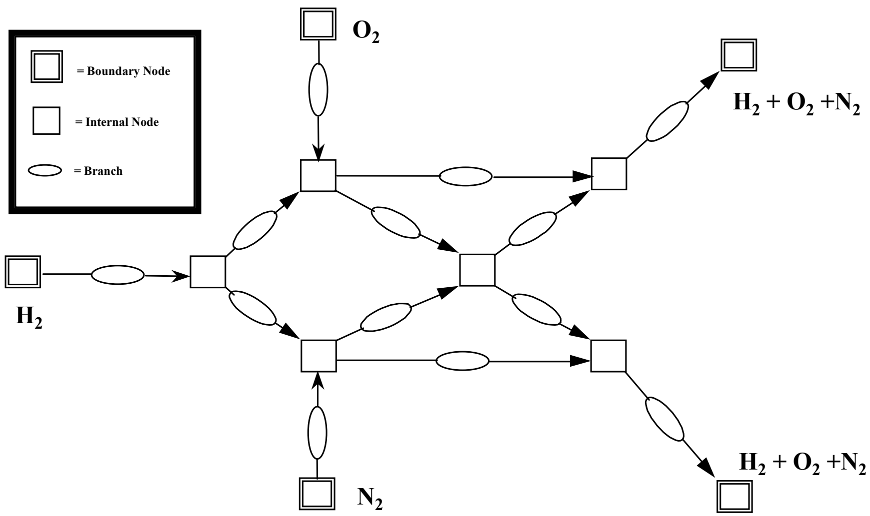
# GFSSP Training Course Lectures

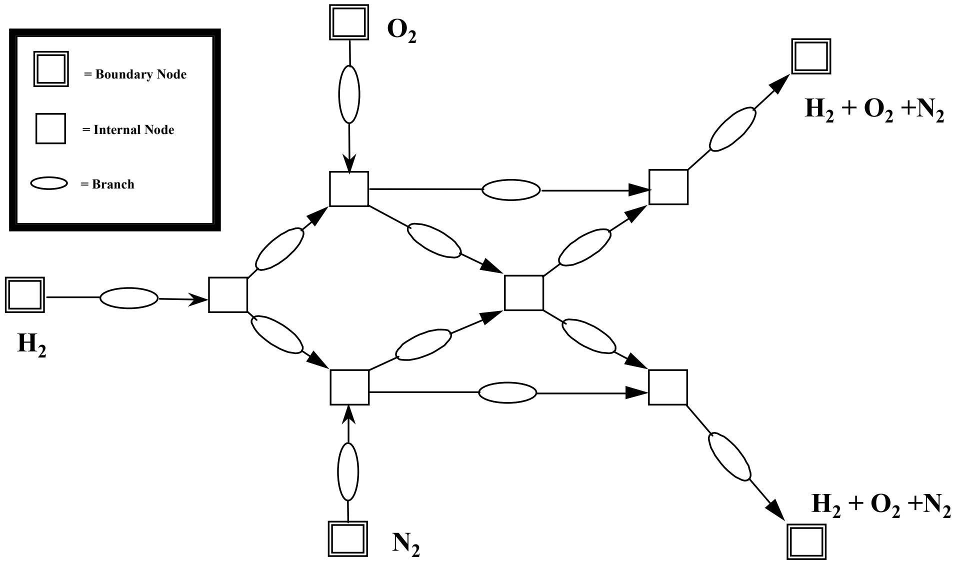



## Thermal & Fluids Analysis Workshop

**NASA/Kennedy Space Center & University of Central Florida**

**August 8-12, 2005**

# INTRODUCTION & OVERVIEW

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**Marshall Space Flight Center**

***alok.majumdar@msfc.nasa.gov***

# CONTENT

- Introduction
  - Background
  - Course Outline
- Overview
  - Network Flow or Navier Stokes Analysis
  - Network Definition
  - Data Structure
  - Mathematical Formulation
  - Program Structure
  - Graphical User Interface
  - Resistance & Fluid Options
  - Advanced Options
  - Applications

# BACKGROUND -1

- GFSSP stands for Generalized Fluid System Simulation Program
- It is a general-purpose computer program to compute pressure, temperature and flow distribution in flow network
- It was primarily developed to analyze
  - Internal Flow Analysis of Turbopump
  - Transient Flow Analysis of Propulsion System
- GFSSP development started in 1994 with an objective to provide a generalized and easy to use flow analysis tool

# BACKGROUND -2

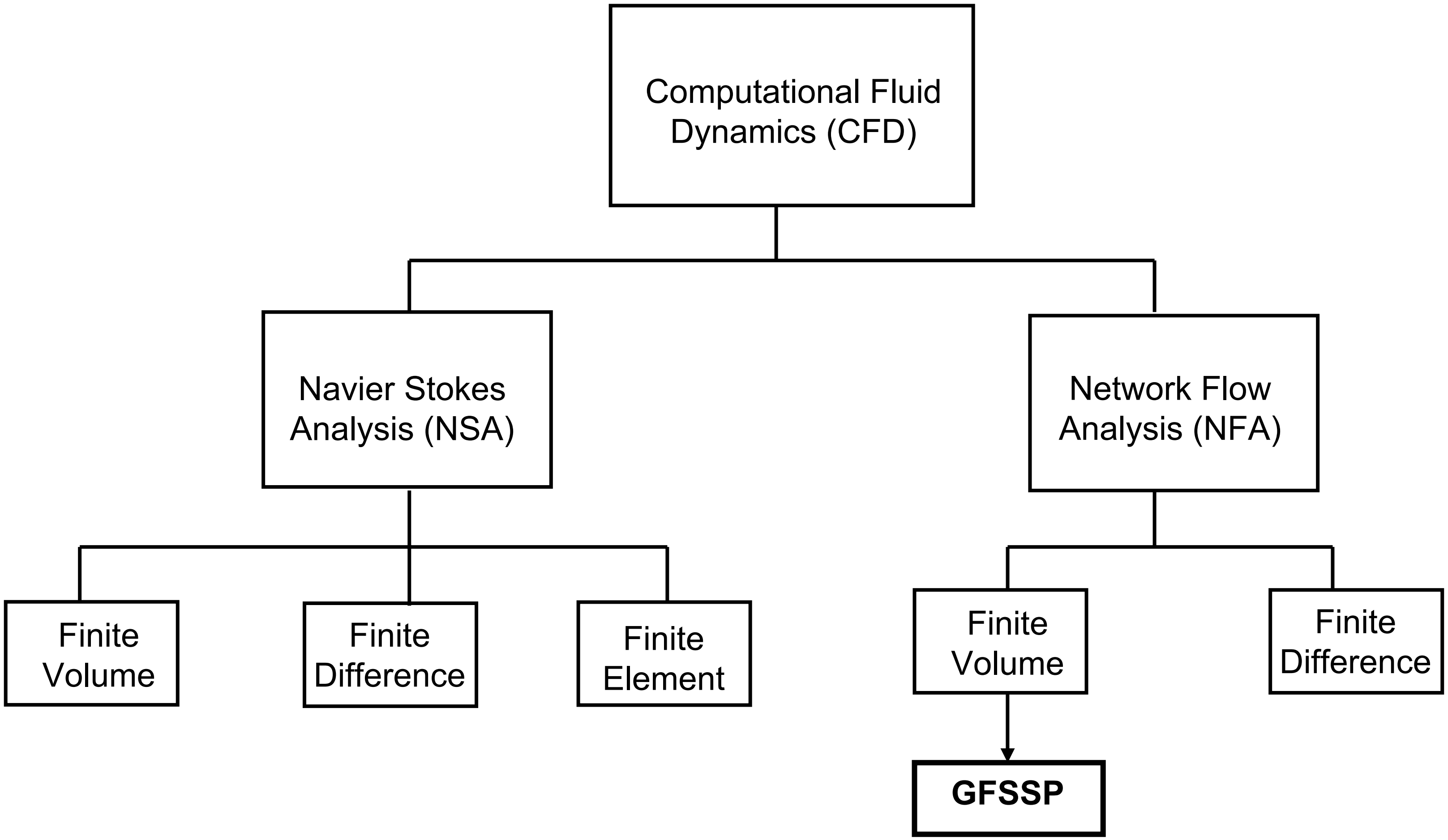
## DEVELOPMENT HISTORY

- Version 1.4 (Steady State) was released in 1996
- Version 2.01 (Thermodynamic Transient) was released in 1998
- Version 3.0 (User Subroutine) was released in 1999
- Graphical User Interface, VTASC was developed in 2000
- Selected for NASA Software of the Year Award in 2001
- Version 4.0 (Fluid Transient and post-processing capability) is released in 2003

# COURSE OUTLINE

1. Introduction & Overview
2. Graphical User Interface
3. Mathematical Formulation
4. User Subroutine
5. Pressurization, Waterhammer & Conjugate Heat Transfer
6. Tutorials (Afternoon)

# NETWORK FLOW OR NAVIER STOKES ANALYSIS - 1



# NETWORK FLOW OR NAVIER STOKES ANALYSIS - 2

## Navier Stokes Analysis

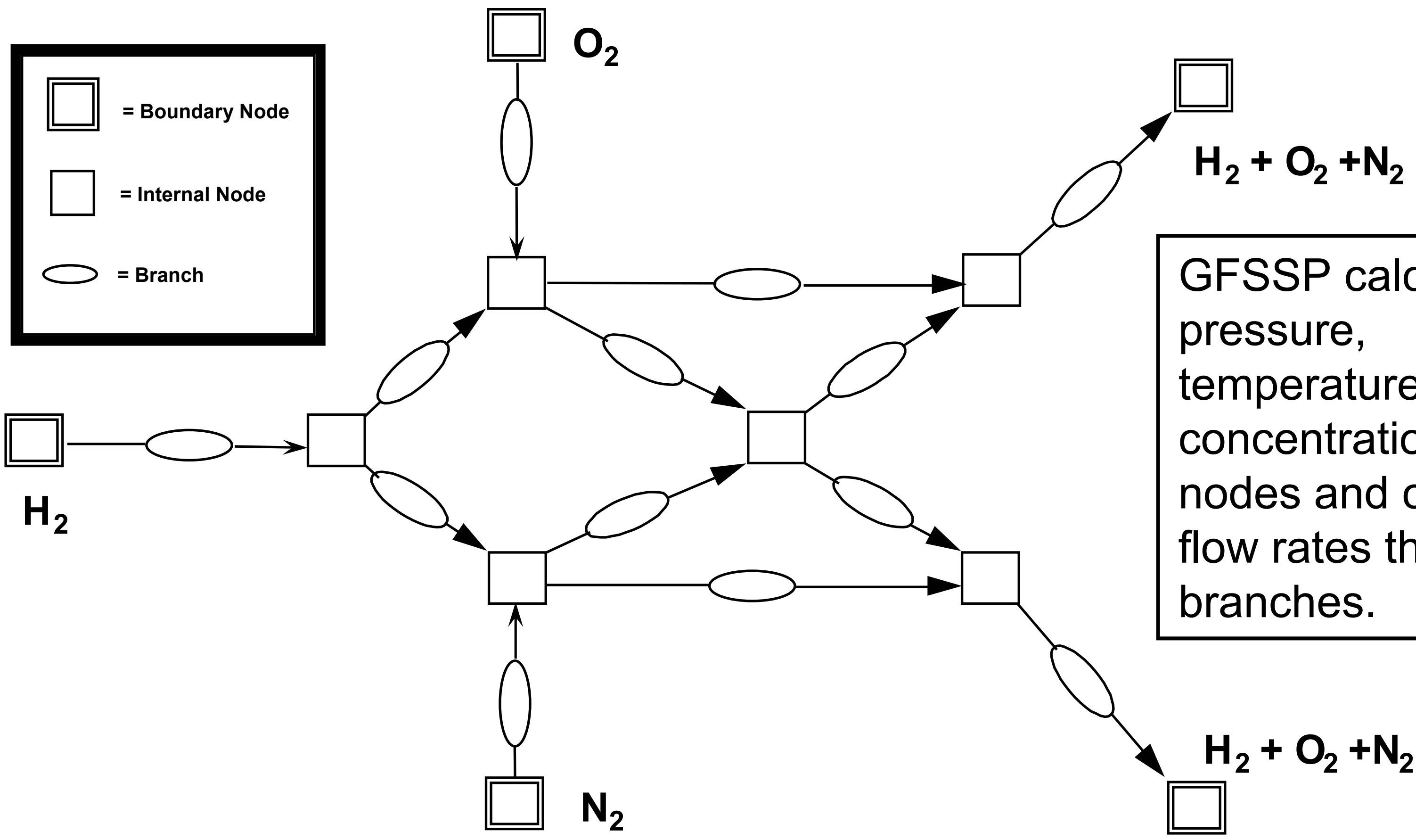
- Suitable for detailed flow analysis within a component
- Requires fine grid resolution to accurately model transport processes
- Used after after preliminary design

## Network Flow Analysis

- Suitable for flow analysis of a system consisting of several components
- Uses empirical laws of transport process
- Used during preliminary design

# NETWORK DEFINITION – 1

## GFSSP FLOW CIRCUIT

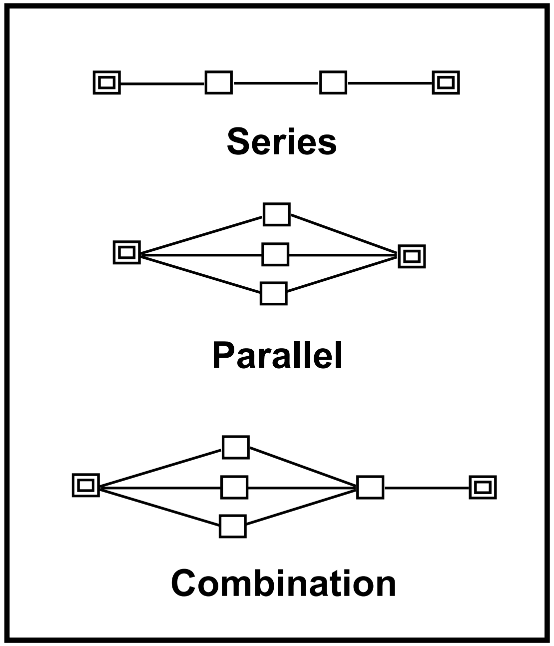



GFSSP calculates pressure, temperature, and concentrations at nodes and calculates flow rates through branches.

# NETWORK DEFINITIONS - 2

- **Network:**

  **Boundary node**
  **Internal node**
  **Branch**




- **At boundary nodes, all dependent variables must be specified**

- **At internal nodes, all dependent variables must be guessed for steady flow and specified for transient flow.**

# NETWORK DEFINITIONS - 3

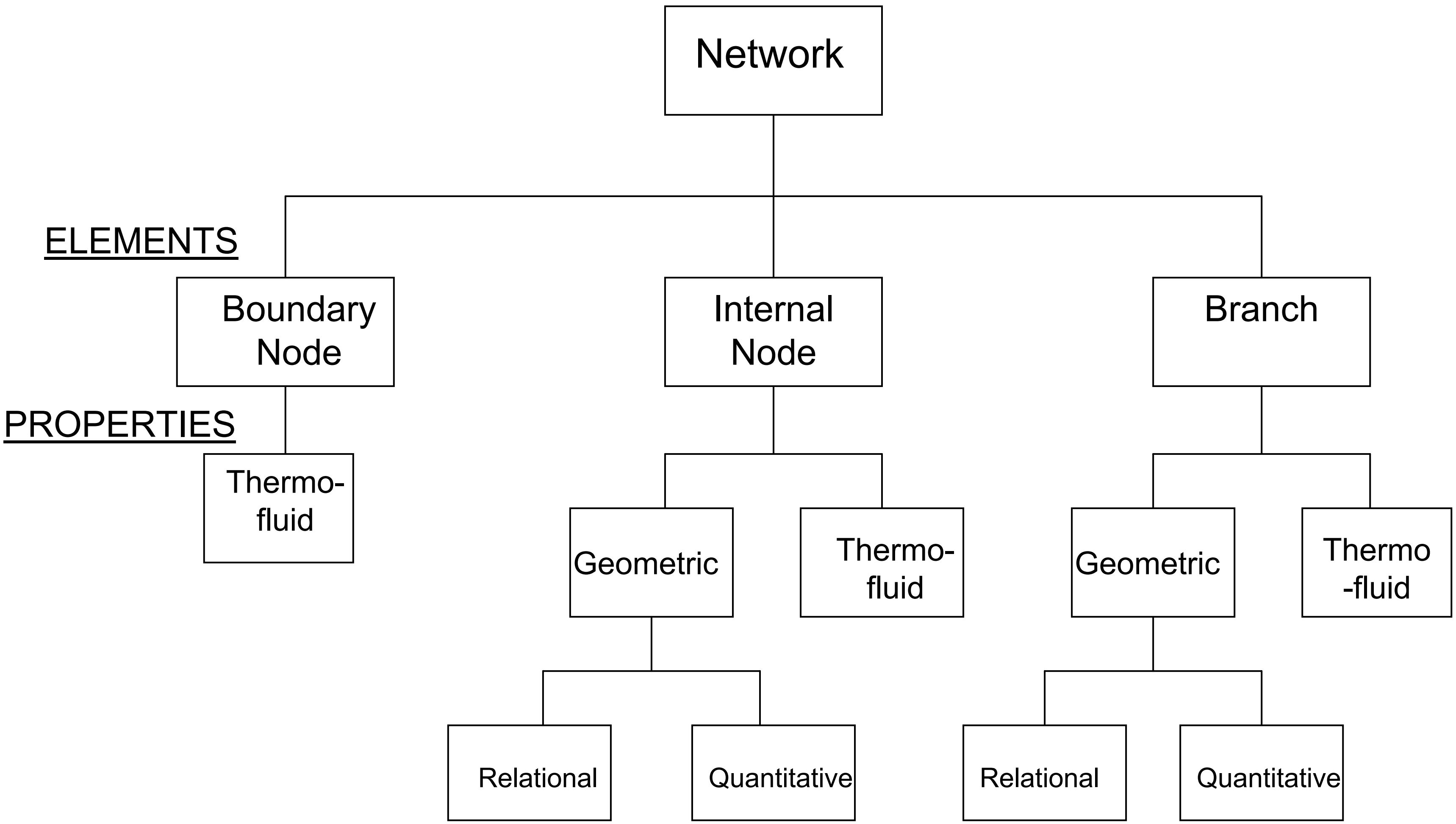
## UNITS AND SIGN CONVENTIONS

- Units

| | **External** (input/output) | **Internal** (inside GFSSP) |
|---|---|---|
| – Length | - inches | - feet |
| – Area | - $inches^2$ | - $feet^2$ |
| – Pressure | - psia | - psf |
| – Temperature | - °F | - °R |
| – Mass injection | - lbm/sec | - lbm/sec |
| – Heat Source | - Btu/s OR Btu/lbm | - Btu/s OR Btu/lbm |

- Sign Convention
  - Mass input to node = positive
  - Mass output from node = negative
  - Heat input to node = positive
  - Heat output from node = negative

# DATA STRUCTURE



# MATHEMATICAL FORMULATION - 1

## MATHEMATICAL CLOSURE - 1

**Principal Variables:**

| Unknown Variables | Available Equations to Solve |
|---|---|
| 1. Pressure | 1. Mass Conservation Equation |
| 2. Flowrate | 2. Momentum Conservation Equation |
| 3. Temperature | 3. Energy Conservation Equation (First or Second Law of Thermodynamics) |
| 4. Specie Concentrations | 4. Conservation Equations for Mass Fraction of Species |
| 5. Mass | 5. Thermodynamic Equation of State |

# MATHEMATICAL FORMULATION - 2

## MATHEMATICAL CLOSURE -2

**Auxiliary Variables:**
Thermodynamic Properties & Flow Resistance Factor

| Unknown Variables | Available Equations to Solve |
|---|---|
| Density<br>Specific Heats<br>Viscosity<br>Thermal Conductivity | Equilibrium Thermodynamic Relations<br>[GASP, WASP & GASPAK Property Programs] |
| Flow Resistance Factor | Empirical Relations |

# MATHEMATICAL FORMULATION - 3

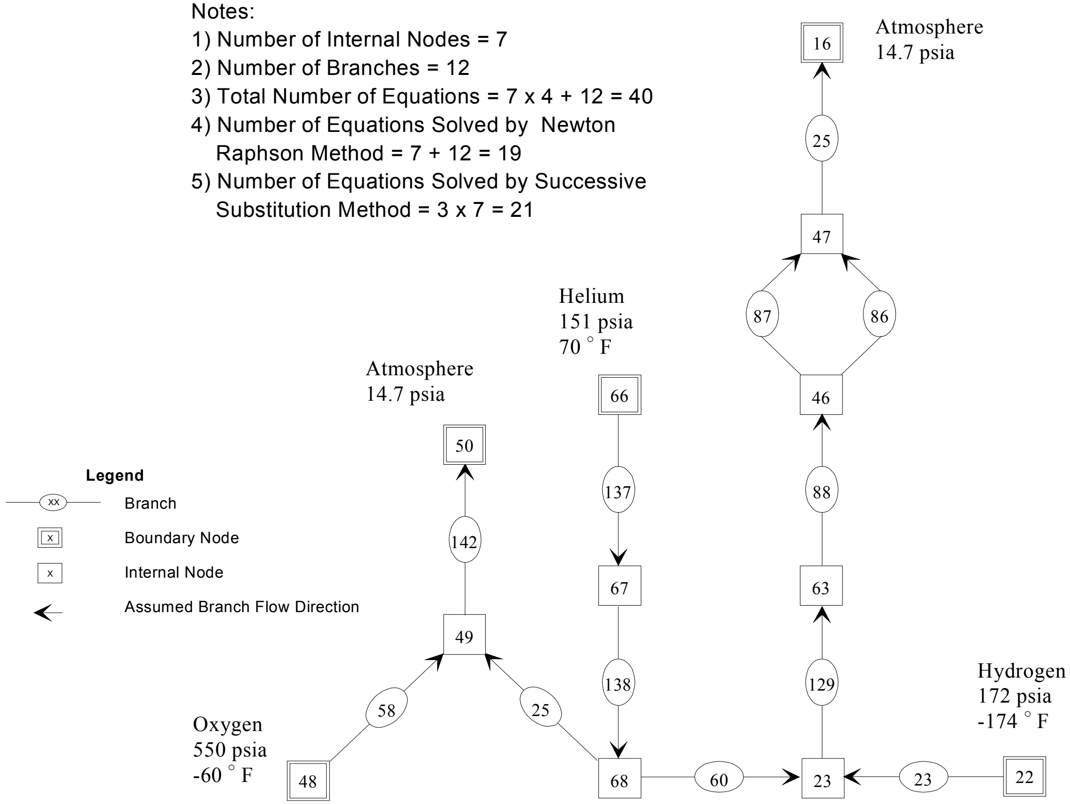
## BOUNDARY CONDITIONS

- Governing equations can generate an infinite number of solutions
- A unique solution is obtained with a given set of boundary conditions
- User provides the boundary conditions

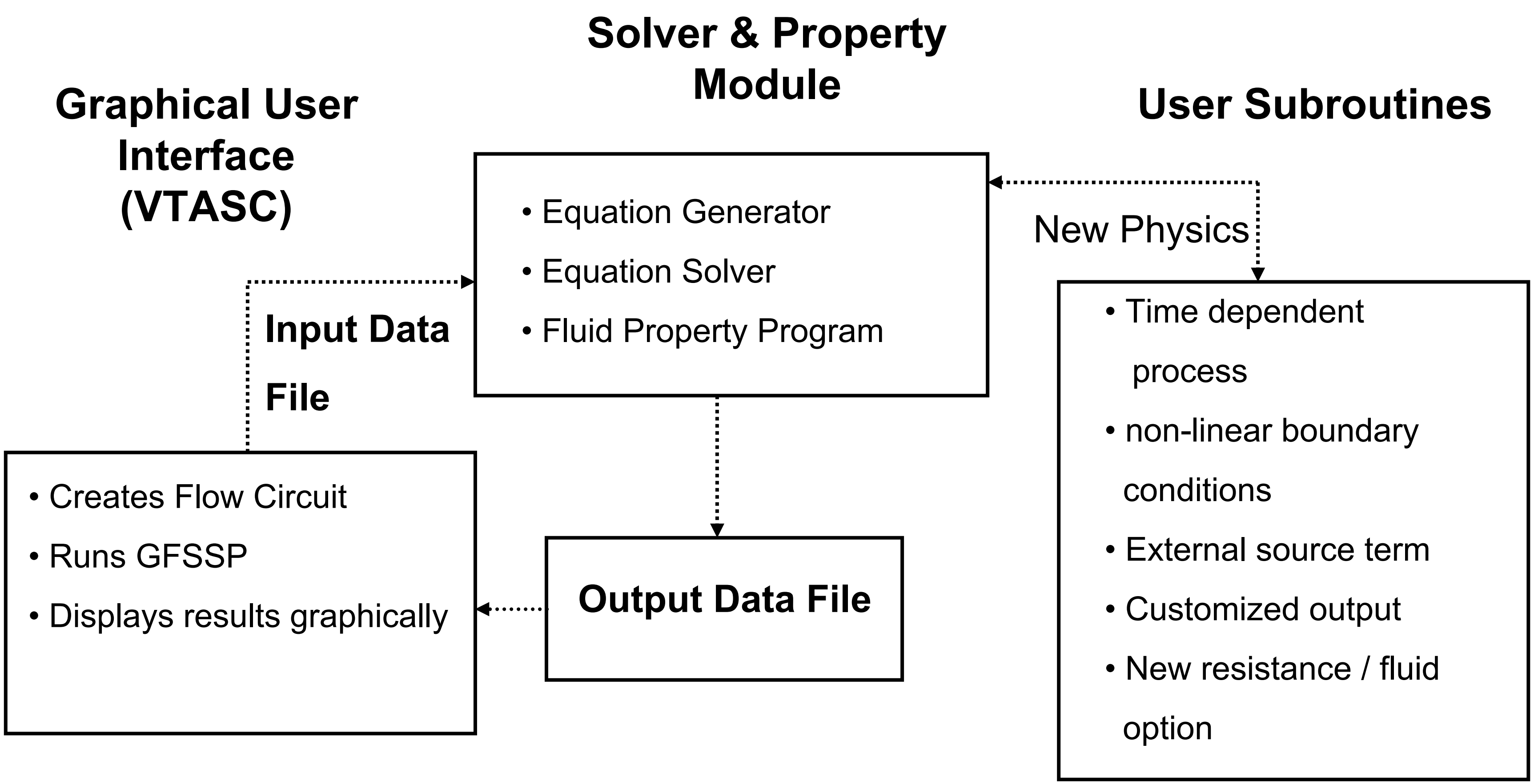
# MATHEMATICAL FORMULATION - 3

## A TYPICAL FLOW CIRCUIT

Notes:
1) Number of Internal Nodes = 7
2) Number of Branches = 12
3) Total Number of Equations = 7 x 4 + 12 = 40
4) Number of Equations Solved by Newton Raphson Method = 7 + 12 = 19
5) Number of Equations Solved by Successive Substitution Method = 3 x 7 = 21

