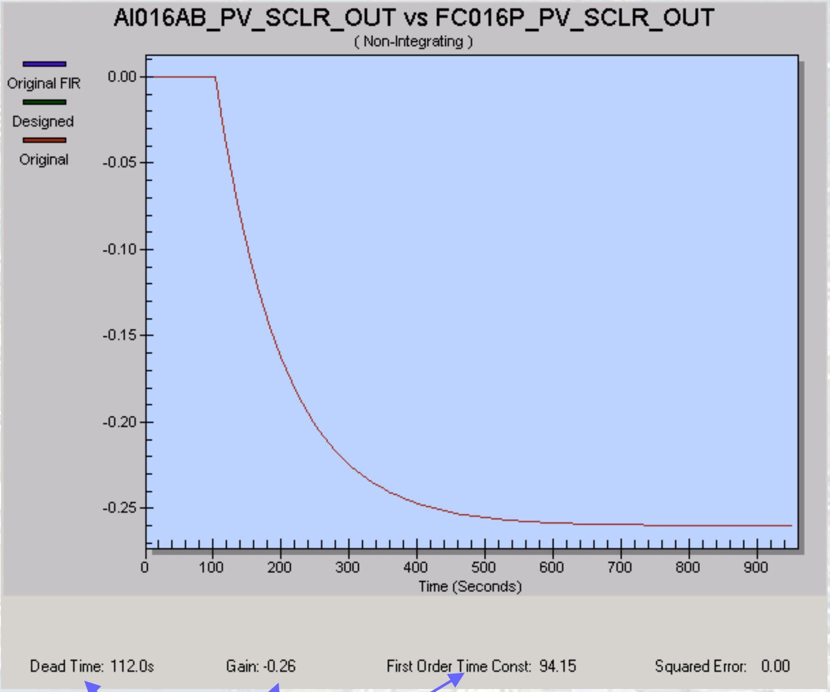


CV (ACT. + SIM.)

MV (PRBS)