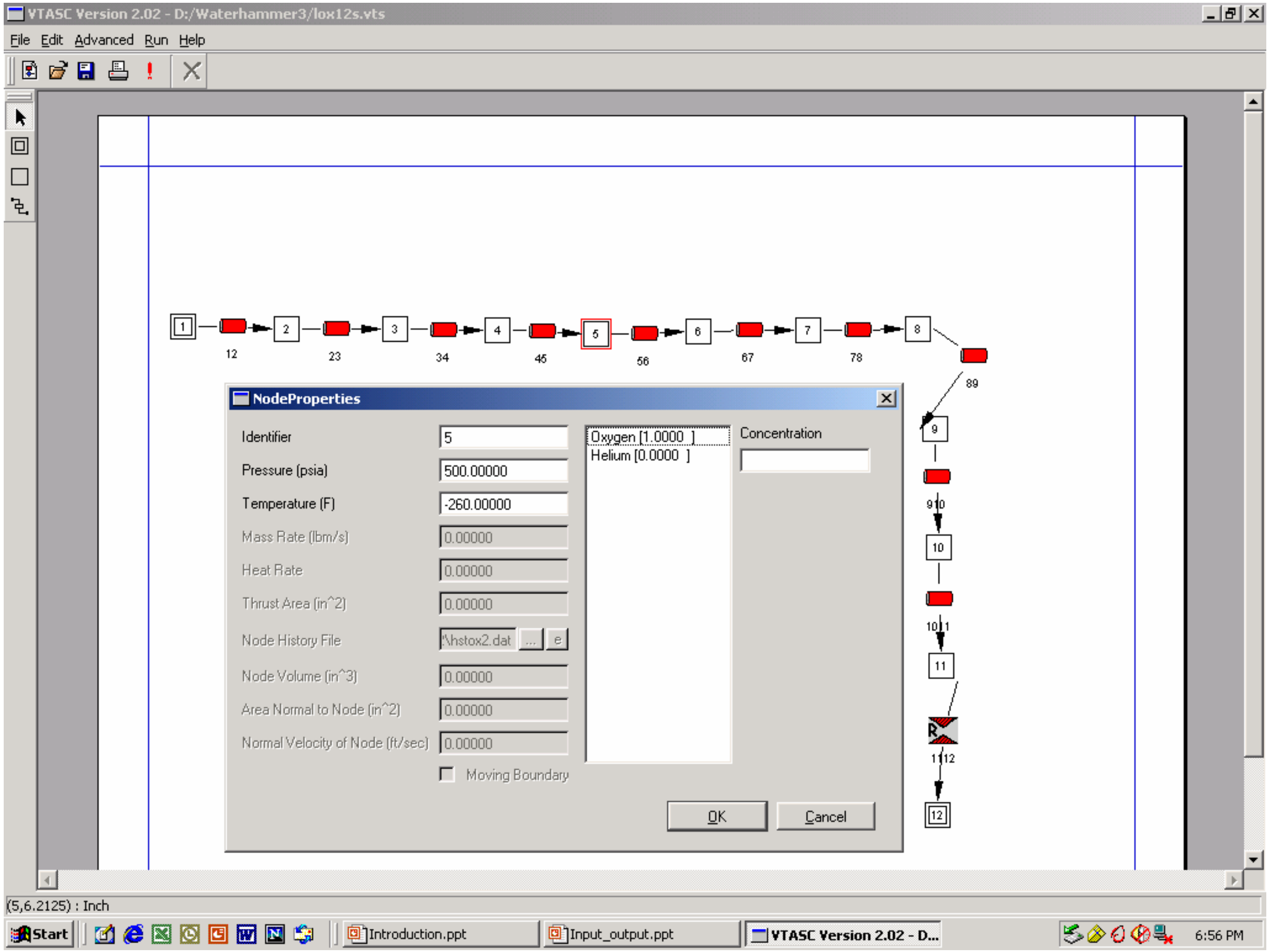


# PROGRAM STRUCTURE



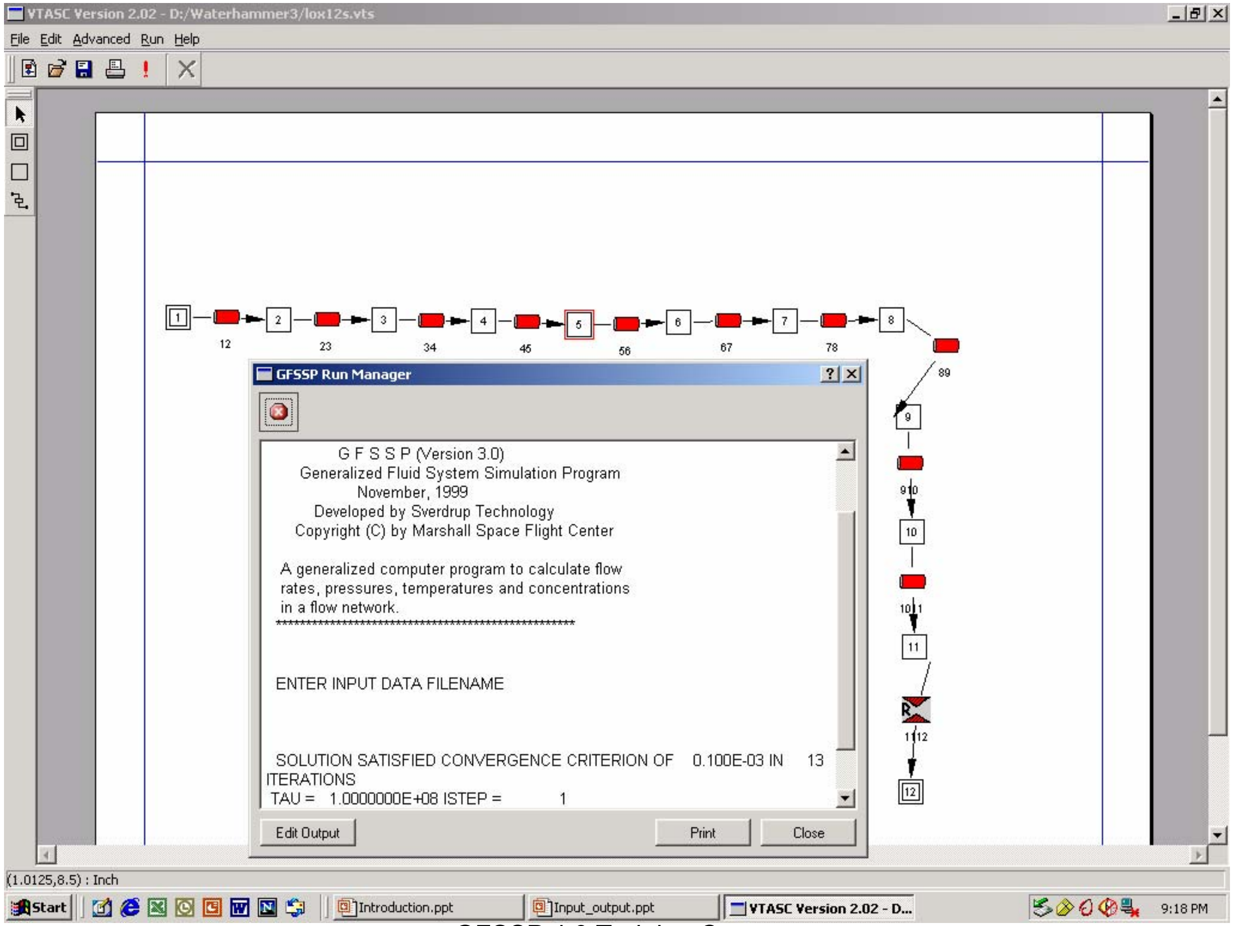
# GRAPHICAL USER INTERFACE - 1

## MODEL BUILDING



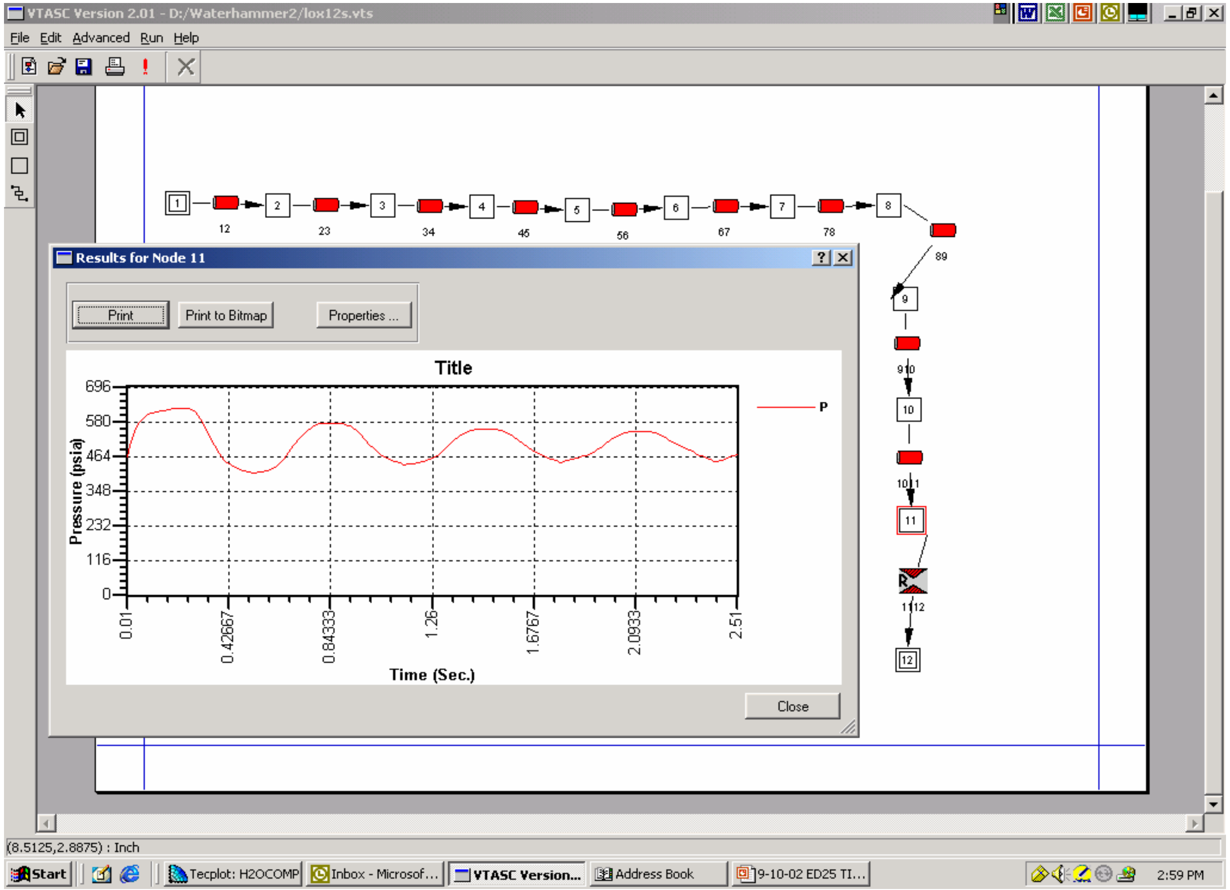
# GRAPHICAL USER INTERFACE - 2

## MODEL RUNNING

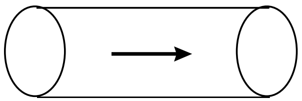


# GRAPHICAL USER INTERFACE - 3

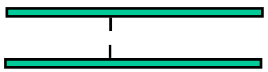
## MODEL RESULTS



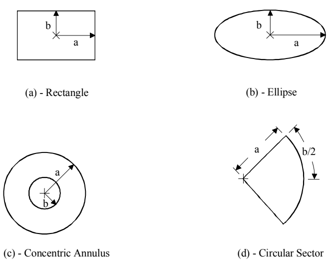
# RESISTANCE & FLUID OPTIONS - 1



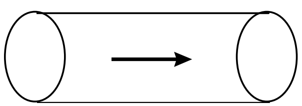
**1. Pipe Flow**



**2. Flow Through a Restriction**

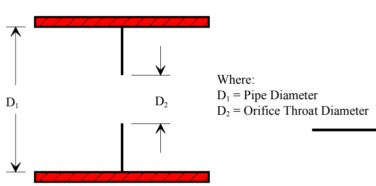



**3. Non-Circular Duct**



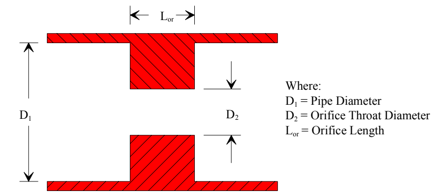
**4. Pipe Flow with Entrance & Exit Losses**

Thin Sharp Orifice



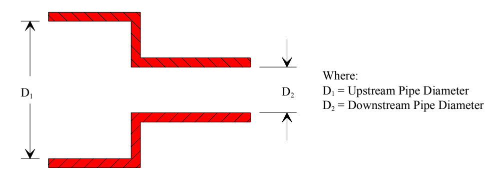

**5. Thin, Sharp Orifice**

Thick Orifice



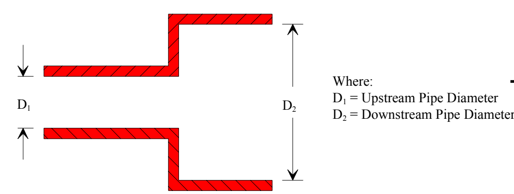

**6. Thick Orifice**

Square Reduction



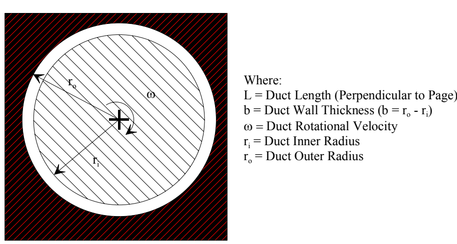

**7. Square Reduction**

Square Expansion



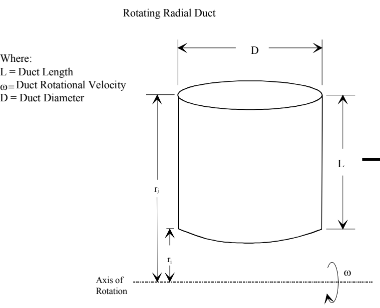

**8. Square Expansion**

Rotating Annular Duct

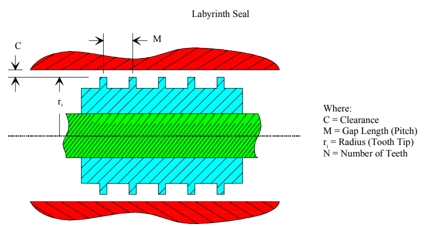



**9. Rotating Annular Duct**

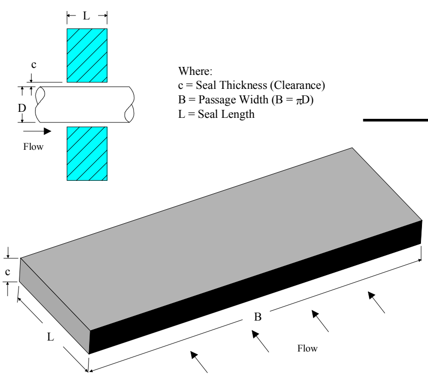
# RESISTANCE & FLUID OPTIONS -2



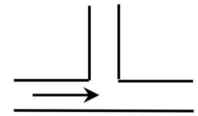

10. Rotating Radial Duct



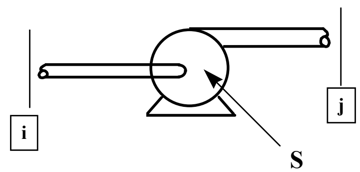

11. Labyrinth Seal



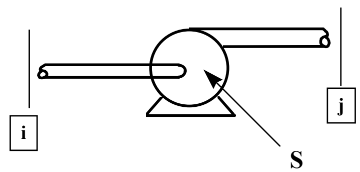

12. Face Seal



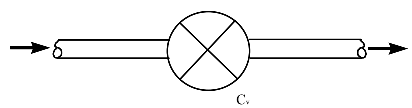
13. Common Fittings & Valves



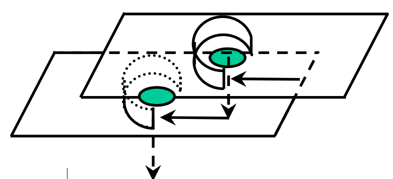

14. Pump Characteristics



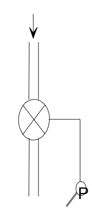

15. Pump Power




16. Valve with Given Cv



17. Viscojet




18. Control Valve

# RESISTANCE & FLUID OPTIONS - 3

## GASP & WASP

| Index | Fluid | Index | Fluid |
|---|---|---|---|
| 1 | HELIUM | 7 | ARGON |
| 2 | METHANE | 8 | CARBON DIOXIDE |
| 3 | NEON | 9 | FLUORINE |
| 4 | NITROGEN | 10 | HYDROGEN |
| 5 | CARBON MONOXIDE | 11 | WATER |
| 6 | OXYGEN | 12 | RP-1 |

# RESISTANCE & FLUID OPTIONS - 4

## GASPAK

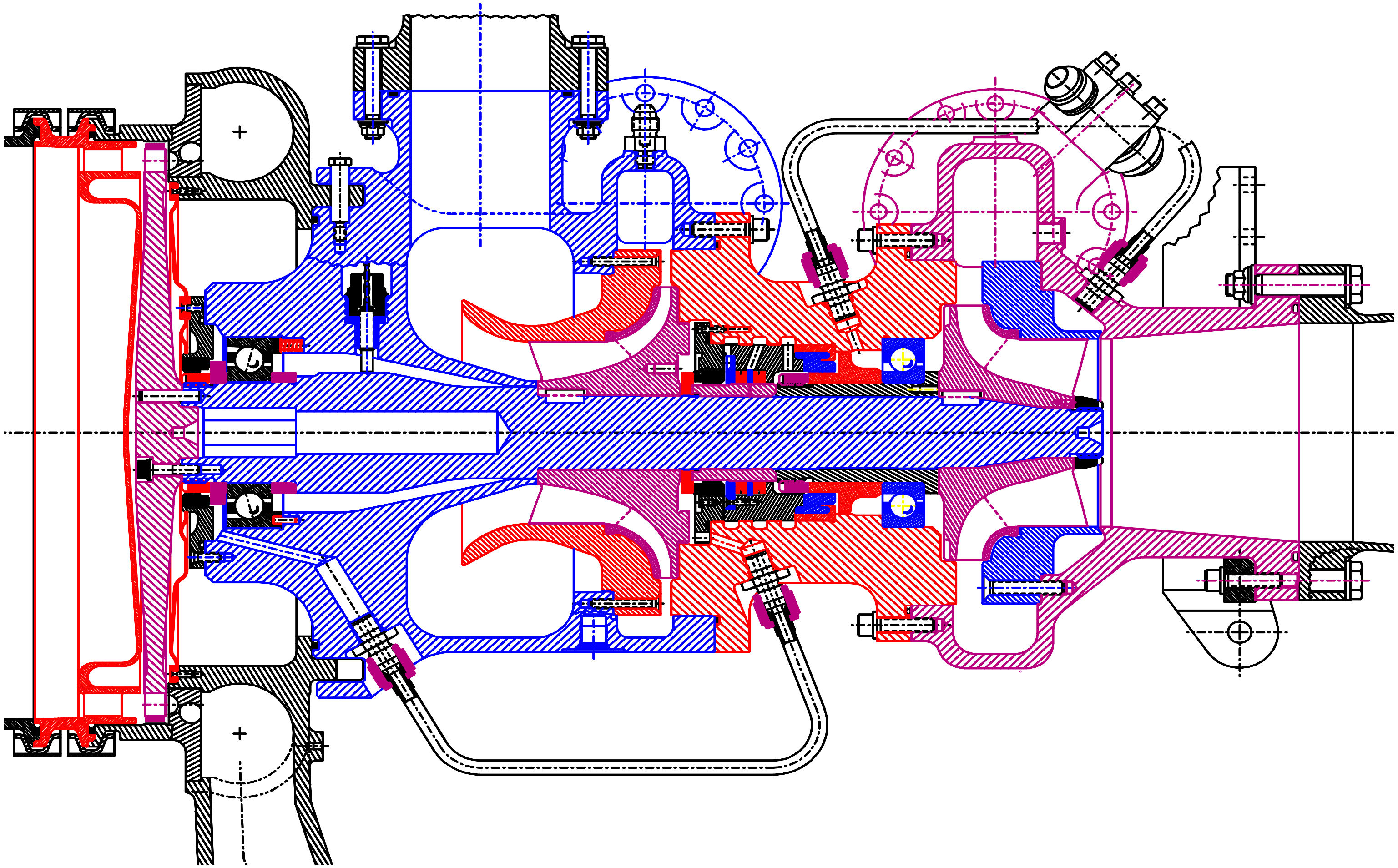
| Index | Fluid | Index | Fluid |
|---|---|---|---|
| 1 | HELIUM | 18 | HYDROGEN SULFIDE |
| 2 | METHANE | 19 | KRYPTON |
| 3 | NEON | 20 | PROPANE |
| 4 | NITROGEN | 21 | XENON |
| 5 | CO | 22 | R-11 |
| 6 | OXYGEN | 23 | R12 |
| 7 | ARGON | 24 | R22 |
| 8 | $CO_2$ | 25 | R32 |
| 9 | PARAHYDROGEN | 26 | R123 |
| 10 | HYDROGEN | 27 | R124 |
| 11 | WATER | 28 | R125 |
| 12 | RP-1 | 29 | R134A |
| 13 | ISOBUTANE | 30 | R152A |
| 14 | BUTANE | 31 | NITROGEN TRIFLUORIDE |
| 15 | DEUTERIUM | 32 | AMMONIA |
| 16 | ETHANE | 33 | IDEAL GAS |
| 17 | ETHYLENE | 34 | AIR |
| | | 35 | HYDROGEN PEROXIDE |

# ADDITIONAL OPTIONS

- Variable Geometry Option
- Variable Rotation Option
- Variable Heat Addition Option
- Turbopump Option
- Heat Exchanger
- Tank Pressurization
- Control Valve

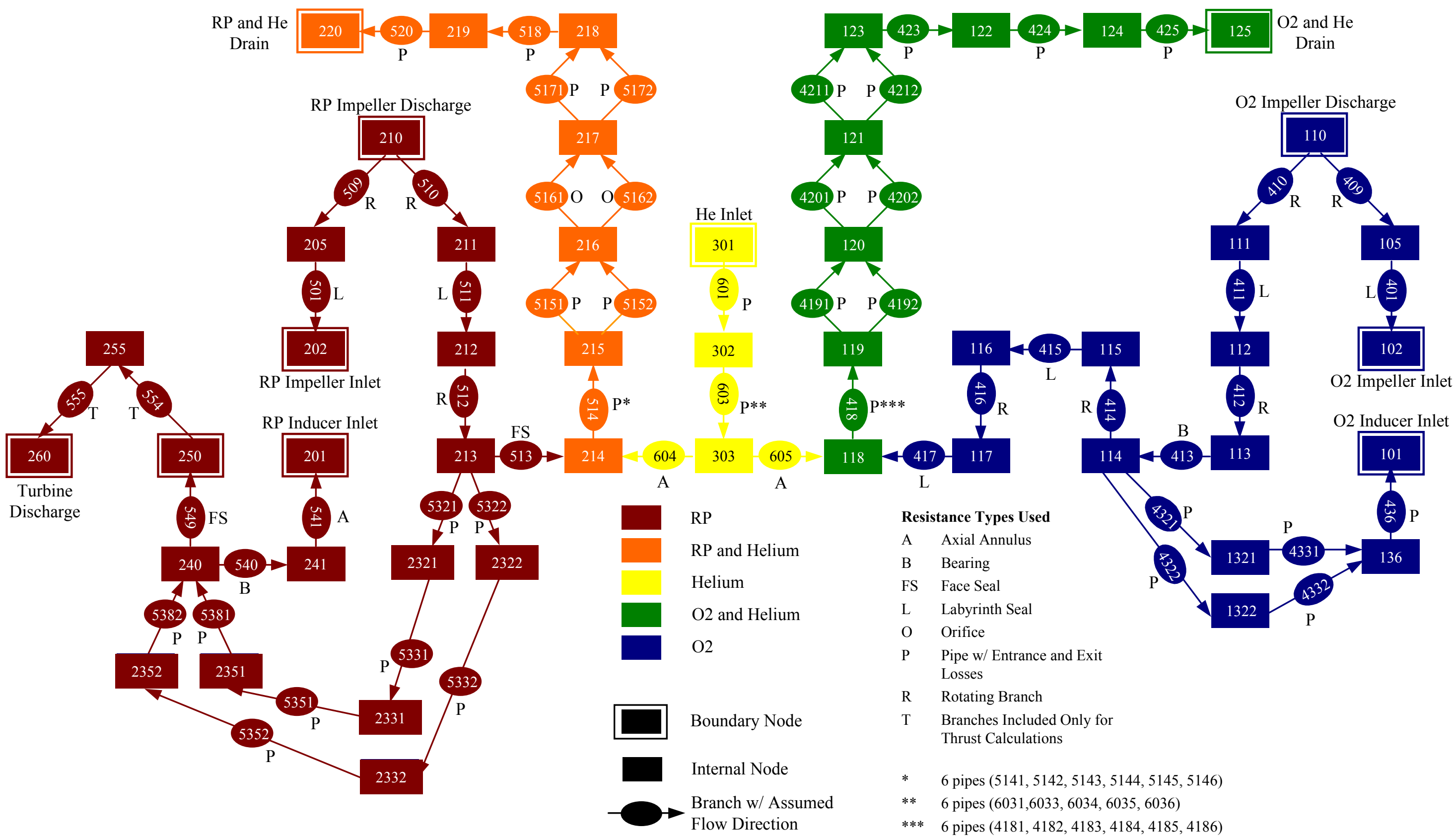
# APPLICATIONS - 1

## FASTRAC TURBOPUMP



# APPLICATIONS - 2

## GFSSP Model of the Fastrac Turbopump



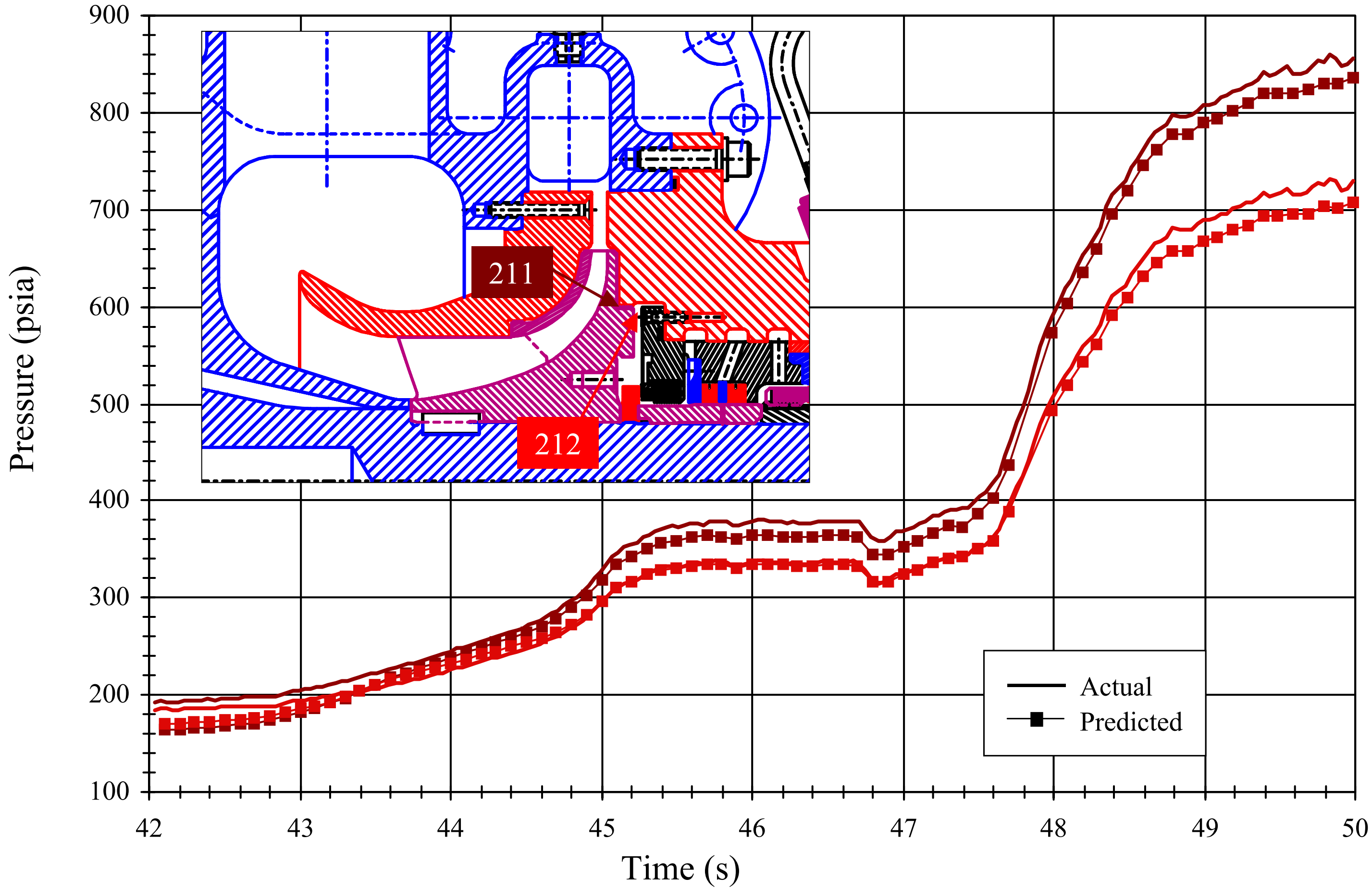
# APPLICATIONS - 3

## Turbopump Test to 20000 RPM with Gas Generator

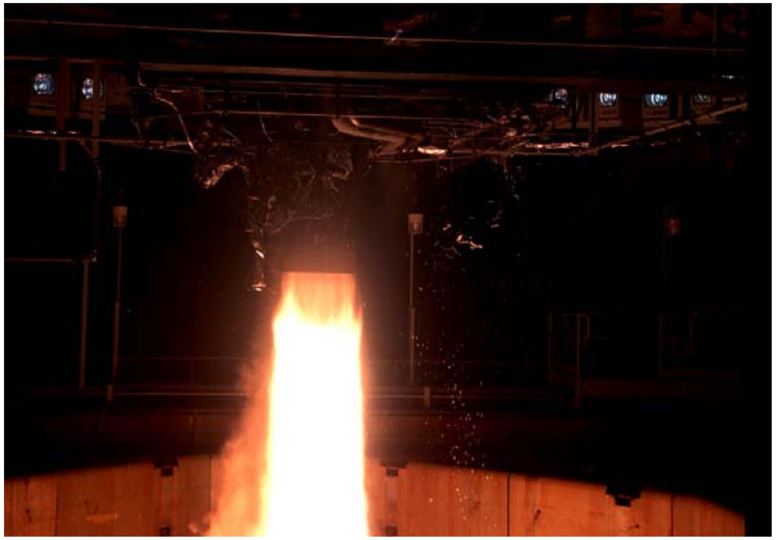
# APPLICATIONS - 4

## Fastrac Turbopump Model Results

Pressure history comparison at RP-1 Impeller back face [Labyrinth seal inlet (211) and outlet (212)]



# APPLICATIONS - 5



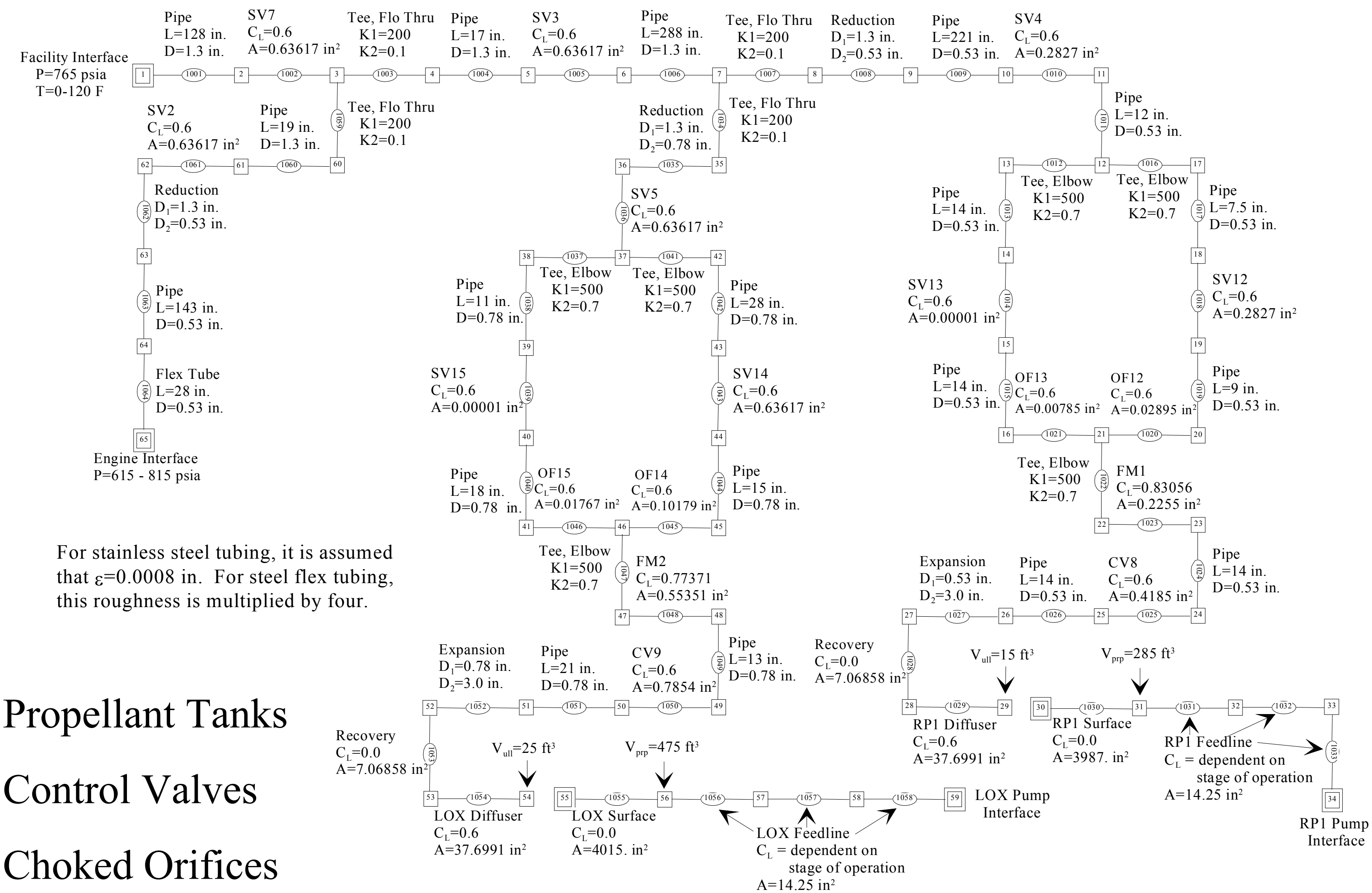
LOX Tank

RP-1 Tank

Engine Interface

# APPLICATIONS - 6

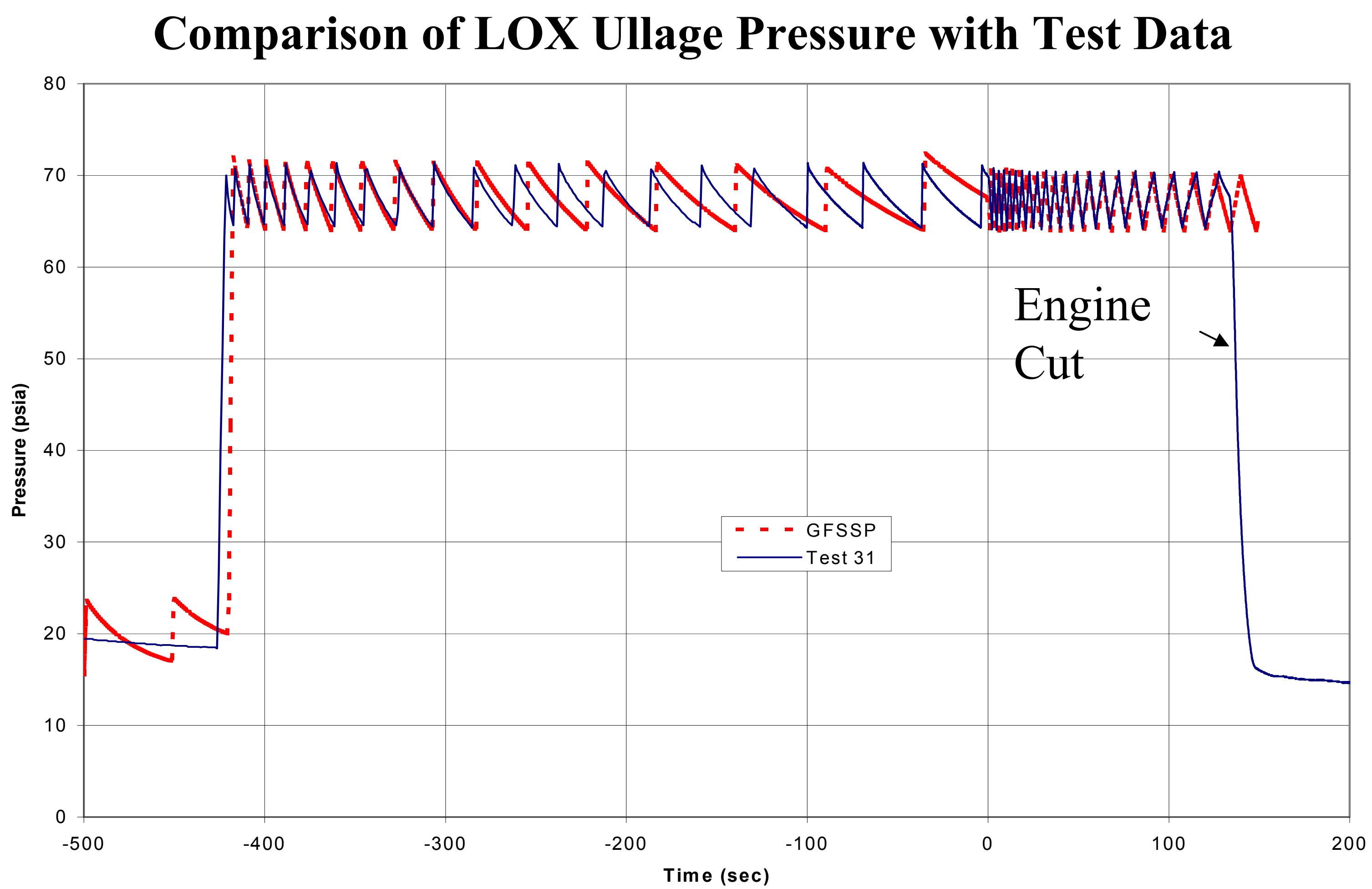
## GFSSP Model of PTA Helium Pressurization System




For stainless steel tubing, it is assumed that $\varepsilon$=0.0008 in. For steel flex tubing, this roughness is multiplied by four.

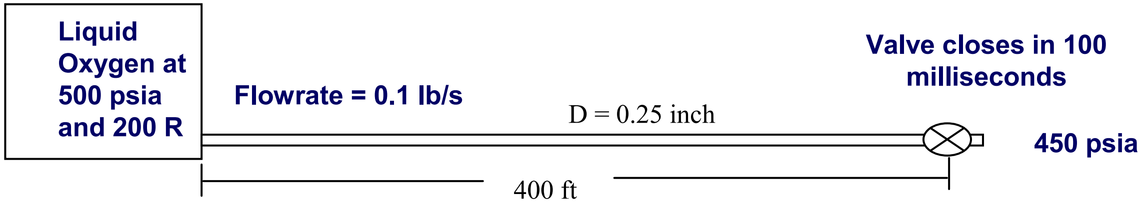
- Propellant Tanks
- Control Valves
- Choked Orifices
- Various fittings

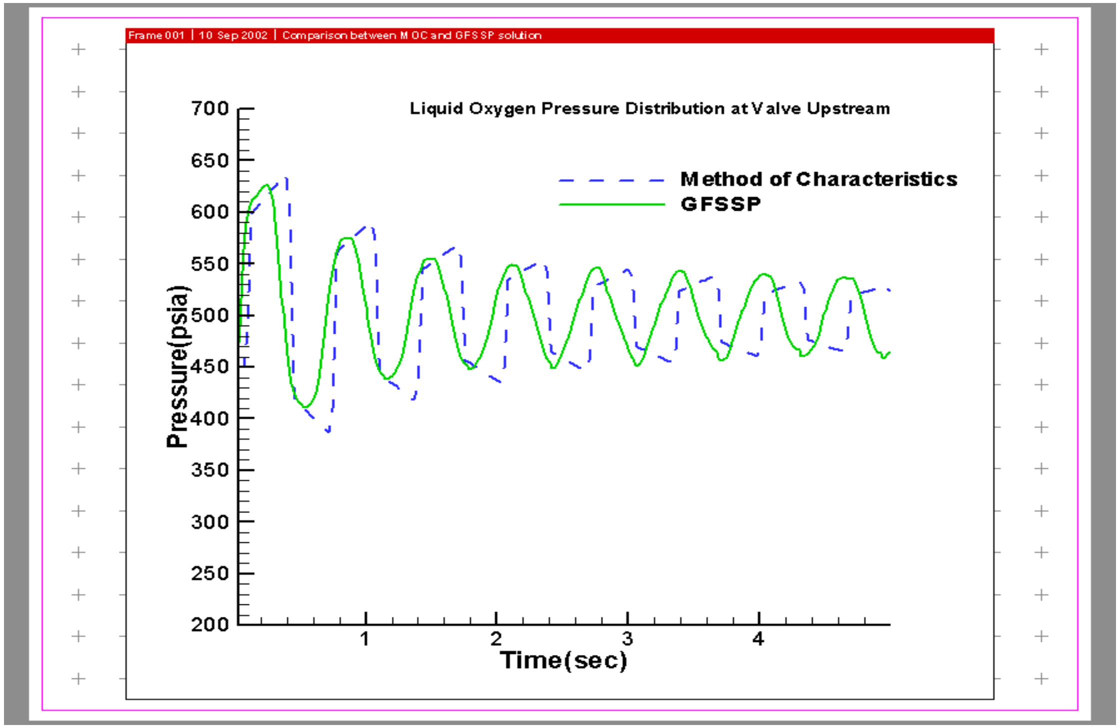
# APPLICATIONS - 7



# APPLICATIONS - 8

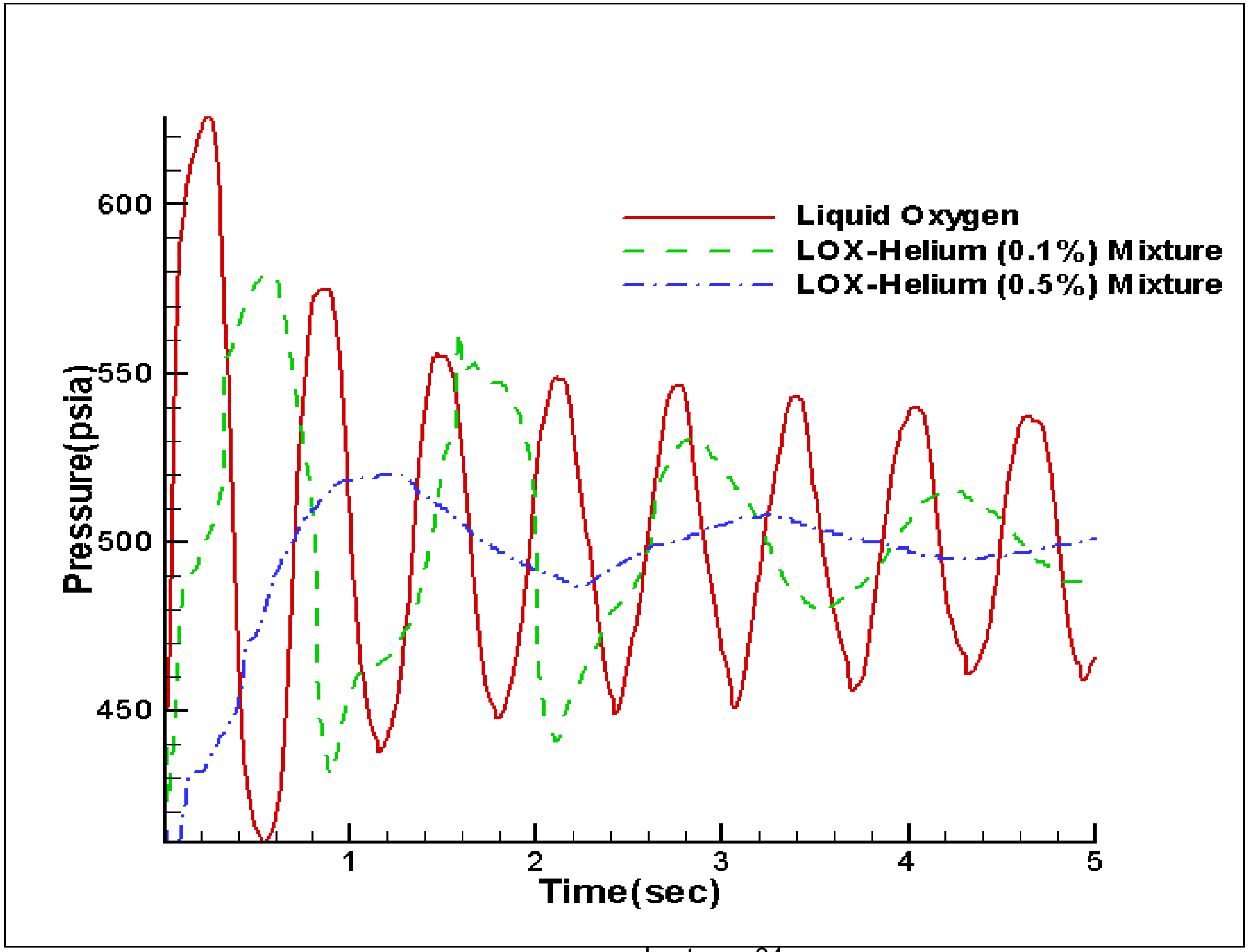
## Verification of Fluid Transient Computation



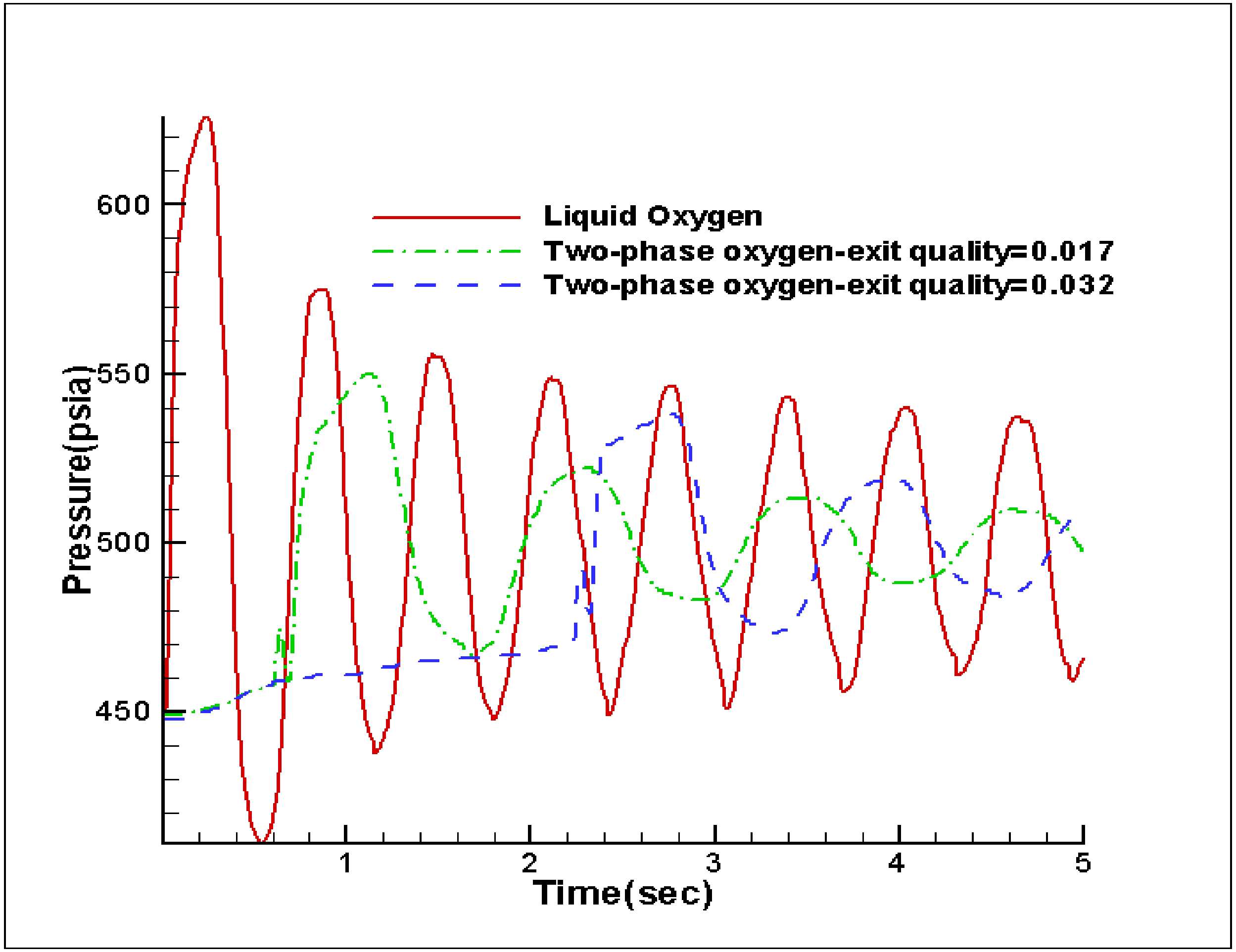
# APPLICATIONS - 9

## Fluid Transient in Two phase flow



# APPLICATIONS - 10

## Predicted Fluid Transient Due to Condensation



# SUMMARY - 1

- GFSSP is a finite volume based Network Flow Analyzer
- Flow circuit is resolved into a network consisting of nodes and branches
- Mass, energy and specie conservation are solved at internal nodes. Momentum conservation is solved at branch
- Generalized data structure allows generation of all types of flow network
- Modular code structure allows to add new capabilities with ease

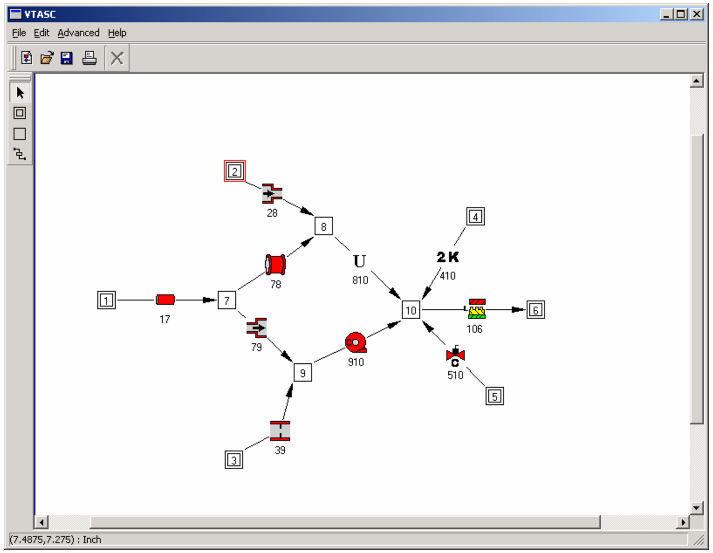
# SUMMARY – 2

- Unique mathematical formulation allows effective coupling of thermodynamics and fluid mechanics
- Numerical scheme is robust; adjustment of numerical control parameters is seldom necessary
- Intuitive Graphical User Interface makes it easy to build, run and evaluate numerical models
- GFSSP has been successfully applied in various applications that included
  - Incompressible & Compressible flows
  - Phase change (Boiling & Condensation)
  - Fluid Mixture
  - Thermodynamic transient (Pressurization & Blowdown)
  - Fluid Transient (Waterhammer)
  - Conjugate Heat Transfer

# SUMMARY – 3

- GFSSP is available from NASA/MSFC's Technology Transfer Office for US Government agencies and contractors
- An Audio-Video Training Course is also available
- More information about the code and its methodology is available at http://mi.msfc.nasa.gov/GFSSP/index.shtml

# VTASC – AN INTERACTIVE PREPROCESSOR FOR GFSSP




**Todd Steadman**

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**Marshall Space Flight Center**

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# BACKGROUND -1

Visual Thermo-fluid dynamic Analyzer for Systems and Components (VTASC) is a program designed to efficiently build flow network models for use in the GFSSP program.