Batch Bioprocess MPC Project Overview – Process Response Models



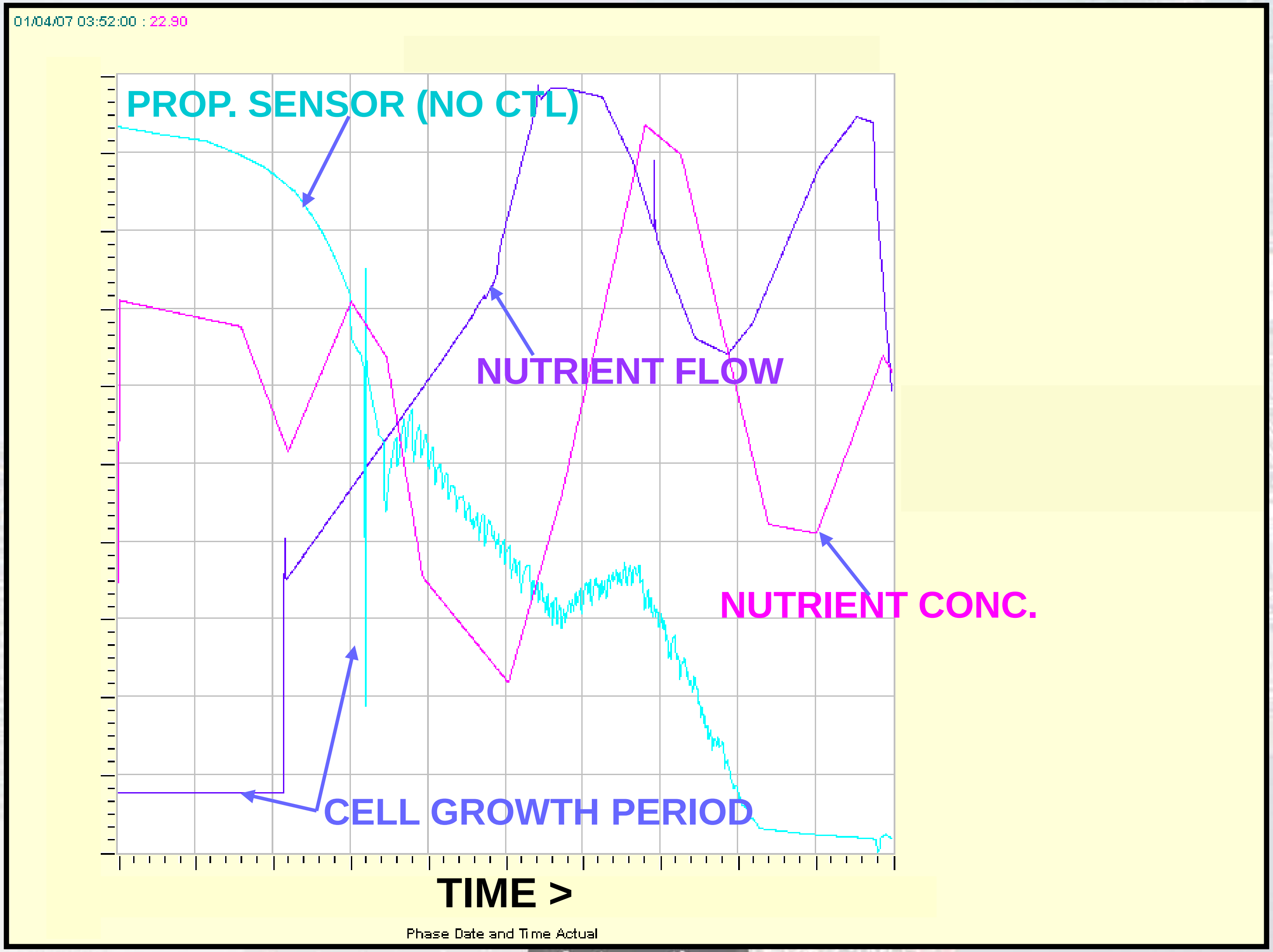


Prop. Sensor vs. Nutrient Flow

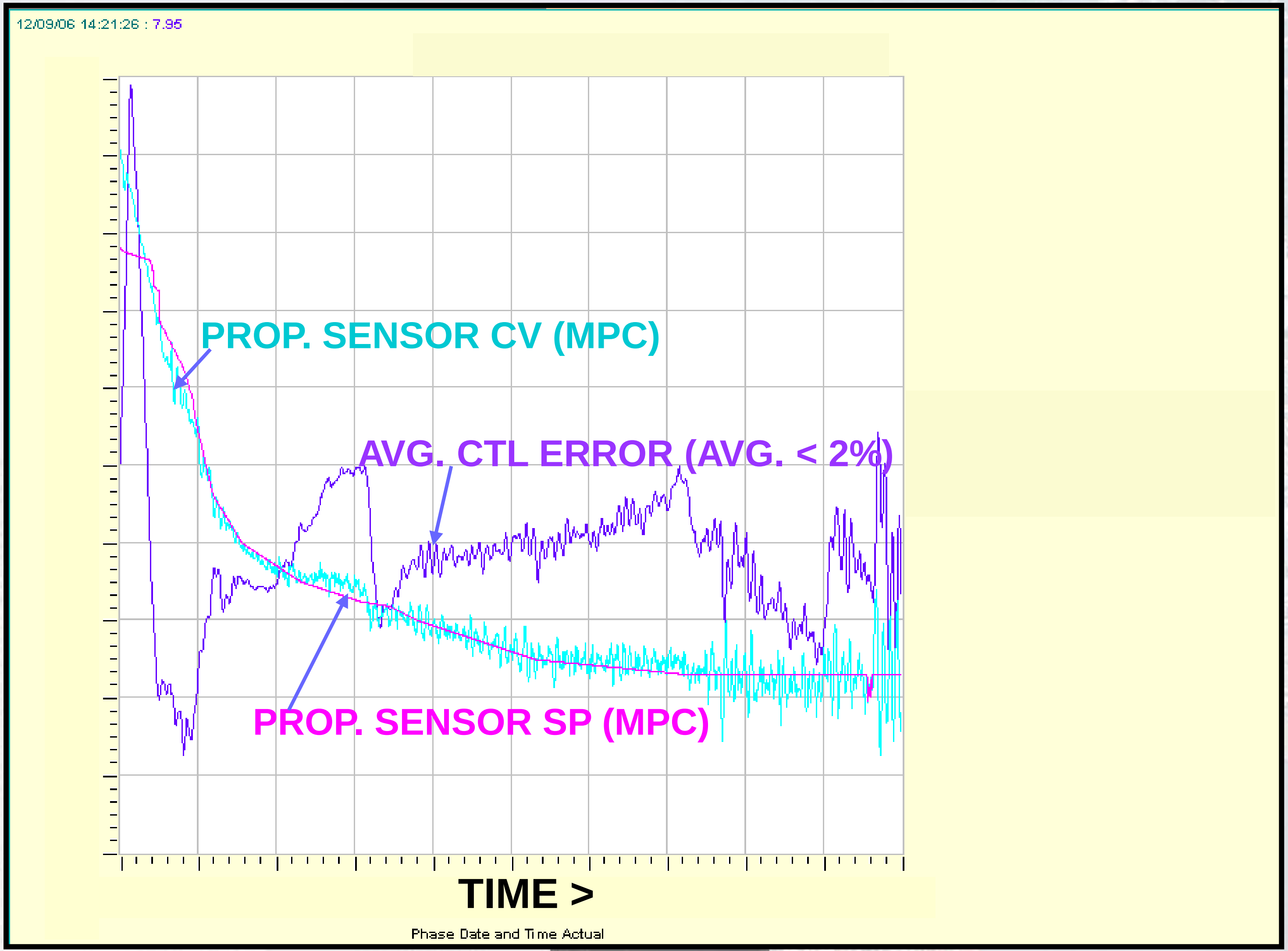
Prop. Sensor vs. Disturbance Var.

Process Model Constants Determined Using ExperTune Then Entered Directly into Model

Batch Bioprocess MPC Project - Nutrient Conc. Control Results



Batch Bioprocess MPC Project - Nutrient MP Control Results



Batch Bioprocess MPC Project Summary

Results Summary

- Pharma Batch MP Controller Models Developed using DCS + ExperTune Tuner Tools
- MPC models tested offline using DCS MPC Simulator
- MP controller fully implemented within DCS
- Developmental control strategy tested on Production-scale Bioreactor
- Model Predictive control proven to meet project objectives