- Visually Interactive
  - Eliminates pre-design of models
  - Immediate feedback on model
- Self-Documenting
  - Hard copy of flow network
  - Bitmap image of flow network for inclusion into papers and presentations

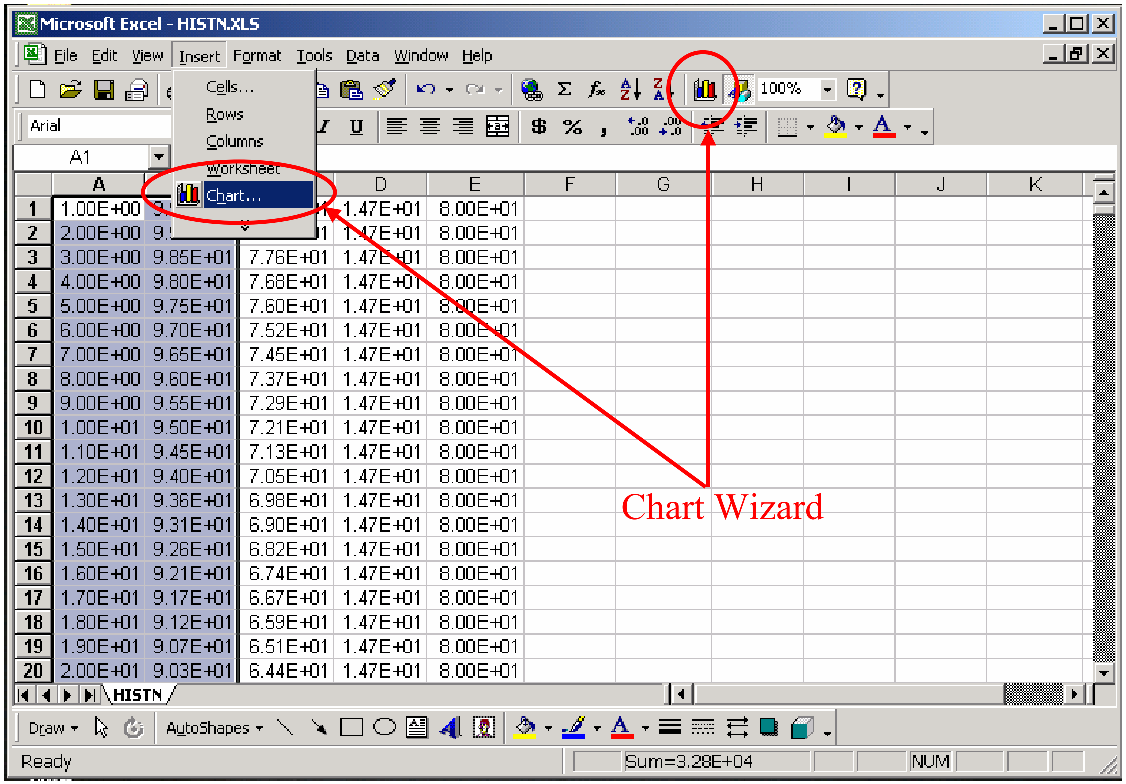
# BACKGROUND -2

- Eliminates errors during model building process
  - Automatic node and branch numbering
  - Save and restore models at any point in the model building process
  - Robust
- Pushbutton generation of GFSSP input file
  - Steady and Transient cases
  - Advanced features such as Turbopump, Tank Pressurization and Heat Exchangers
- Run GFSSP directly from VTASC window
  - GFSSP Run Manager acts as VTASC/GFSSP interface

# BACKGROUND -3

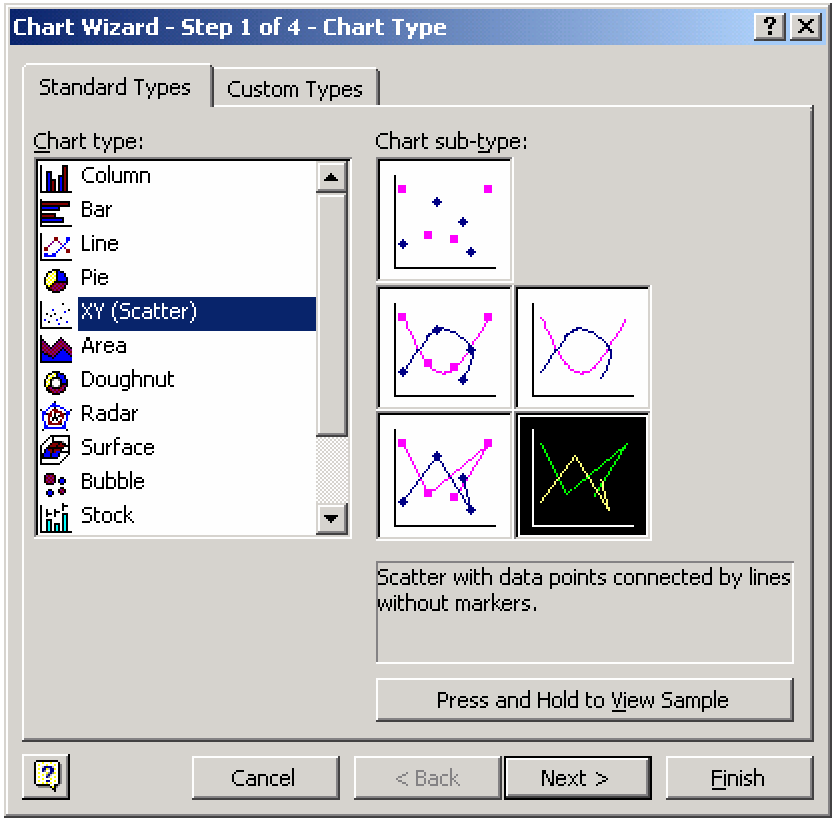
- Post-processing capability allows quick study of results
  - Pushbutton access to GFSSP output file
  - Point and click access to output at each node and branch
  - Built-in plotting capability for transient cases
  - Capable of plotting through Winplot
- Cross platform operation
  - Program written in C++
  - Uses cross platform C++ GUI toolkit

# CREATING A CHART IN EXCEL -1



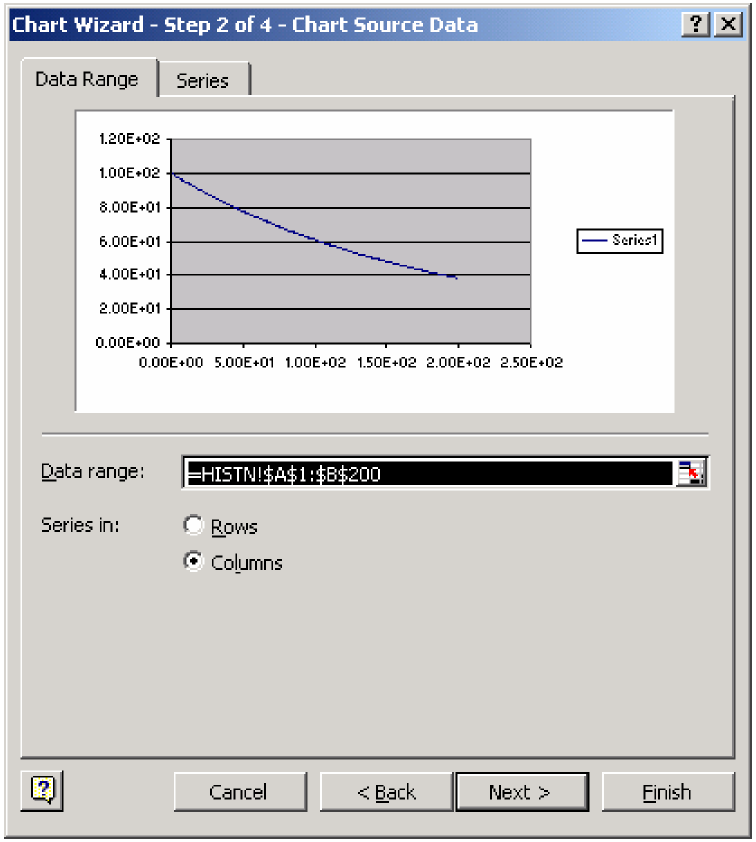

- Highlight Data to Plot
- Start Chart Wizard from Either Toolbar Button or “Insert Chart…” Menu

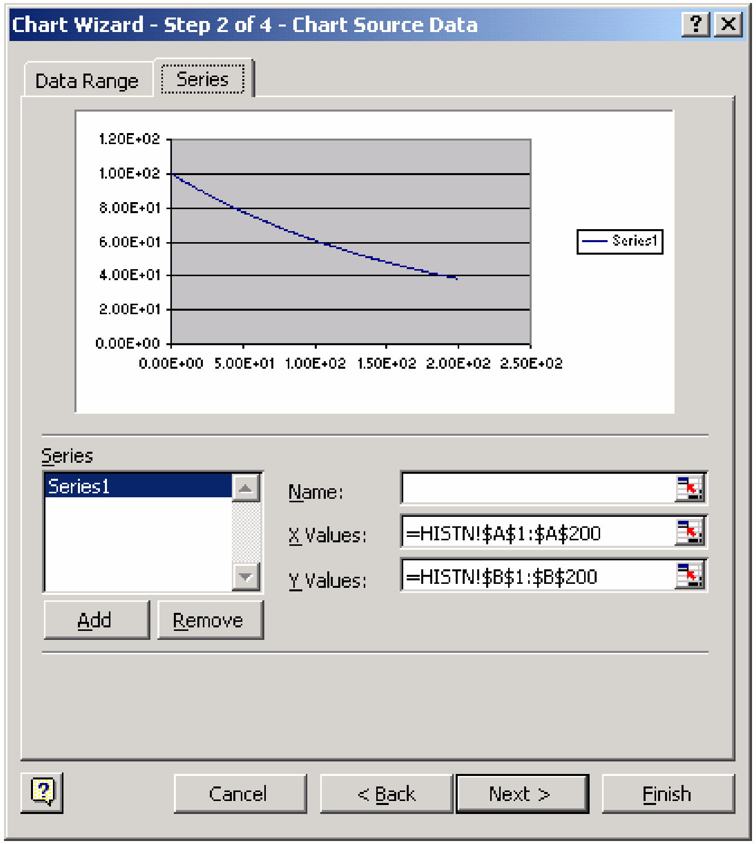
# CREATING A CHART IN EXCEL -2




•Select Chart Type and Chart sub-type from Standard Types Tab of Chart Wizard Step 1

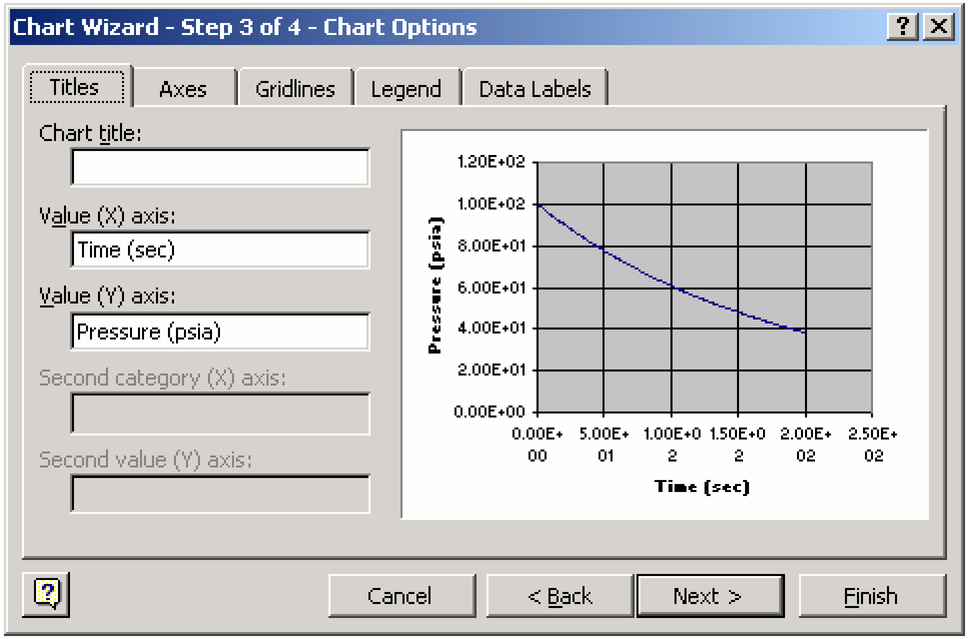
# CREATING A CHART IN EXCEL -3



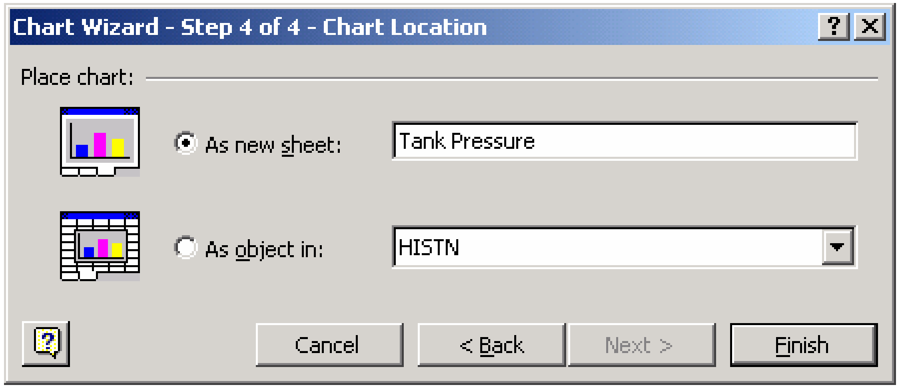

- Manipulate Source Data as Necessary for Chart Wizard Step 2

# CREATING A CHART IN EXCEL -4



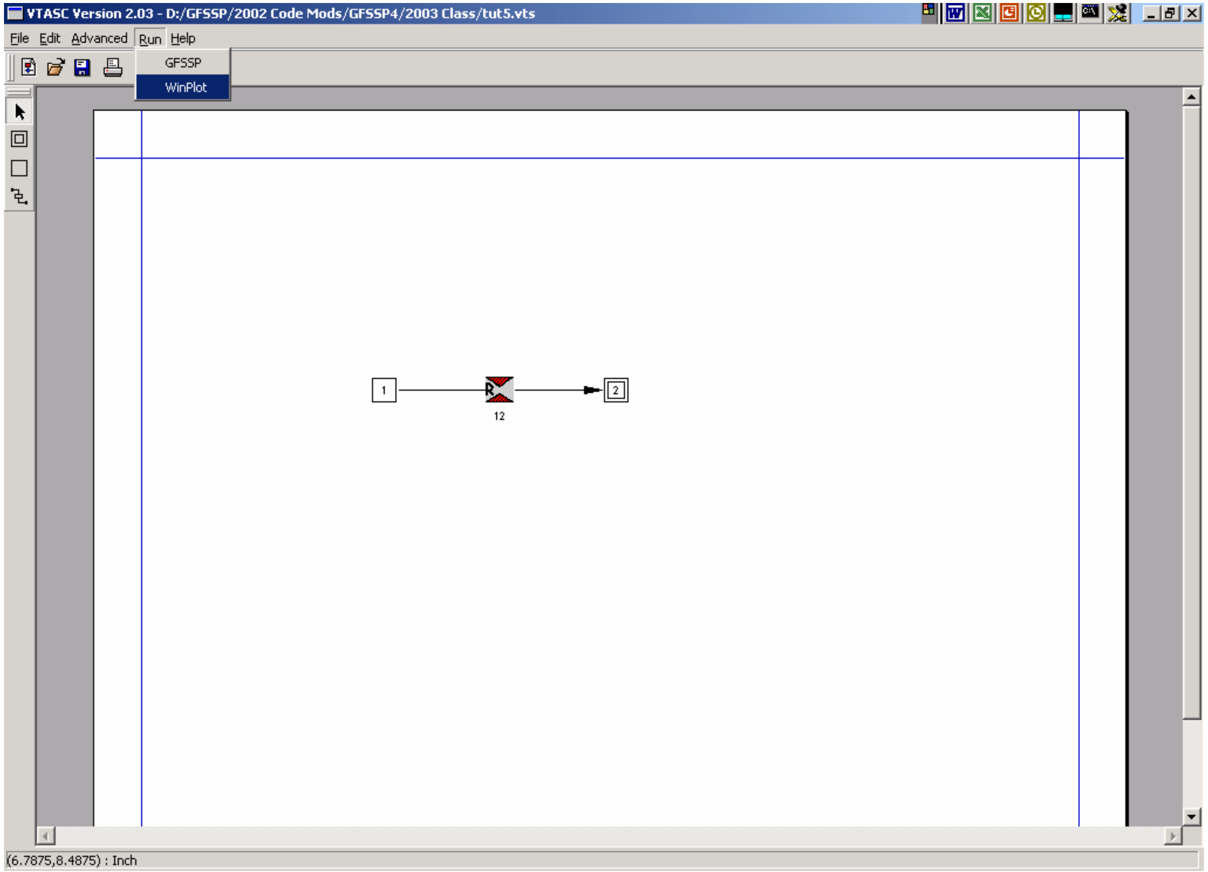

- Specify Labels and Chart Preferences for Chart Wizard Step 3

# CREATING A CHART IN EXCEL -5



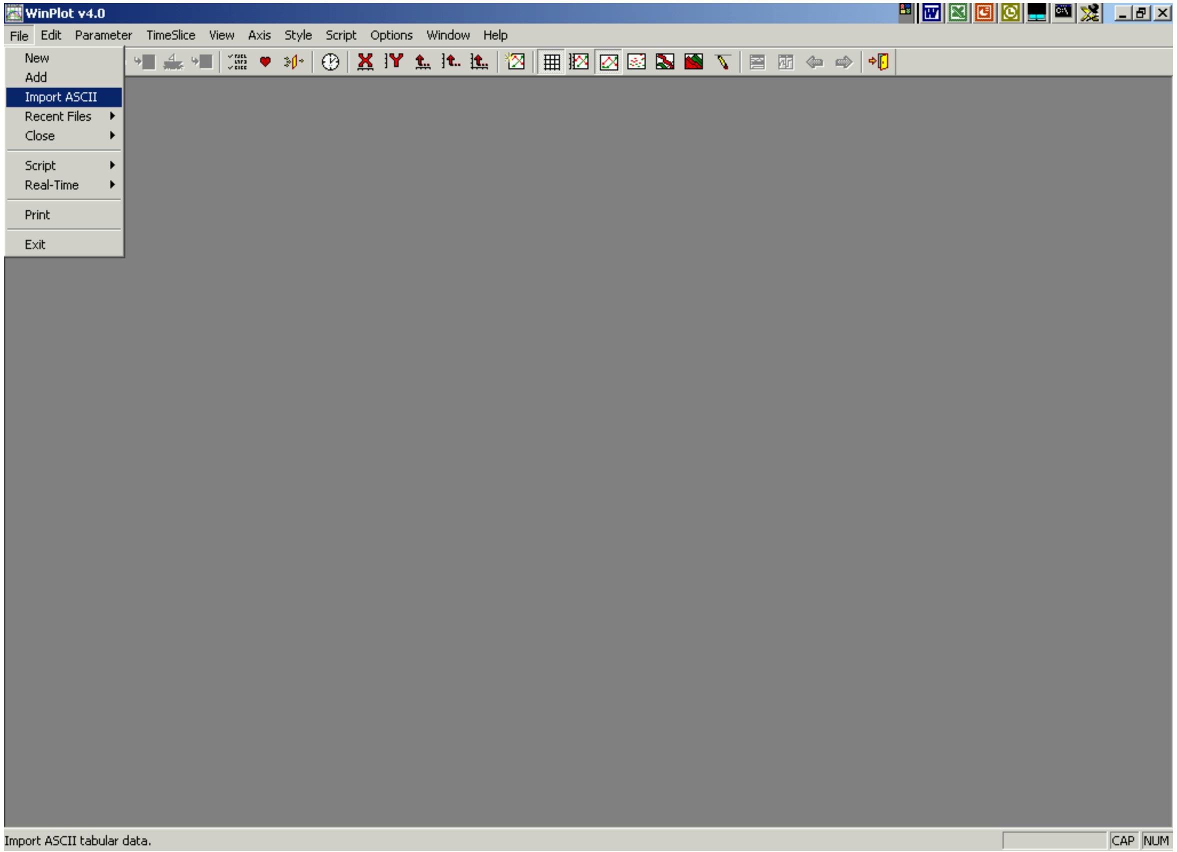

- Select Chart Placement in Worksheet for Chart Wizard Step 4
- Click Finish to Create Chart
- Once Created, Chart May be Further Edited by Selecting Chart and Clicking on Area You Wish to Change

# CREATING A CHART IN WINPLOT -1



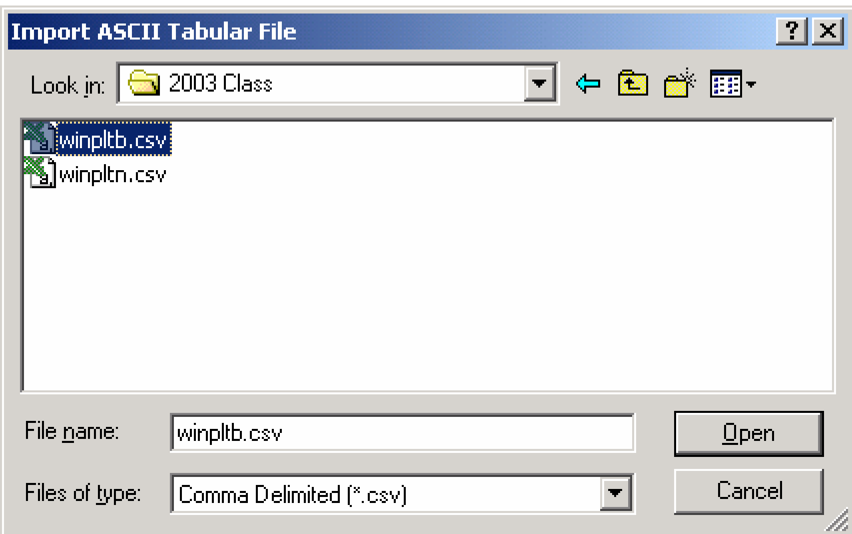

- After completing a model run, select Winplot from the VTASC Run Menu

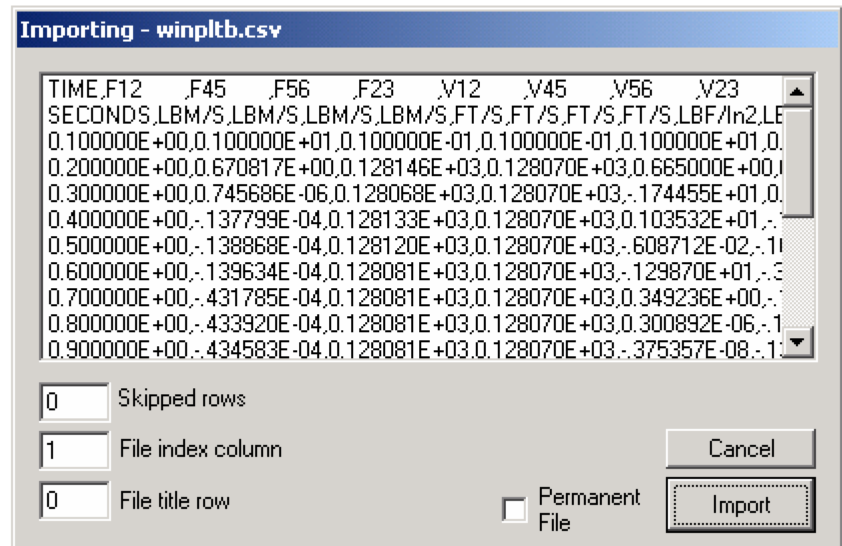
# CREATING A CHART IN WINPLOT -2




•From Winplot's File Menu, select "Import ASCII"

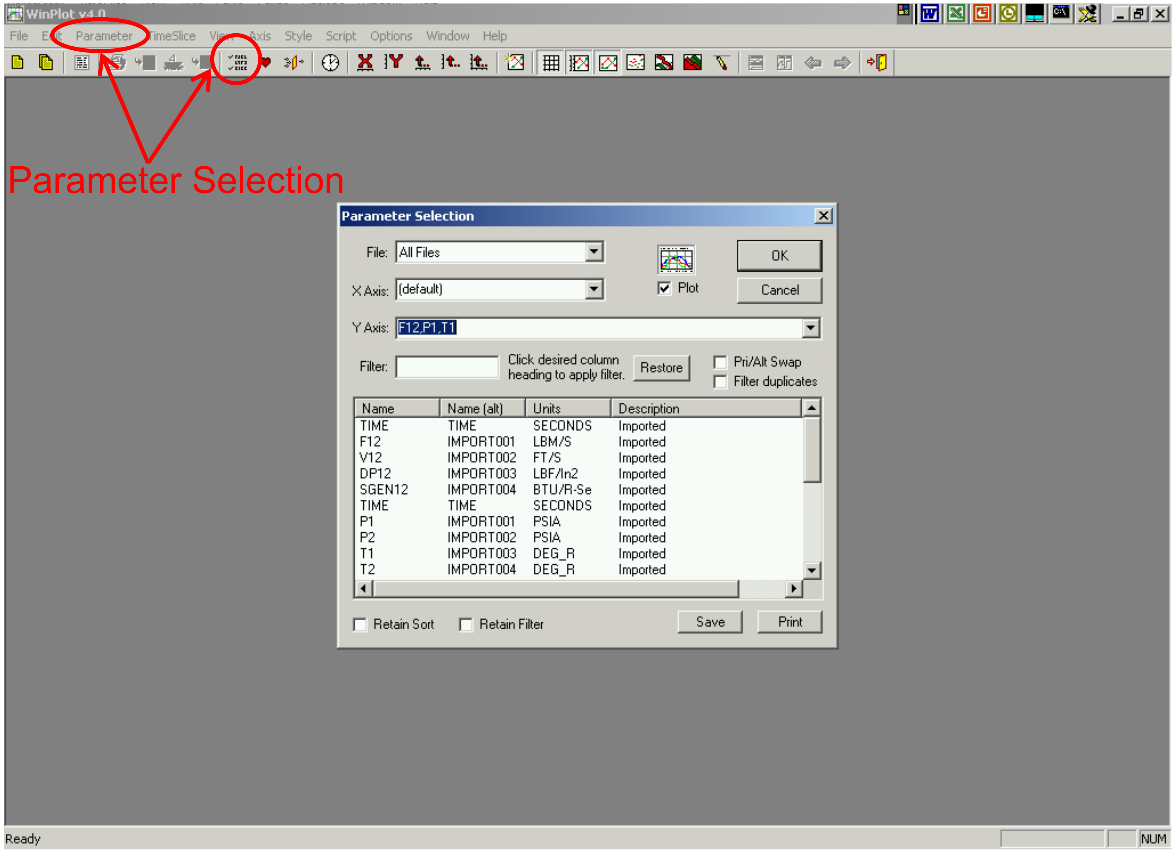
# CREATING A CHART IN WINPLOT -3



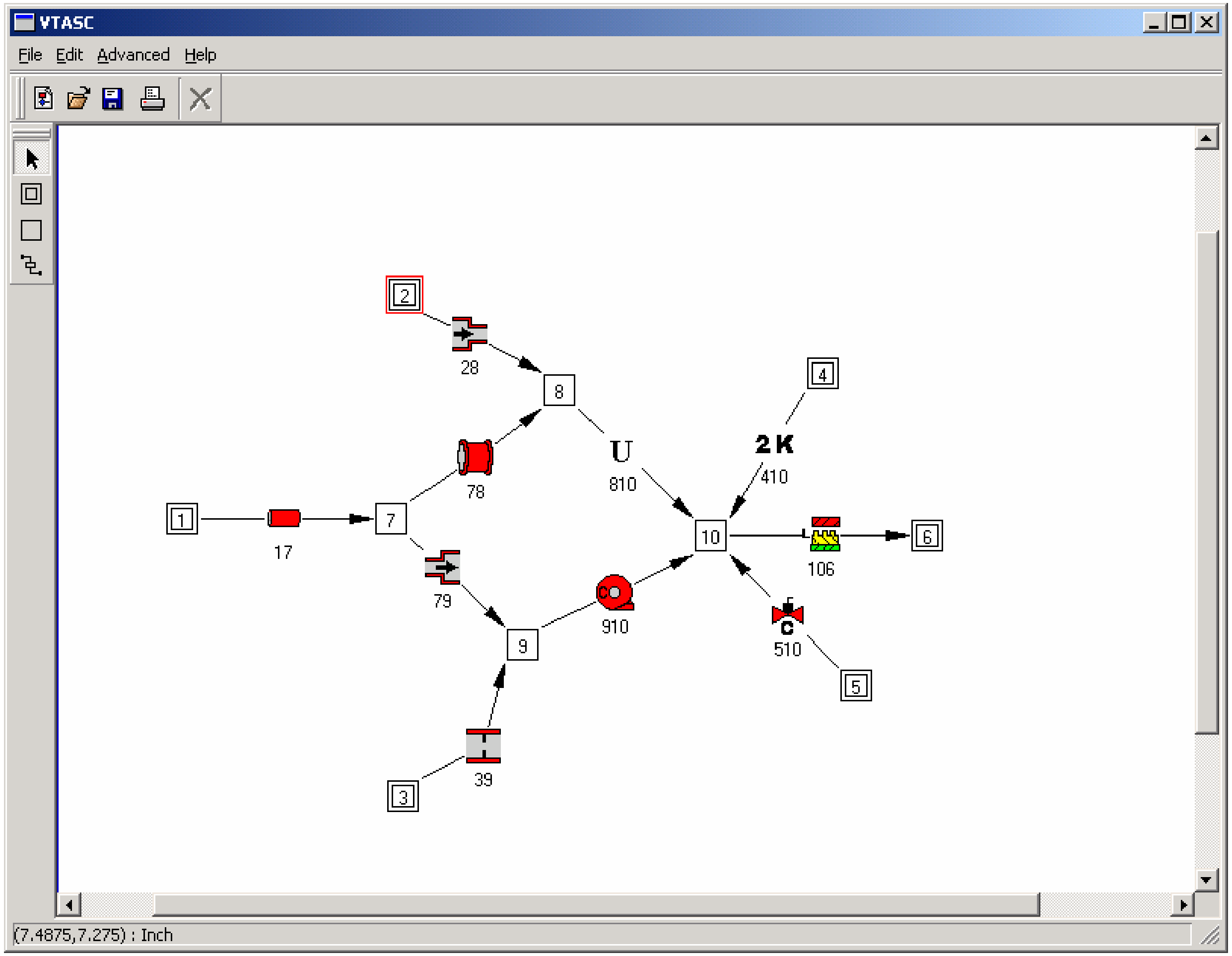

- Use the Browse window to select the files you wish to import
- The default GFSSP Winplot files are “winpltb.csv” & “winpltn.csv”
- Selecting a file opens the Importing window.  Click Import.

# CREATING A CHART IN WINPLOT -4

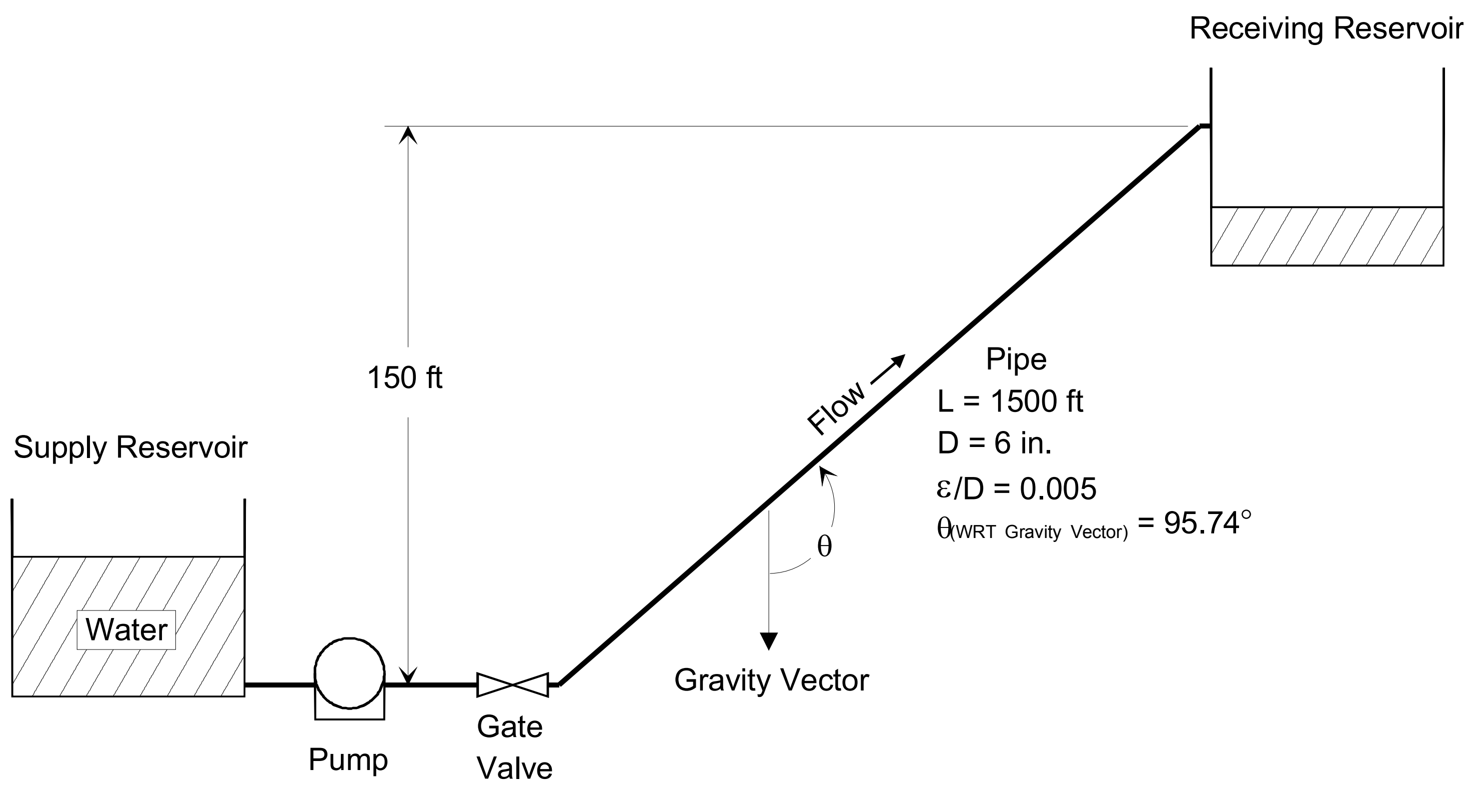



- From the Parameter Selection window, select the data you wish to plot

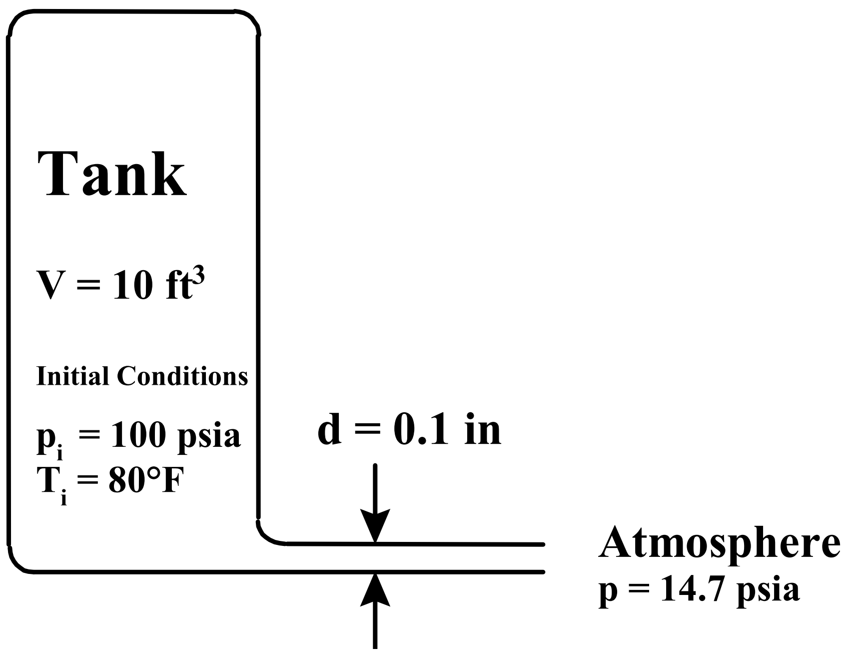
# DEMONSTRATION



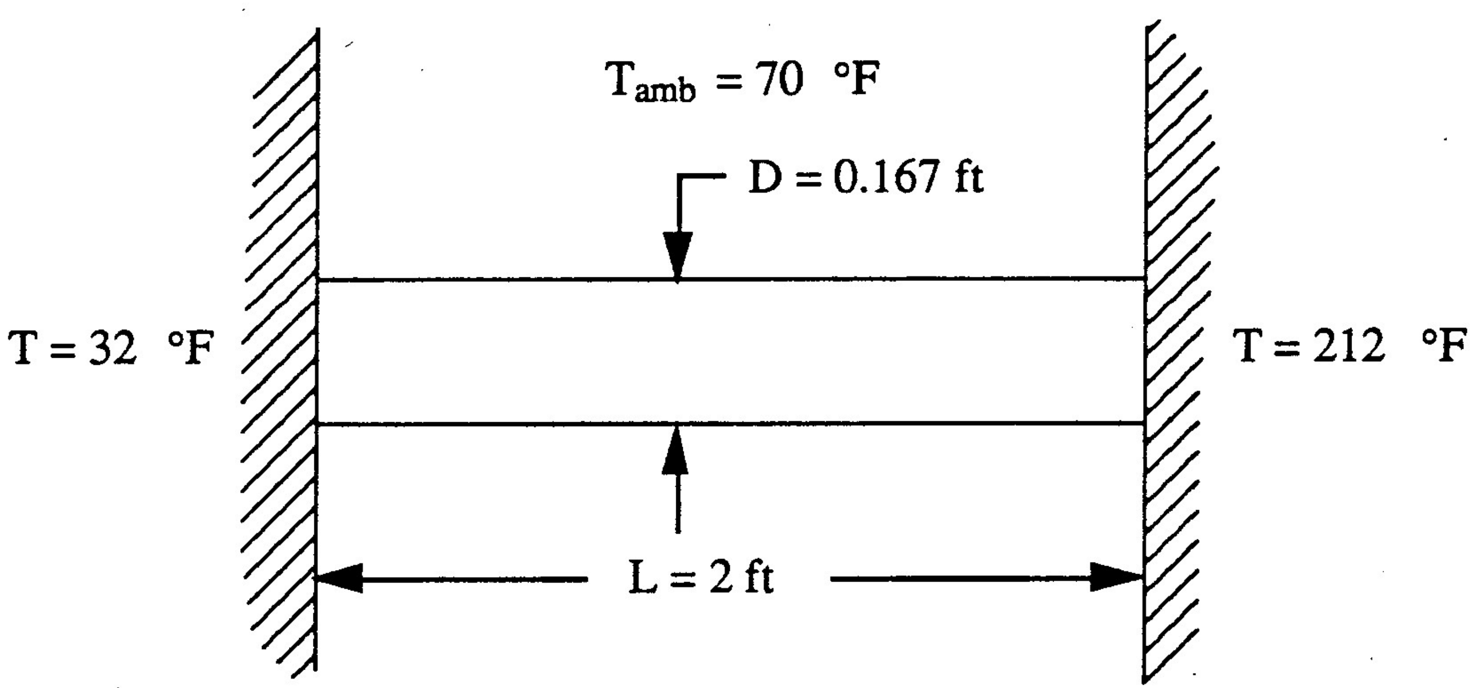
# VTASC DEMONSTRATION PROBLEMS -1



# VTASC DEMONSTRATION PROBLEMS -2



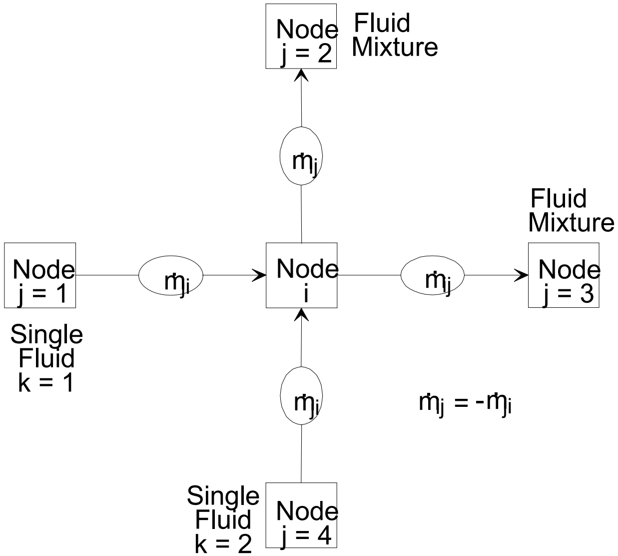
# VTASC DEMONSTRATION PROBLEMS -3



# SUMMARY

- VTASC is a flow network model builder for use with GFSSP
- Flow networks can be designed and modified interactively using a “Point and Click” paradigm
- Generates GFSSP Version 4.0 compatible input files

# MATHEMATICAL FORMULATION





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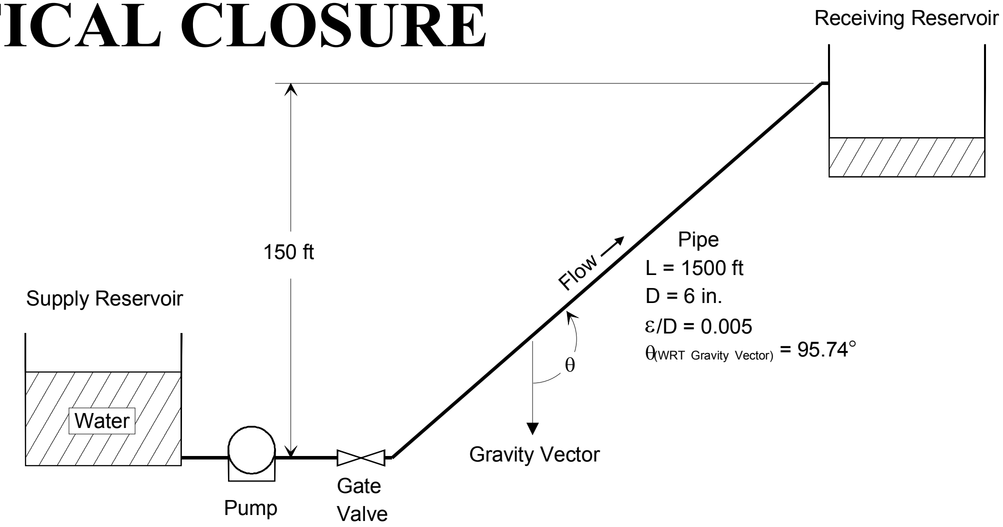
# Content

- Mathematical Closure
- Governing Equations
- Solution Procedure

# MATHEMATICAL CLOSURE

## Problem of a Steady State Flow Network

- **Given** : Pressures and Temperatures at Boundary Nodes
- **Find** : Pressures and Temperatures at Internal Nodes and Flowrates in Branches

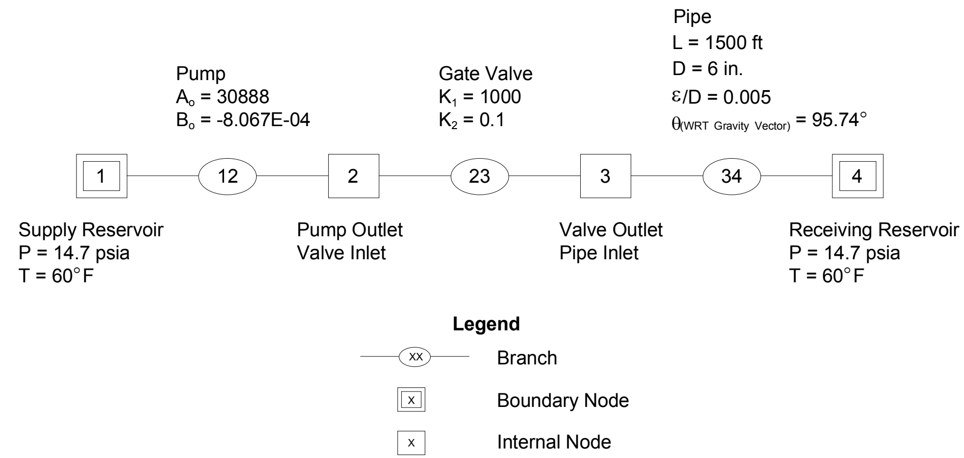



*Primary Variables*

$$p_2, p_3, T_2, T_3, \dot{m}_{12}, \dot{m}_{23}, \dot{m}_{34}$$

*Secondary Variables*

$$\rho_2, \rho_3, \mu_2, \mu_3$$



# MATHEMATICAL CLOSURE

## Problem of an Unsteady Flow Network

- **Given** : Pressures and Temperatures at Boundary Nodes and Initial Values at Internal Nodes

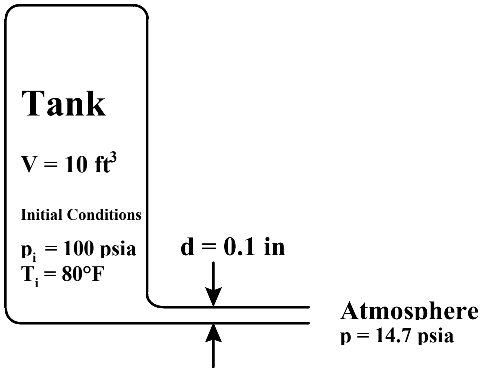
- **Find** : Pressures and Temperatures at Internal Nodes and Flowrates in Branches with Time.

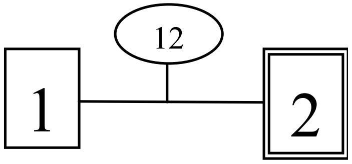
*Primary Variables*

$$p_1(\tau), T_1(\tau), m_1(\tau), \dot{m}(\tau)$$

*Secondary Variables*

$$\rho_1(\tau),\ \mu_1(\tau)$$



# MATHEMATICAL CLOSURE

## Principal Variables:

| **Unknown Variable** | **Available Equations to Solve** |
|---|---|
| 1. Pressure | 1. Mass Conservation Equation |
| 2. Flowrate | 2. Momentum Conservation Equation |
| 3. Temperature | 3. Energy Conservation Equation |
| 4. Specie Concentrations (Mixture) | 4. Conservation Equations for Mass Fraction of Species |
| 5. Mass (Unsteady) | 5. Thermodynamic Equation of State |

# MATHEMATICAL CLOSURE

## Secondary Variables:

### Thermodynamic & Thermophysical Properties

| **Unknown Variable** | **Available Equations to Solve** |
|---|---|
| Density | |
| Specific Heats | Equilibrium Thermodynamic Relations |
| Viscosity | [GASP, WASP & GASPAK Property Programs] |
| Thermal Conductivity | |

### Flow Resistance

| **Unknown Variable** | **Available Equations to Solve** |
|---|---|
| 1. Friction Factor | 1. Empirical Relations |
| 2. Loss Coefficient | 2. User Specified |

# GOVERNING EQUATIONS

- Mass Conservation
- Momentum Conservation
- Energy Conservation
- Fluid Species Conservation
- Equation of State
- Mixture Property

# Coupling of Thermodynamics & Fluid Dynamics

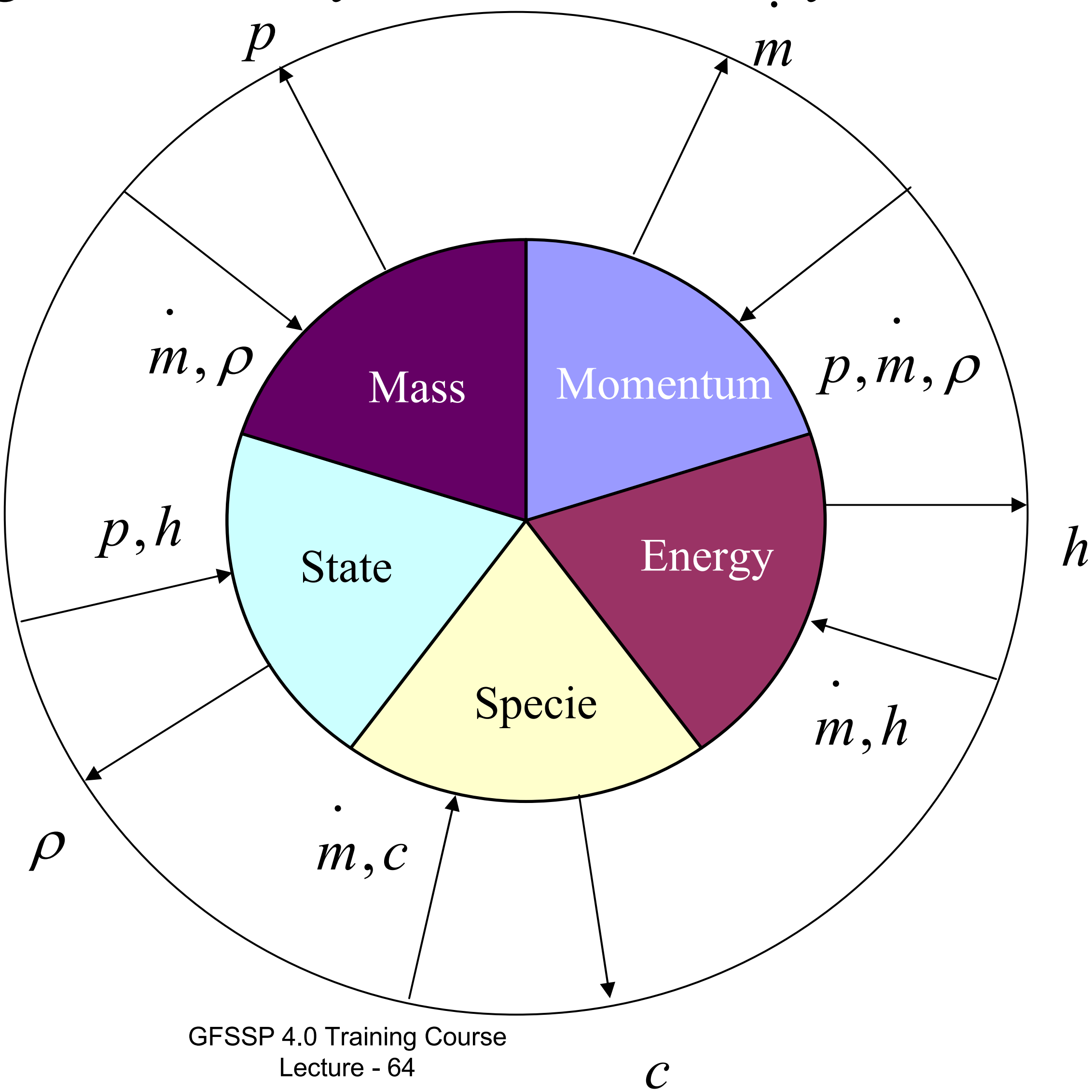
$p$ – Pressure

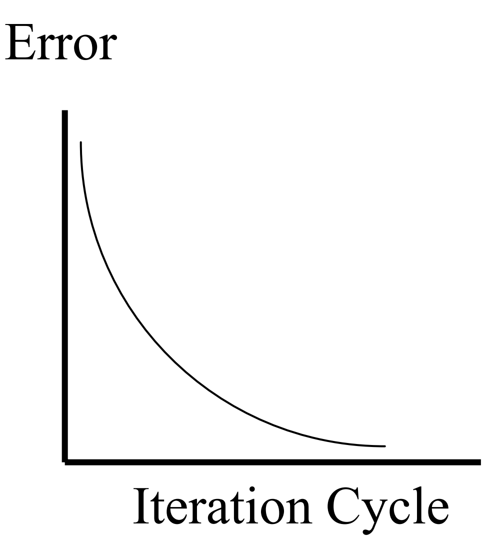
$\dot{m}$ - Flowrate

$h$ - Enthalpy

$c$ - Concentration

$\rho$ - Density

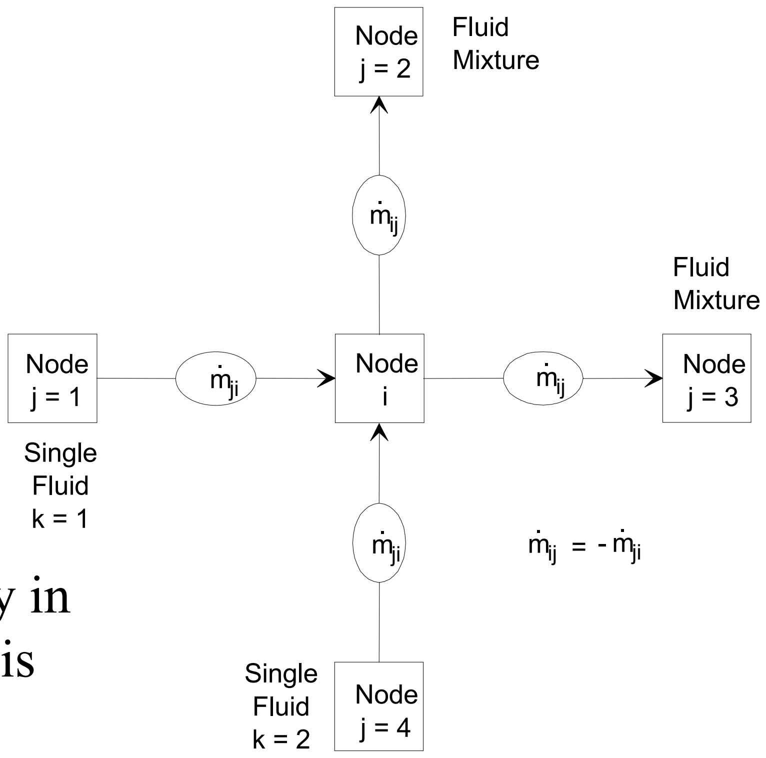


# GOVERNING EQUATIONS

## MASS CONSERVATION EQUATION

$$\frac{m_{\tau+\Delta\tau} - m_{\tau}}{\Delta\tau} = \sum_{j=1}^{j=n} \dot{m}_{ij}$$




Note : Pressure does not appear explicitly in Mass Conservation Equation although it is earmarked for calculating pressures

# GOVERNING EQUATIONS

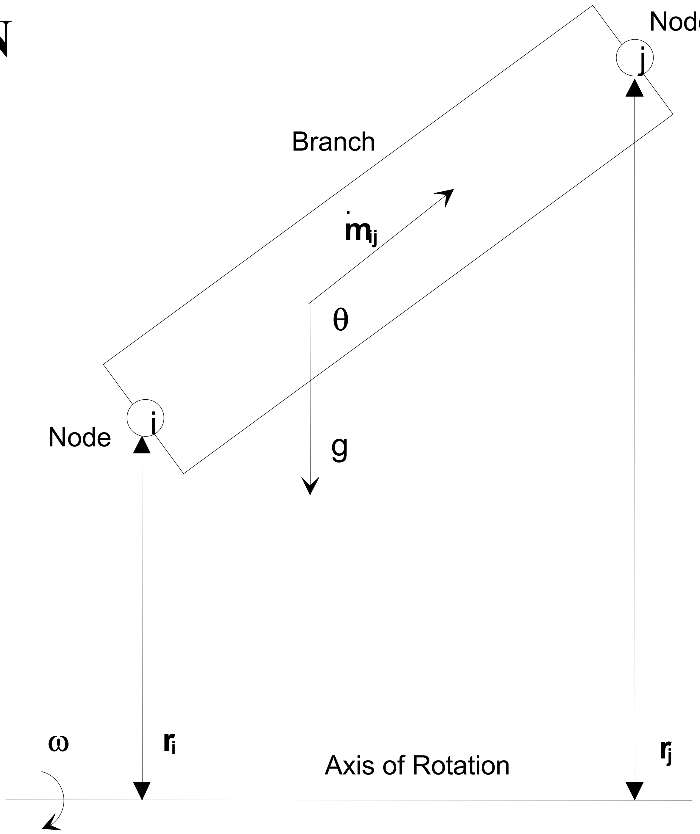
## MOMENTUM CONSERVATION EQUATION

- Represents Newton's Second Law of Motion

*Mass x Acceleration = Forces*

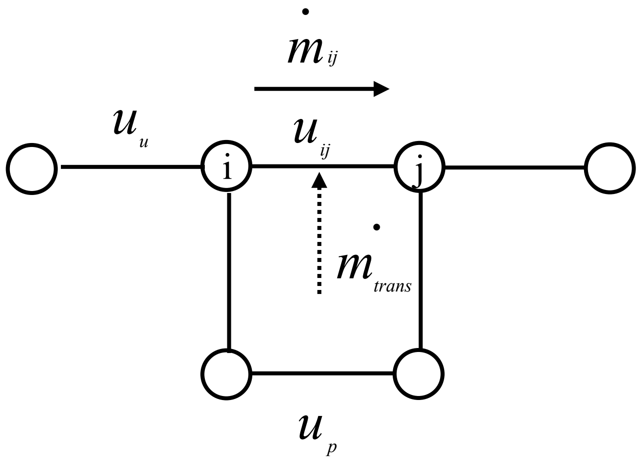
- Unsteady
- Longitudinal Inertia
- Transverse Inertia

- Pressure
- Gravity
- Friction
- Centrifugal
- Shear Stress
- Moving Boundary
- Normal Stress
- External Force



# MOMENTUM CONSERVATION EQUATION

*Mass x Acceleration Terms in GFSSP*




Unsteady

$$\frac{(mu_{ij})_{\tau+\Delta\tau} - (mu_{ij})_{\tau}}{g_c \Delta\tau}$$

Longitudinal Inertia

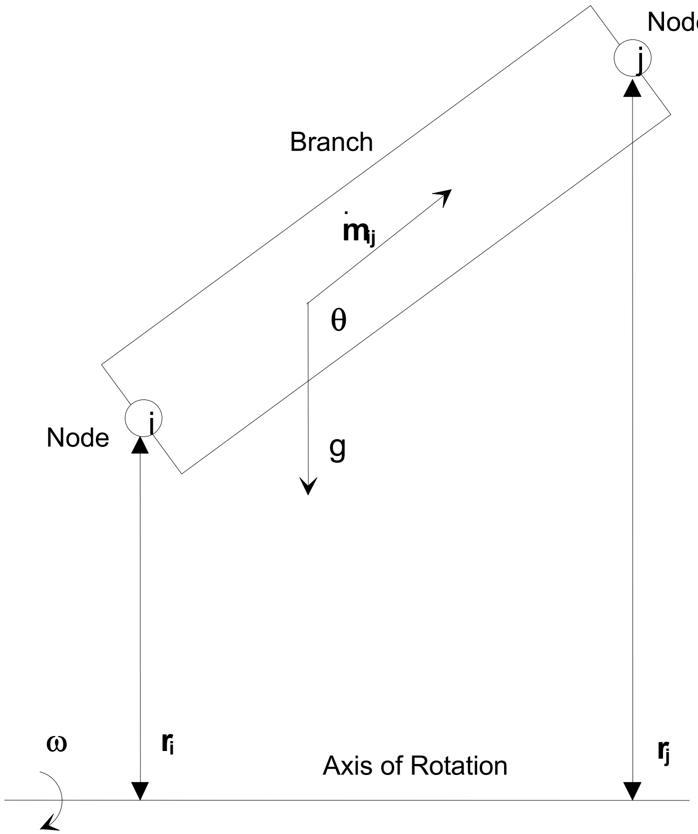
$$MAX\left|\dot{m}_{ij},0\right|(u_{ij}-u_u) - MAX\left|-\dot{m}_{ij},0\right|(u_{ij}-u_u)$$

Transverse Inertia

$$+MAX\left|\dot{m}_{trans},0\right|(u_{ij}-u_p) - MAX\left|-\dot{m}_{trans},0\right|(u_{ij}-u_p)$$

# MOMENTUM CONSERVATION EQUATION

*Force Terms in GFSSP*




Pressure

$$(p_i - p_j)A_{ij}$$

Gravity

$$\frac{\rho g V Cos\theta}{g_c}$$

Friction

$$-K_f \dot{m}_{ij} \left|\dot{m}_{ij}\right| A_{ij}$$

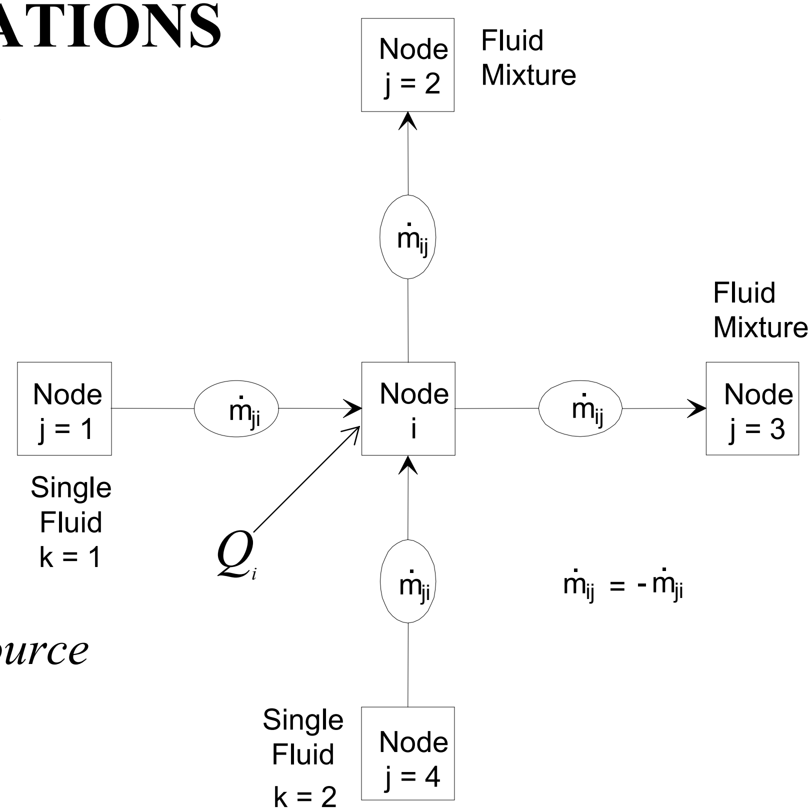
Centrifugal

$$\frac{\rho K_{rot}^2 \omega^2 A}{g_c}$$

# GOVERNING EQUATIONS

## ENERGY CONSERVATION EQUATION

- Energy Conservation Equation can be written in Enthalpy or Entropy
    - Based on Upwind Scheme




### Enthalpy Equation

*Rate of Increase of Internal Energy =*

*Enthalpy Inflow - Enthalpy Outflow + Heat Source*

$$\frac{m\left(h-\frac{p}{\rho J}\right)_{\tau+\Delta\tau}-m\left(h-\frac{p}{\rho J}\right)_{\tau}}{\Delta\tau}=\sum_{j=1}^{j=n}\left\{MAX\left[-\dot{m}_{ij},0\right]h_{j}-MAX\left[\dot{m}_{ij},0\right]h_{i}\right\}+Q_{i}$$

# GOVERNING EQUATIONS

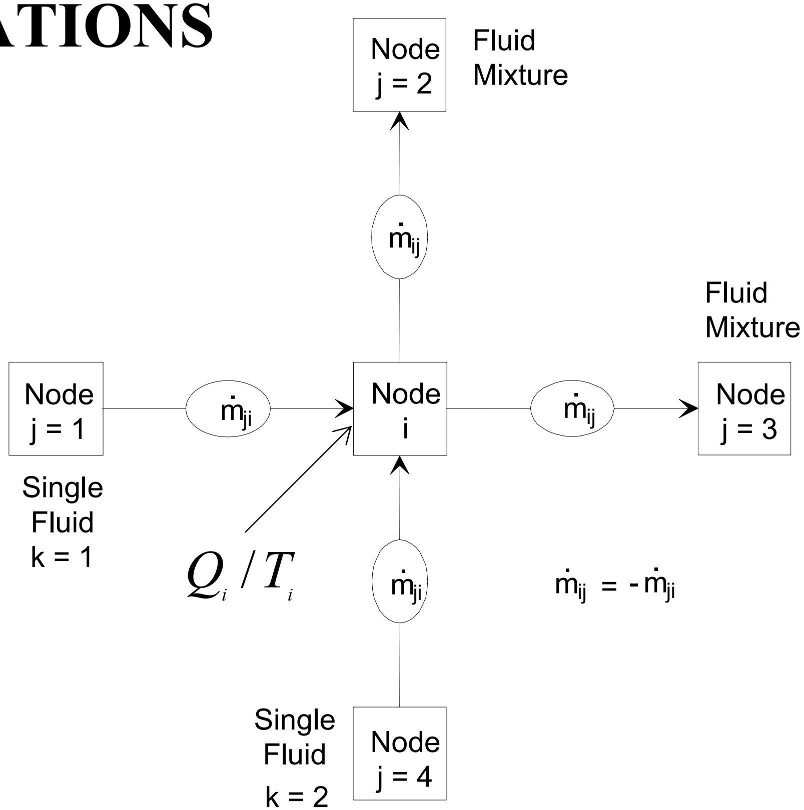
## ENERGY CONSERVATION EQUATION

### Entropy Equation

*Rate of Increase of Entropy =*

*Entropy Inflow - Entropy Outflow +*

*Entropy Generation + Entropy Source*




$$\frac{(ms)_{\tau+\Delta\tau} - (ms)_{\tau}}{\Delta\tau} = \sum_{j=1}^{j=n} \left\{ MAX\left[-\dot{m}_{ij}, 0\right] s_j - MAX\left[\dot{m}_{ij}, 0\right] s_i \right\} + \sum_{j=1}^{j=n} \left\{ \frac{MAX\left[-\dot{m}_{ij}, 0\right]}{\left|\dot{m}_{ij}\right|} \right\} \dot{S}_{ij,gen} + \frac{Q_i}{T_i}$$

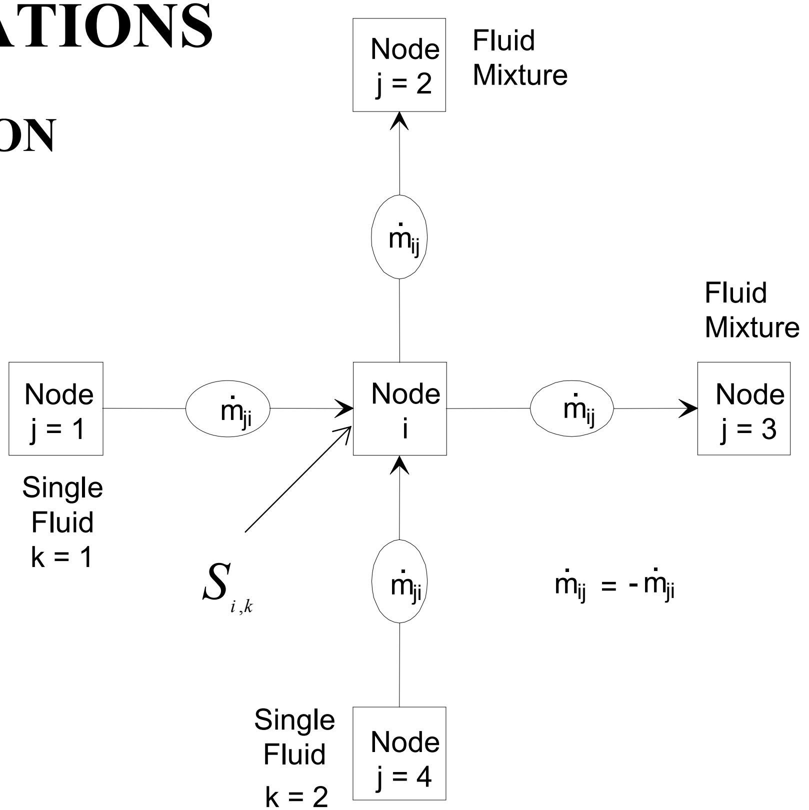
# GOVERNING EQUATIONS

## FLUID SPECIE CONSERVATION EQUATION

*Rate of Increase of Fluid Specie =*

*Fluid Specie Inflow - Fluid Specie Outflow +*

*Fluid Specie Source*




$$\frac{(m_i c_{i,k})_{\tau+\Delta\tau} - (m_i c_{i,k})_{\tau}}{\Delta\tau} = \sum_{j=1}^{j=n} \left\{ MAX\left[-\dot{m}_{ij}, 0\right] c_{j,k} - MAX\left[\dot{m}_{ij}, 0\right] c_{i,k} \right\} + \dot{S}_{i,k}$$

# GOVERNING EQUATIONS

## EQUATION OF STATE

For unsteady flow, resident mass in a control volume is calculated from the equation of state for a real fluid

$$m = \frac{pV}{RTz}$$

Z is the compressibility factor determined from higher order equation of state

# GOVERNING EQUATIONS

## EQUATION OF STATE

- GFSSP uses two separate Thermodynamic Property Packages GASP/WASP and GASPAK
- GASP/WASP uses modified Benedict, Webb & Rubin (BWR) Equation of State
- GASPAK uses "standard reference" equation from
  - National Institute of Standards and Technology (NIST)
  - International Union of Pure & Applied Chemistry (IUPAC)
  - National Standard Reference Data Service of the USSR

# GOVERNING EQUATIONS

## Mixture Property Relation

Density

- Calculated from Equation of State of Mixture with Compressibility Factor

$$\rho_i = \frac{p_i}{z_i R_i T_i}$$

$$R_i = \sum_{k=1}^{k=n} x_k R_k$$

- Compressibility Factor of Mixture is Mole average of Individual Components

$$z_i = \sum_{k=1}^{k=n} x_k z_k$$

$$z_k = \frac{p_i}{\rho_k R_k T_k}$$

# GOVERNING EQUATIONS

## Mixture Property Relation

Thermophysical Properties

• Viscosity, Specific Heat and Specific Heat Ratios are calculated by taking Molar Average

$$\mu_i = \sum_{k=1}^{k=n} x_k \mu_k \qquad \gamma_i = \sum_{k=1}^{k=n} x_k \gamma_k$$

$$C_{p,i} = \sum_{k=1}^{k=n} \frac{C_{p,k} x_k M_k}{x_k M_k}$$

# GOVERNING EQUATIONS

## Mixture Property Relation

Temperature

• Mixture Temperature is calculated from Energy Conservation Equation

$$\left(T_i\right)_{\tau+\Delta\tau} = \frac{\sum_{j=1}^{j=n}\sum_{k=1}^{k=nf} \mathrm{Cp}_k\, x_k T_j\, MAX\left[-\dot{m}_{ij},0\right] + \left(C_{p,i} m_i T_i\right)_\tau / \Delta\tau + Q_i}{\sum_{j=1}^{j=n}\sum_{k=1}^{k=nf} \mathrm{Cp}_k\, x_k\, MAX\left[\dot{m}_{ij},0\right] + \left(C_{p,i} m\right)_\tau / \Delta\tau}$$

Limitation

• Cannot handle phase change of mixture

# GOVERNING EQUATIONS
## Summary

- Familiarity with GFSSP's Governing Equations is not absolutely necessary to use the code
- However, working knowledge about Governing Equations is helpful to implement various options in a complex flow network
- A good understanding of Governing Equations is necessary to introduce new physics in the code

# SOLUTION PROCEDURE

- Successive Substitution
- Newton-Raphson
- Simultaneous Adjustment with Successive Substitution (SASS)
- Convergence

# SOLUTION PROCEDURE

- Non linear Algebraic Equations are solved by
  - Successive Substitution
  - Newton-Raphson
- GFSSP uses a Hybrid Method
  - SASS ( Simultaneous Adjustment with Successive Substitution)
  - This method is a combination of Successive Substitution and Newton-Raphson

# SOLUTION PROCEDURE

## SUCCESSIVE SUBSTITUTION METHOD

*STEPS:*

1. **Guess a solution for each variable in the system of equations**
2. **Express each equation such that each variable is expressed in terms of other variables: e. g. X = f (Y,Z) and Y = f (X,Z) etc**
3. **Solve for each variable**
4. **Under-relax the variable, if necessary**
5. **Repeat steps 1 through 4 until convergence**

*ADVANTAGES:*

**Simple to program; takes less computer memory**

*DISADVANTAGES:*

**It is difficult to make a decision in which order the equations must be solved to ensure convergence**

# SOLUTION PROCEDURE

## NEWTON-RAPHSON METHOD

*STEPS:*

1. **Guess a solution for each variable in the system of equations**
2. **Calculate the residuals of each equation**
3. **Develop a set of correction equations for all variables**
4. **Solve for the correction equations by Gaussian Elimination method**
5. **Apply correction to each variable**
6. **Iterate until the corrections become very small**

*ADVANTAGES:*

**No decision making process is involved to determine the order in which equations must be solved**

*DISADVANTAGES:*

**Requires more computer memory; difficult to program.**

# SOLUTION PROCEDURE

## SASS (Simultaneous Adjustment with Successive Substitution) Scheme

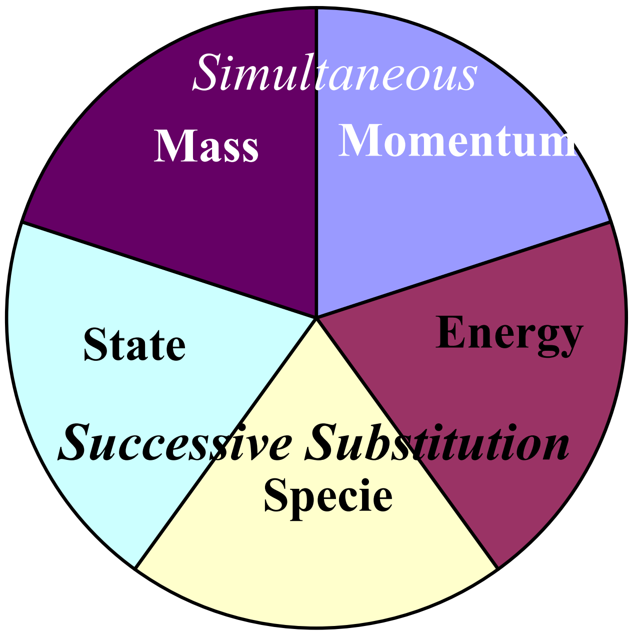
- SASS is a combination of successive substitution and Newton-Raphson method
- Mass conservation and flowrate equations are solved by Newton-Raphson method
- Energy Conservation and concentration equations are solved by successive substitution method
- Underlying principle for making such division:
  - Equations which have strong influences to other equations are solved by the Newton-Raphson method
  - Equations which have less influence to other are solved by the successive substitution method
- This practice reduces code overhead while maintains superior convergence characteristics

# GFSSP Solution Scheme

**SASS** : **S**imultaneous **A**djustment
with **S**uccessive **S**ubstitution

**Approach** : Solve simultaneously when equations are strongly coupled and non-linear

**Advantage** : Superior convergence characteristics with affordable computer memory



# CONVERGENCE

- Numerical solution can only be trusted when fully converged
- GFSSP's convergence criterion is based on difference in variable values between successive iterations. Normalized Residual Error is also monitored
- GFSSP's solution scheme has two options to control the iteration process
  – Simultaneous (SIMUL = TRUE)
  – Non-Simultaneous (SIMUL = FALSE)

# CONVERGENCE

## Simultaneous Option

- Single Iteration Loop
  - First solve mass, momentum and equation of state by the Newton-Raphson (NR) scheme
  - Next solve energy and specie conservation equation by Successive Substitution (SS) scheme
  - Solution is converged when the normalized maximum correction, $\Delta_{max}$ is less than the convergence criterion

$$\Delta_{\max} = MAX\left|\sum_{i=1}^{N_E} \frac{\Phi_i'}{\Phi_i}\right|$$

$N_E$ is the total number of equations solved by the Newton-Raphson scheme

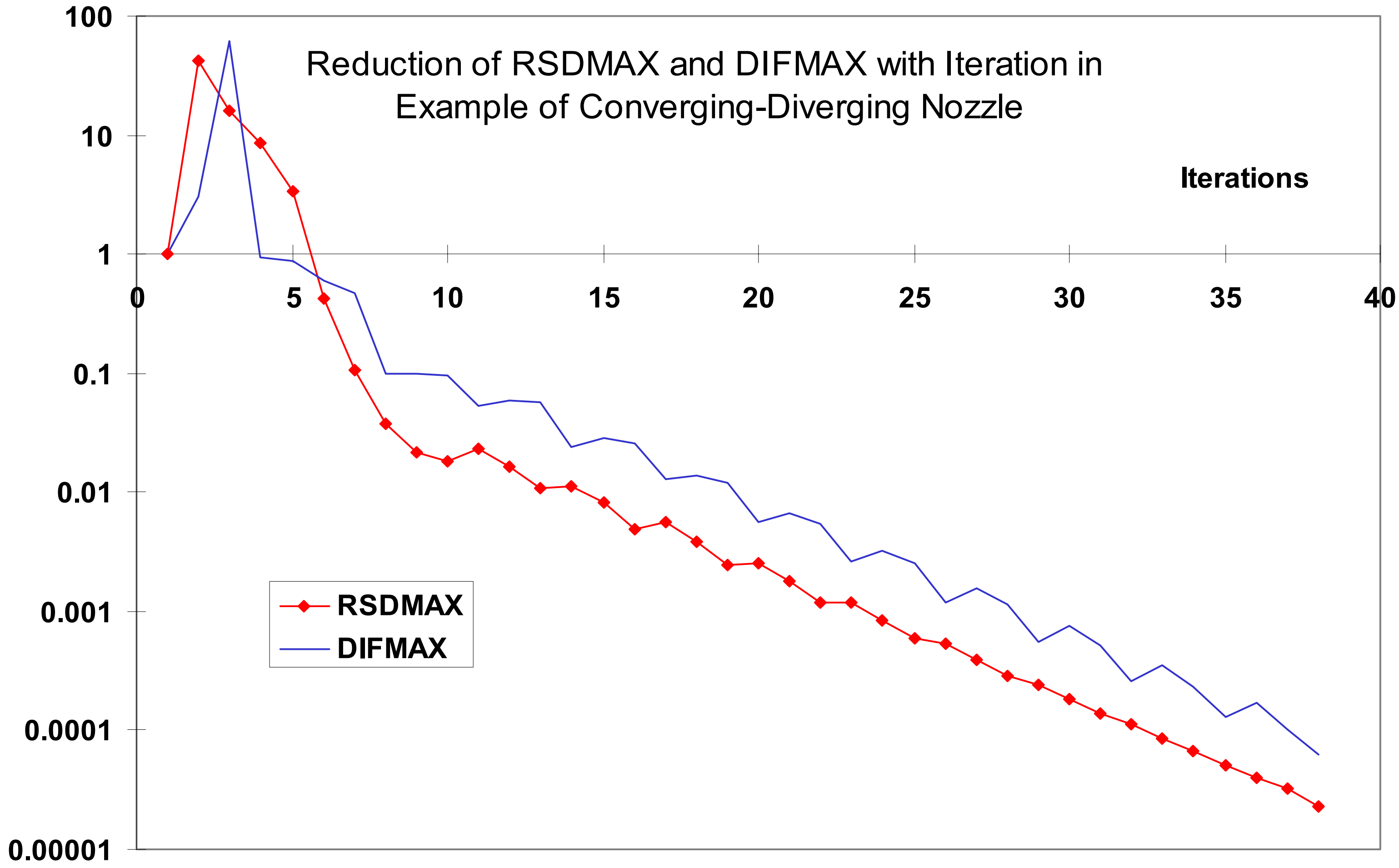
# CONVERGENCE

## Non-Simultaneous Option

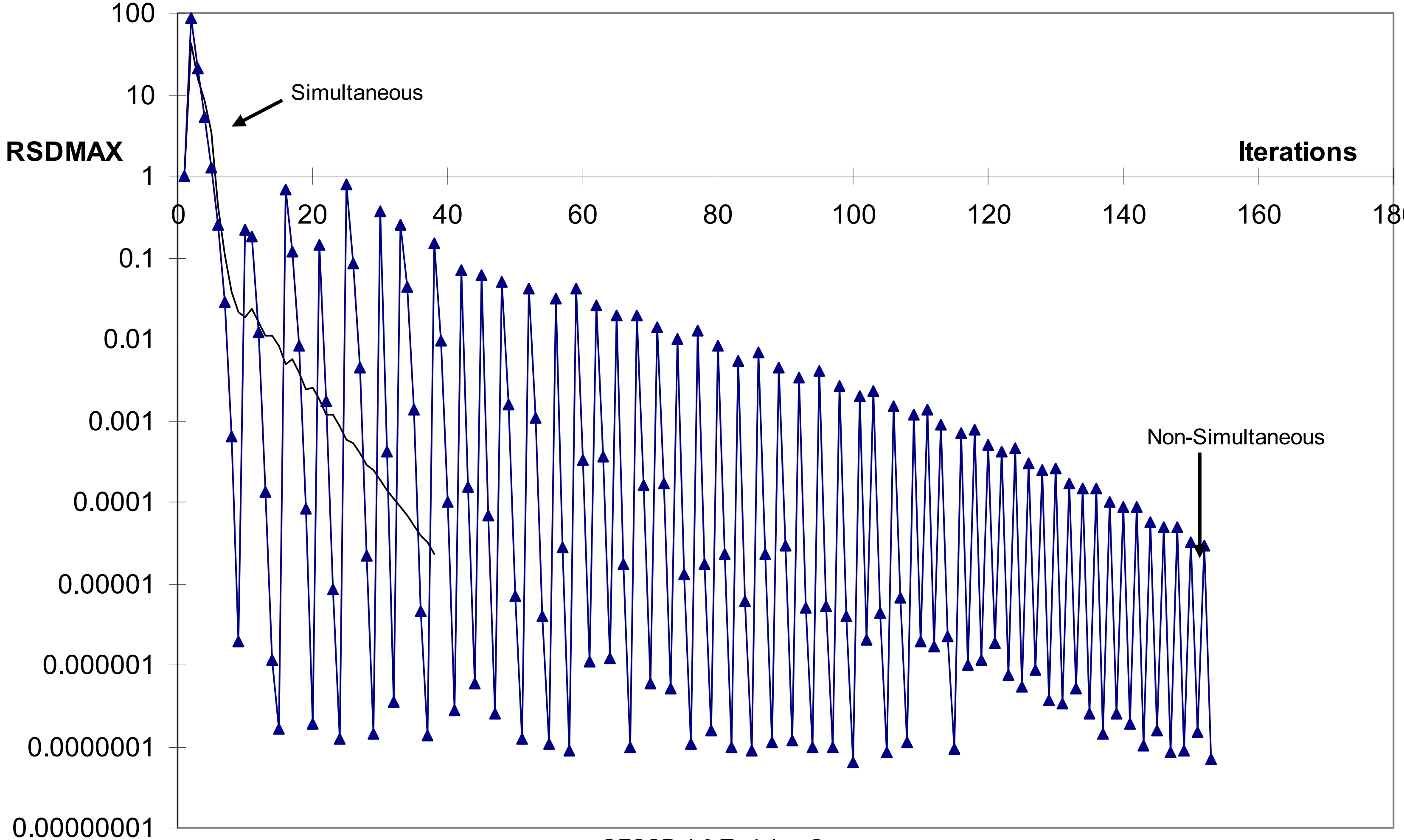
- Inner & Outer Iteration Loop
  - Mass, Momentum and Equation of state is solved in inner iteration loop by NR scheme
  - Energy and Specie conservation equations are solved in outer iteration loop by SS scheme
  - Convergence of NR scheme is determined by $\Delta_{max}$
  - Convergence of SS scheme is determined by $\Delta^{o}_{max}$

$$\Delta^{o}_{max} = MAX\left|\Delta_{K_f}, \Delta_{\rho}, \Delta_{h} \text{ or } \Delta_{s}\right| \qquad \Delta_{K_f} = MAX\left|\sum_{i=1}^{N_B} \frac{K'_f}{K_f}\right| \qquad \text{etc.}$$

# Convergence Characteristics For Simultaneous Option



Comparison of Convergence Characteristics between Simultaneous and Non-Simultaneous Option in Converging-Diverging Nozzle



# SOLUTION PROCEDURE
## Summary

- Simultaneous option is more efficient than Non-Simultaneous option
- Non-Simultaneous option is recommended when Simultaneous option experiences numerical instability
- Under-relaxation and good initial guess also help to overcome convergence problem
- A lack of realism in problem specification can lead to convergence problem
- Lack of realism includes:
  - Unrealistic geometry and/or boundary conditions
  - Attempt to calculate properties beyond operating range

# USER SUBROUTINES

| **Solver Module**/function | **User Subroutine**/function |
|---|---|
| **MAIN** Controls program | **FILENUM** Defines input and output files numbers within the code |
| | **TSTEP** Allows user to overwrite the input deck defined time step |
| **READIN** Reads input data file | **USRSET** Allows user to redefine input file to custom format |
| **INIT** Provides initial value and steady state boundary conditions | **USRINT** Allows user to overwrite initial values and steady state boundary conditions |
| **BOUND** Provides time-dependant boundary conditions from history file | **BNDUSER** Allows user to define time-dependant boundary conditions |
| **EQNS** Generates mass & momentum conservation equations along with equation of resident mass | **SORCEM** Allows user to provide an external mass source |
| | **SORCEF** Allows user to provide an external momentum source |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# CONTENT

- Motivation and Benefit
- How they work

# MOTIVATION AND BENEFIT

- Motivation: To allow users to access GFSSP solver module to develop additional modeling capability

- Benefit: GFSSP users can work independently without Developer's active involvement

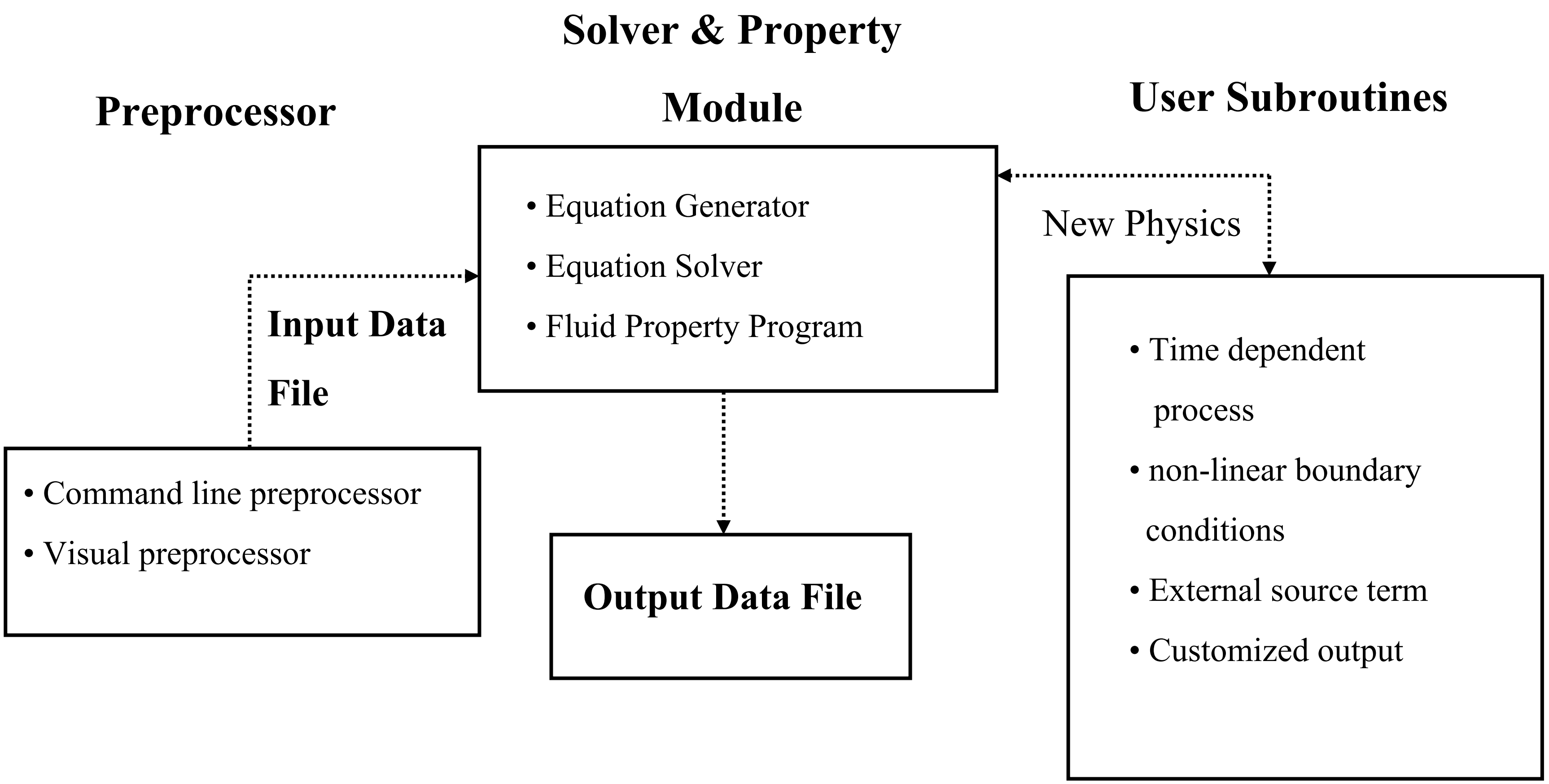
# How do they work?

- A series of subroutines are called from various locations of solver module
- The subroutines do not have any code but includes the common block
- The users can write FORTRAN code to develop any new physical model in any particular node or branch

# What users need to do?

- Users need to compile a new file containing all user routines and link that with GFSSP to create a new executable

# GFSSP PROCESS FLOW DIAGRAM



# DESCRIPTION OF USER SUBROUTINES

Twelve User Subroutines were provided:

- SORCEM: External Mass Source
- SORCEF: External Force
- SORCEQ: External Heat source
- SORCEC: External Concentration source
- KFUSER: New resistance option
- PRPUSER: New fluid property
- TSTEP: Variable time step during a transient run

# DESCRIPTION OF USER SUBROUTINES

– BNDUSER: Variable boundary condition during transient run (Alternative to history file)

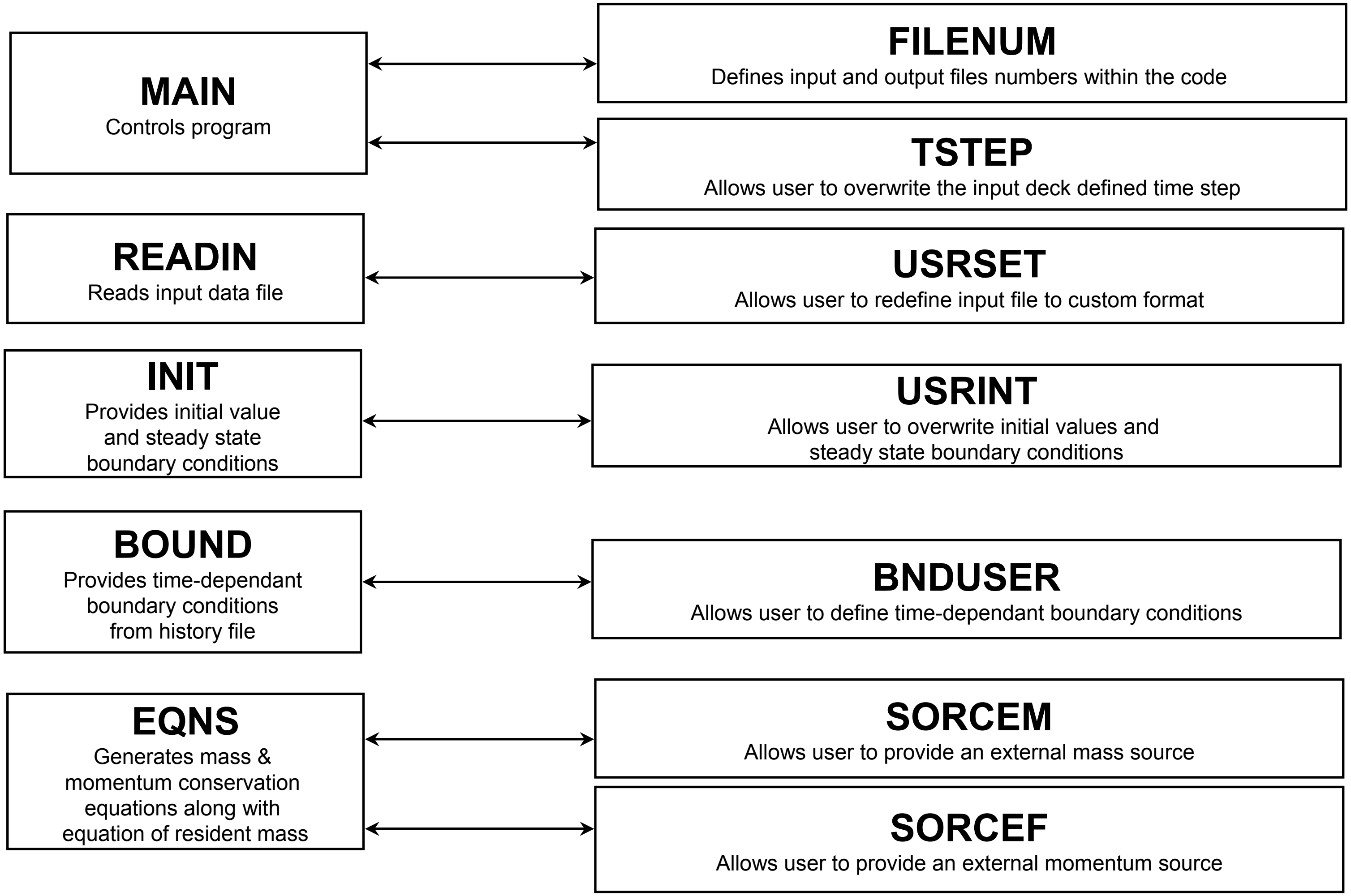
– USRINT: Provide initial values and steady state boundary conditions

– PRNUSER: Additional print out or creation of additional file for post processing

– FILNUM: Assign file numbers; users can define new file numbers

– USRSET: User can supply all the necessary information by writing their own code

**Solver Module/**function | **User Subroutine/**function



| **Solver Module/**function | **User Subroutine/**function |
| --- | --- |
| **ENTHALPY/ ENTROPY**<br>Generates and solves the energy conservation equation | **SORCEQ**<br>Allows user to provide an external heat source |
| **MASSC**<br>Generates and solves the specie conservation equation | **SORCEC**<br>Allows user to provide an external specie source |
| **RESIST**<br>Calculates the flow resistance coefficient | **KFUSER**<br>Allows user to define new resistance options |
| **DENSITY**<br>Calculates the fluid properties | **PRPUSER**<br>Allows user to define new fluid properties |
| **PRINT**<br>Generates the Output files | **PRNUSER**<br>Allows user to provide any additional output file(s) |

# GFSSP INDEXING SYSTEM

- Node and Branch Variables are stored in one-dimensional array
- Node variables include:
  - Name
  - Pressure, Temperature, Concentration, Thermodynamic properties
- Branch variables include:
  - Name
  - Flowrate, Velocity, Resistance coefficients, Reynolds number
- Three subroutines are made available to Users for finding location and indices for a given node or branch

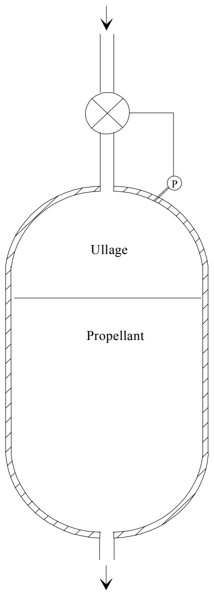
# NODE & BRANCH INDEX

- User defined node names are stored in NODE-array.
- NODE-array includes both internal and boundary nodes.
- Total number of elements in NODE-array is NNODES
- The internal nodes are stored in INODE-array.
- There are NINT elements in INODE-array.
- Branch names are stored in IBRANCH-array
- There are NBR elements in IBRANCH-array

# SUMMARY

- User Subroutines can be used to add new capabilities that are not available to Users through Logical Options
- New capabilities may include:
  - Introducing new type of resistance
  - Incorporating heat or mass transfer in any given node
  - Variable time step for a transient problem
  - Customized output
- Checklist for User Subroutines
  - Identify subroutines that require modifications
  - Select GFSSP variables that require to be modified
  - Make use of GFSSP provided User variables in your coding

# TANK PRESSURIZATION





Todd Steadman

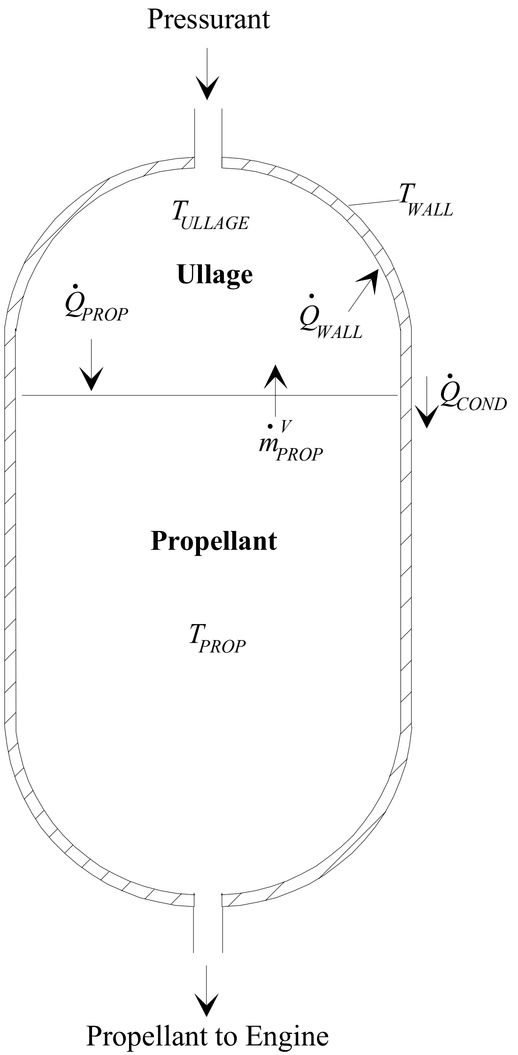
Sverdrup Technology

Marshall Space Flight Center

# TANK PRESSURIZATION

- Predict the ullage conditions considering heat and mass transfer between the propellant and the tank wall

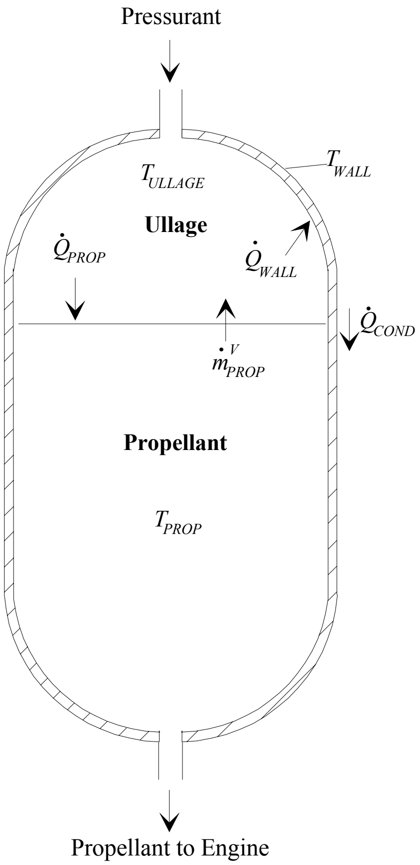
- Predict the propellant conditions leaving the tank



# TANK PRESSURIZATION

## ADDITIONAL PHYSICAL PROCESSES

- Change in ullage and propellant volume.
- Change in gravitational head in the tank.
- Heat transfer from pressurant to propellant.
- Heat transfer from pressurant to the tank wall.
- Heat conduction between the pressurant exposed tank surface and the propellant exposed tank surface.
- Mass transfer between the pressurant and propellant.

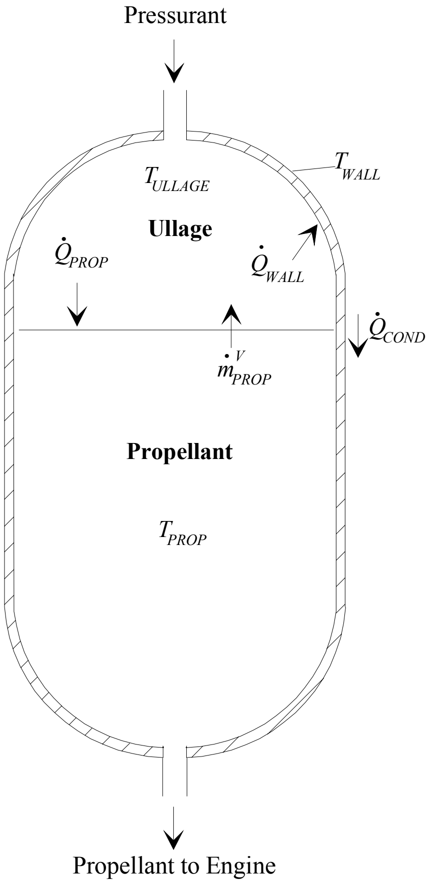


# TANK PRESSURIZATION

## CALCULATION STEPS

For each time step calculate

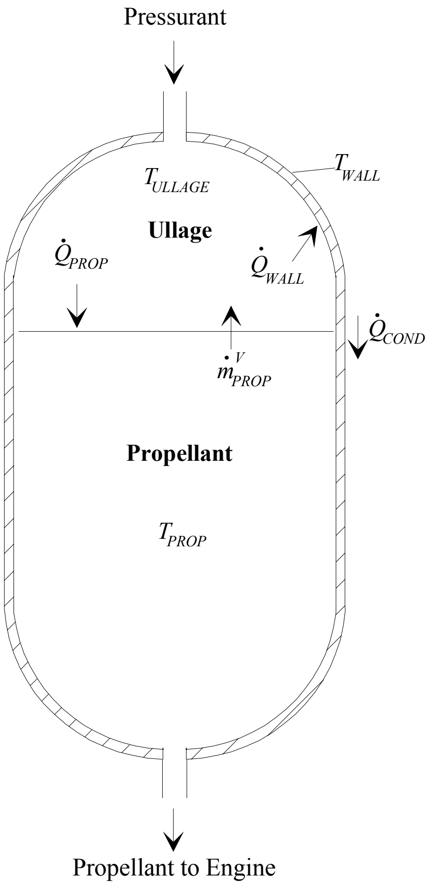
- Ullage and Propellant Volumes
- Tank Bottom Pressure
- Heat Transfer between pressurant and propellant and pressurant and wall
- Wall Temperature
- Mass Transfer from propellant to ullage



# TANK PRESSURIZATION

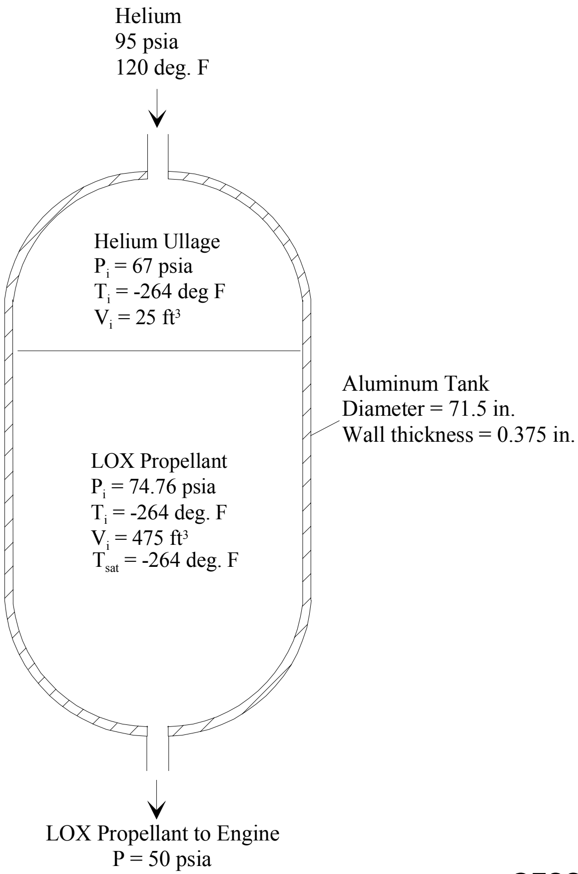
## ADDITIONAL INPUT DATA FOR PRESSURIZATION

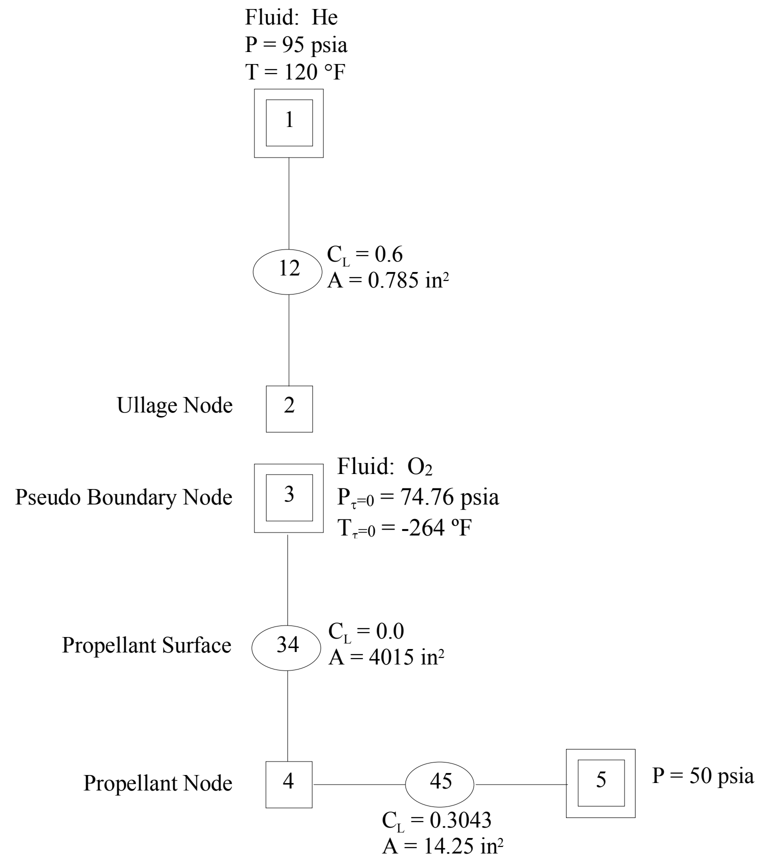
| | |
|---|---|
| PRESS | Logical Variable to Activate the Option |
| NTANK | Number of Tanks in the Circuit |
| NODUL | Ullage Node |
| NODULB | Pseudo Boundary Node at interface |
| NODPRP | Propellant Node |
| IBRPRP | Branch number connecting NODULB & NODPRP |
| TNKAR | Tank Surface Area in Ullage at Start, $in^2$ |
| TNKTH | Tank Thickness, in |
| TNKRHO | Tank Density, $lbm/ft^3$ |
| TNKCP | Tank Specific Heat, Btu/lbm - R |
| TNKCON | Tank Thermal Conductivity, Btu/ft-sec-R |
| ARHC | Propellant Surface Area, $in^2$ |
| FCTHC | Multiplying Factor in Heat Transfer Coefficient |
| TNKTM | Initial Tank Temperature, $^{o}$ F |



# TANK PRESSURIZATION

## EXAMPLE 10 TANK SCHEMATIC AND GFSSP MODEL



# TANK PRESSURIZATION

## EXAMPLE 10 PRESSURIZATION INPUT

```
 NODE   PRES (PSI)   TEMP(DEGF)    MASS SOURC    HEAT SOURC   THRST AREA   VOLUME       CONCENTRATION
     2  0.6700E+02 -0.2640E+03  0.0000E+00  0.0000E+00  0.0000E+00  0.4320E+05 1.0000 0.0000
     4  0.7476E+02 -0.2640E+03  0.0000E+00  0.0000E+00  0.0000E+00  0.8208E+06 0.0000 1.0000
ex10h1.dat
ex10h3.dat
ex10h5.dat
                                          .
                                          .
                                          .
NUMBER OF TANKS IN THE CIRCUIT
     1
NODUL NODULB NODPRP IBRPRP TNKAR TNKTH TNKRHOTNKCP TNKCON ARHC FCTHC TNKTM
     2     3     4     34 6431.91  0.375 170.00  0.20 0.0362 4015.00  1.00 -264.00
 NODE DATA FILE
FNODE.DAT
 BRANCH DATA FILE
FBRANCH.DAT
```

**Tank Input Units**

VOLUME, $in^3$
TNKAR, $in^2$
TNKTH, in
TNKRHO, $lbm/ft^3$
TNKCP, Btu/lbm-R
TNKCON, Btu/ft-s-R
ARHC, $in^2$
TNKTM, deg. F

# TANK PRESSURIZATION

## EXAMPLE 10 PRESSURIZATION OUTPUT

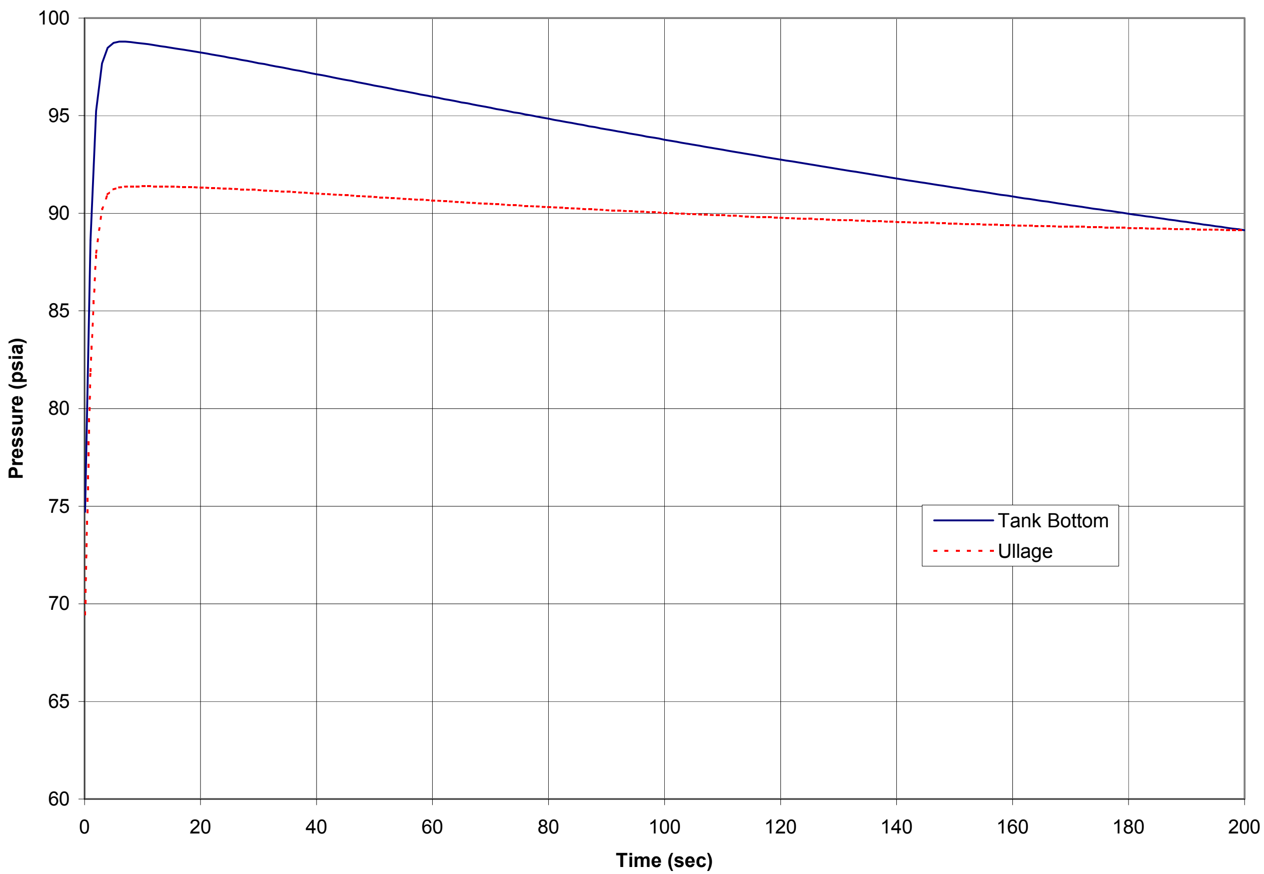
```
SOLUTION
INTERNAL NODES
    NODE      P(PSI)        TF(F)           Z            RHO          EM(LBM)     CONC
                                                     (LBM/FT^3)
                                                                                    HE          O2
     2     0.9138E+02  -0.1347E+03   0.1006E+01   0.1047E+00   0.5144E+01   0.9690E+00   0.0310
     4     0.9869E+02  -0.2640E+03   0.2310E-01   0.6514E+02   0.2937E+05   0.0000E+00   1.0000

BRANCHES
BRANCH   KFACTOR           DELP     FLOW RATE     VELOCITY     REYN. NO.    MACH NO.  ENTROPY GEN.  LOST WORK
 (LBF-S^2/(LBM-FT)^2)  (PSI)    (LBM/SEC)    (FT/SEC)                                BTU/(R-SEC)   LBF-FT/SEC
12      0.238E+05      0.362E+01    0.148E+00   0.445E+03   0.156E+06   0.129E+00   0.281E-02   0.127E+04
34      0.000E+00      0.000E+00    0.163E+03   0.899E-01   0.412E+06   0.114E-03   0.000E+00   0.000E+00
45      0.263E+00      0.487E+02    0.163E+03   0.253E+02   0.690E+07   0.323E-01   0.115E+00   0.176E+05

   NUMBER OF PRESSURIZATION SYSTEMS =   1
  NODUL   NODPRP   QULPRP    QULWAL      QCOND    TNKTM      VOLPROP    VOLULG
     2       4     1.9642     8.5069     0.0022   196.4447   450.8641   49.1359

  SOLUTION SATISFIED CONVERGENCE CRITERION OF    0.100E-02 IN   5 ITERATIONS
TAU =       10.0000     ISTEP =           100
```

**Tank Output Units**

QULPROP, Btu/s
QULWAL, Btu/s
QCOND, Btu/s
TNKTM, deg. R
VOLPROP, $ft^3$
VOLULG, $ft^3$

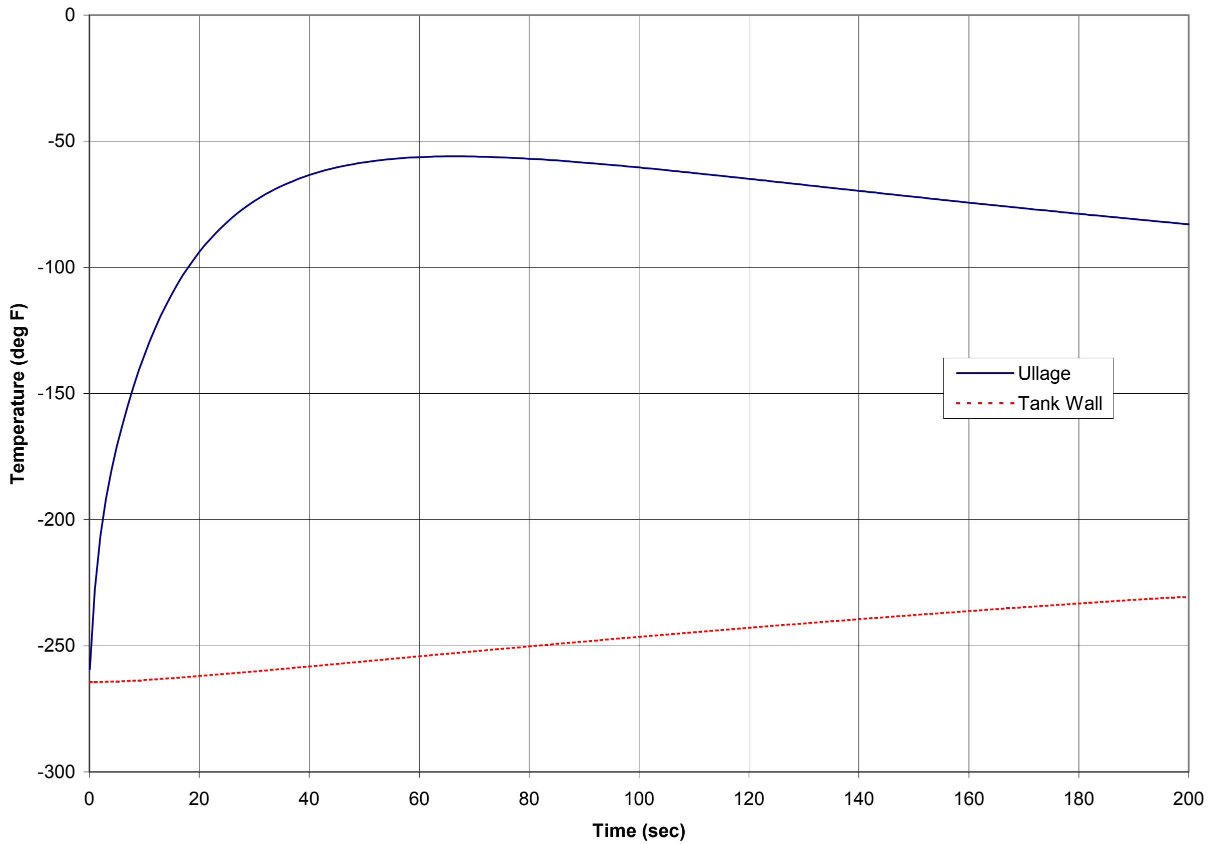
# TANK PRESSURIZATION

## EXAMPLE 10 ULLAGE AND TANK BOTTOM PRESSURE HISTORY



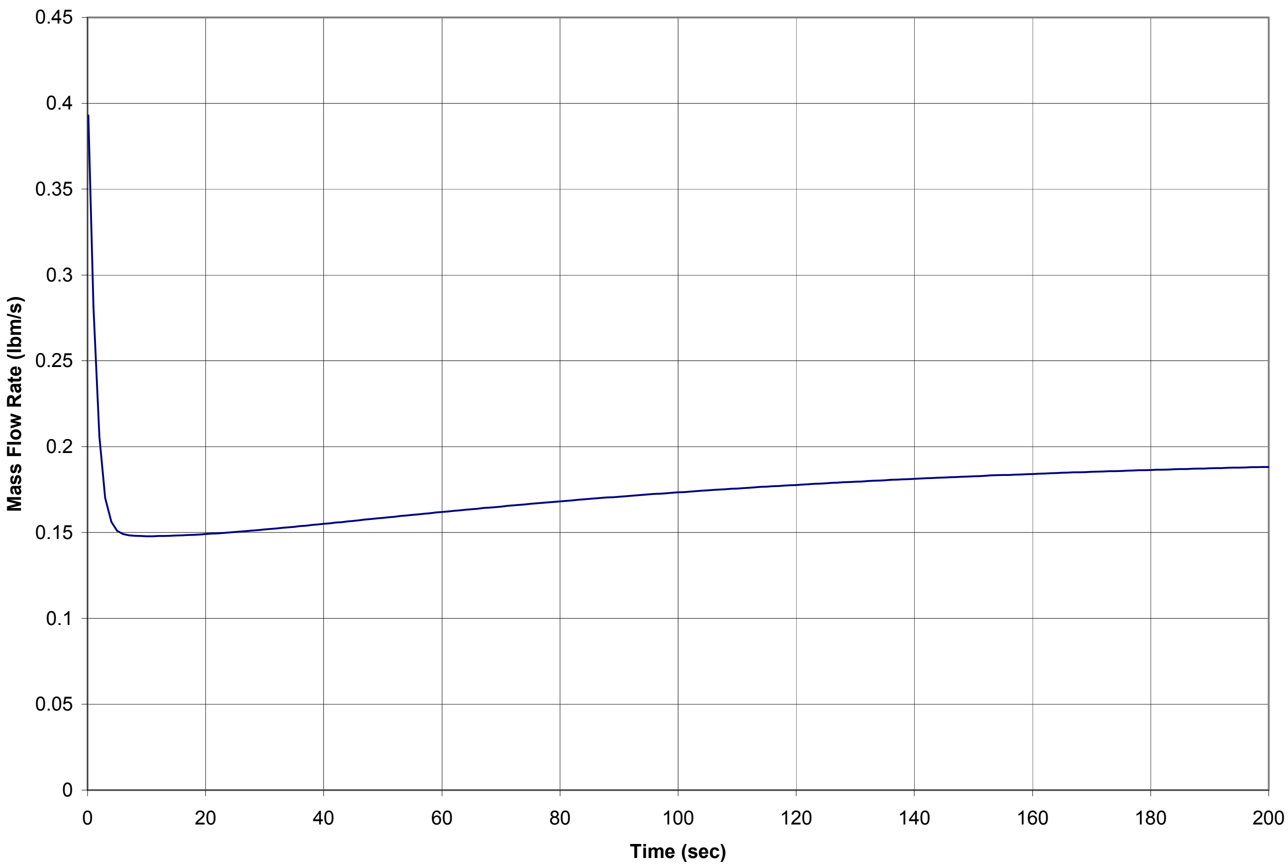
# TANK PRESSURIZATION

## EXAMPLE 10 ULLAGE AND TANK WALL TEMPERATURE HISTORY

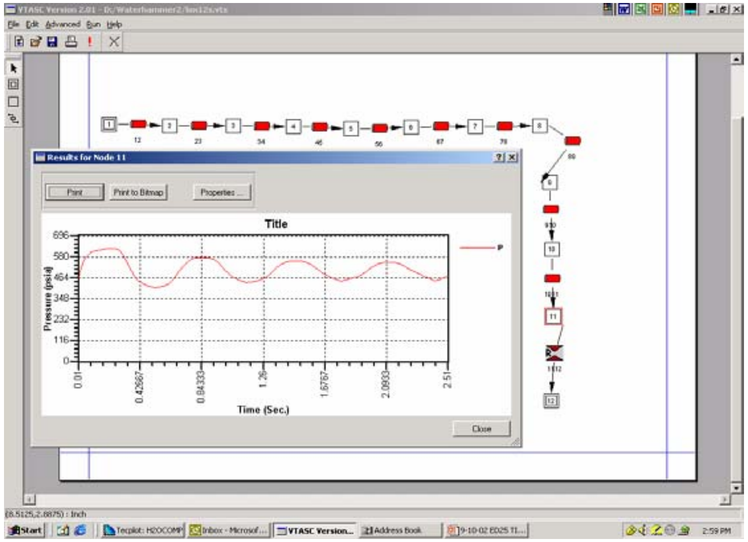


# TANK PRESSURIZATION

## EXAMPLE 10 HELIUM FLOW RATE HISTORY



# FLUID TRANSIENT





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# CONTENT

- Classification of Unsteady Flow
- Causes of Transient
- Valve Closing
  - Comparison with Method of Characteristics
- Valve Opening
- Conclusions

# CLASSIFICATION OF UNSTEADY FLOW

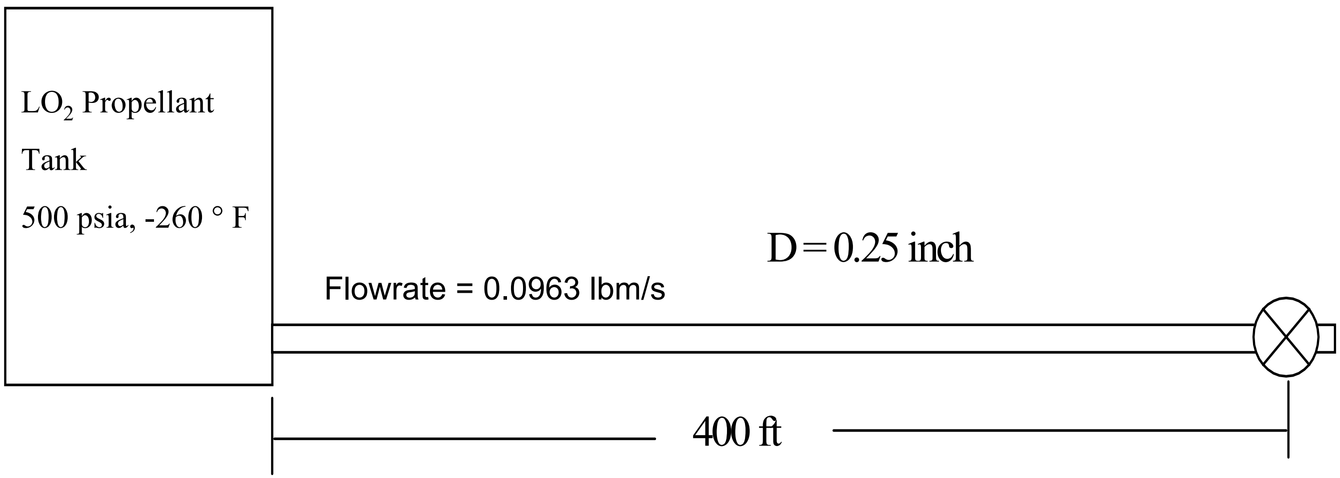
- Quasi-steady flow is a type of unsteady flow when flow changes from one steady-state situation to another steady-state situation
  - Time dependant terms in conservation equation is not activated
  - Solution is time dependant because boundary condition is time dependant
- Unsteady flow formulation has time dependant terms in all conservation equations
  - Time dependant term is a function of density, volume and variables at previous time step

# CAUSES OF TRANSIENT

- Changes in valve settings, accidental or planned
- Starting or stopping of pumps
- Changes in power demand of turbines
- Action of reciprocating pumps
- Changing elevation of reservoir
- Waves in reservoir
- Vibration of impellers or guide vanes in pumps or turbines
- Unstable pump characteristics
- Condensation

# PROBLEM DESCRIPTION

## Rapid valve closing




**Valve Closure History**

| Time (sec) | Area (in$^2$) |
|---|---|
| 0.00 | 0.0491 |
| 0.02 | 0.0164 |
| 0.04 | 0.0055 |
| 0.06 | 0.0018 |
| 0.08 | 0.0006 |
| 0.10 | 0.00 |

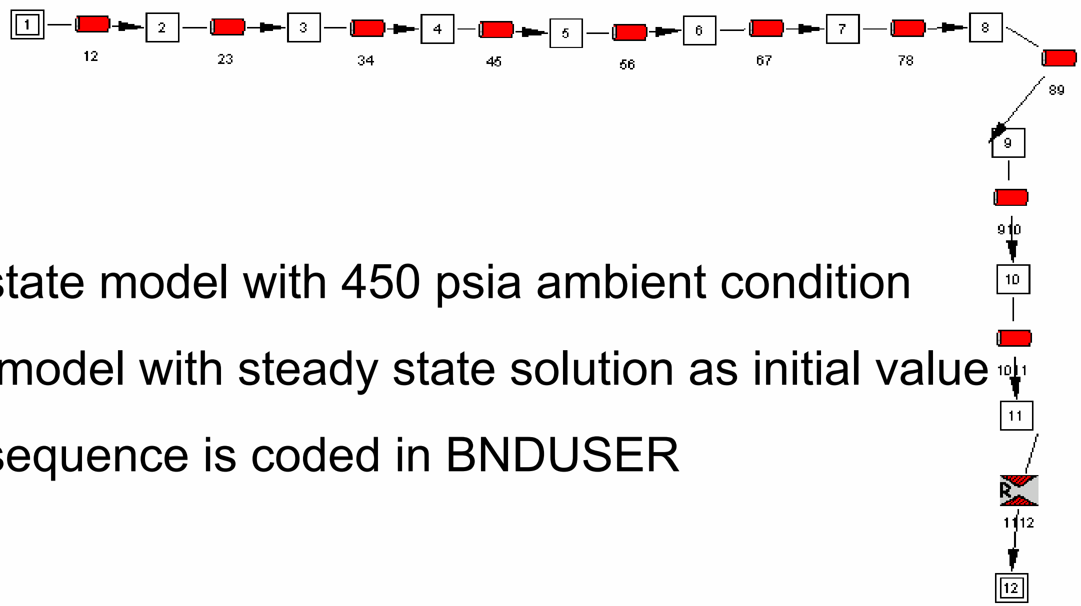
### Objectives of Analysis:

- **Maximum Pressure**
- **Frequency of Oscillation**

# GFSSP Model

LO$_2$ Propellant Tank

500 psia, -260 ° F




- Run a steady state model with 450 psia ambient condition
- Run unsteady model with steady state solution as initial value
- Valve closing sequence is coded in BNDUSER

# Description of Test cases

$P_{tank}$ = 500 psia

$T_{tank}$ = -260 ° F (Oxygen) = 70 ° F (Water) = -414 ° F (Hydrogen)

| Case No. | Fluid | Number of Branches | Time Step (sec) | Sound Speed (ft/sec) | Flowrate (lb/sec) | $p_{max}$ (psia) | Period of Oscillation (sec) |
|---|---|---|---|---|---|---|---|
| 1 | $LO_2$ | 10 | 0.01 | 2462 | 0.0963 | 626 | 0.65 |
| 2 | $LO_2$ | 20 | 0.005 | 2462 | 0.0963 | 632 | 0.65 |
| 3 | $LO_2$ | 5 | 0.02 | 2462 | 0.0966 | 620 | 0.65 |
| 4 | $H_2O$ | 10 | 0.005 | 4874 | 0.071 | 704 | 0.33 |
| 5 | $LH_2$ | 10 | 0.02 | 3577 | 0.0278 | 545 | 0.43 |
| 6 | $LO_2$ & GHe (0.1%) | 10 | 0.01 | 1290** | 0.0963 | 580 | 1.24 |
| 7 | $LO_2$ & GHe (0.5%) | 10 | 0.01 | 769** | 0.0963 | 520 | 2.08 |
| 8* | $LO_2$ (2 Phase) $x_{exit}$ = 0.017 | 10 | 0.01 | ----- | 0.0963 | 550 | 1.17 |
| 9* | $LO_2$ (2 Phase) $x_{exit}$ = 0.032 | 10 | 0.01 | ------ | 0.0963 | 538 | 1.22 |
| 10 | $LO_2$ | | 0.01 | 2462 | 0.0963 | 611 | 0.65 |

* Pressure oscillations are due to condensation

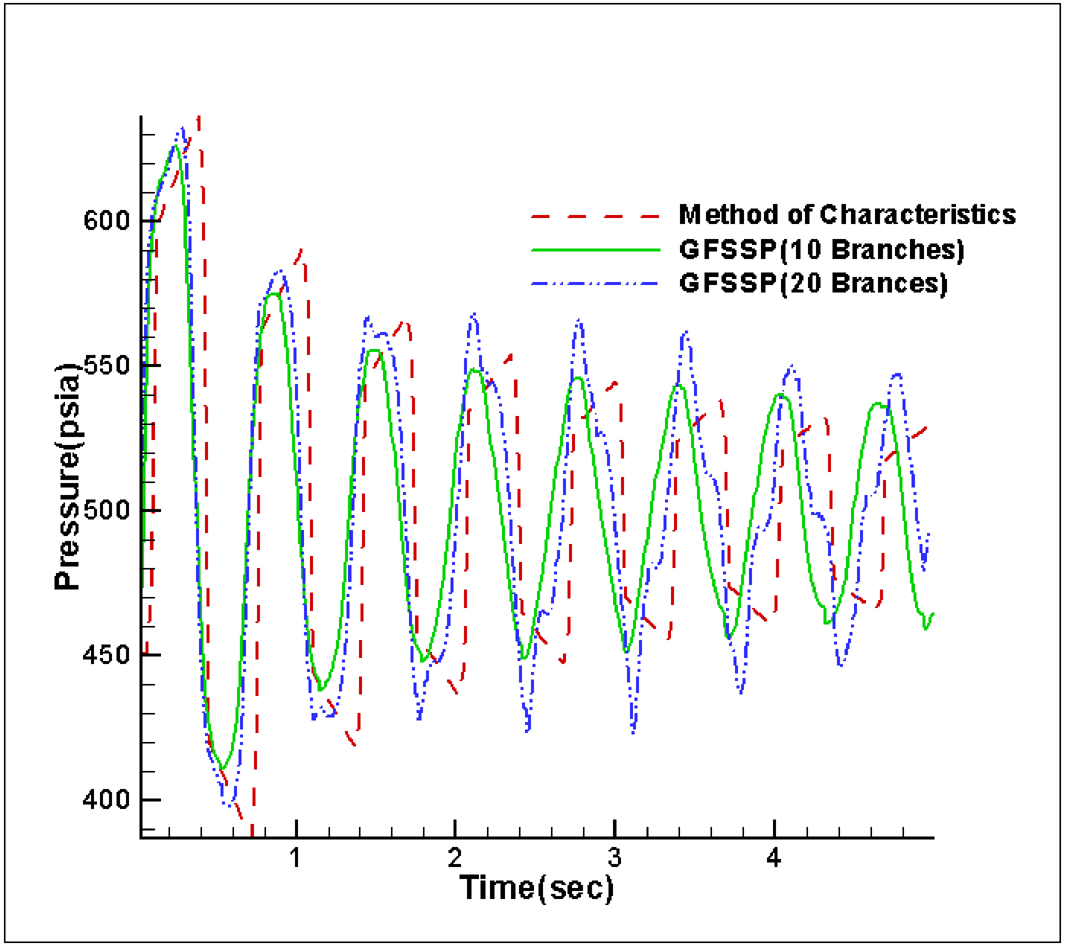
** Estimated from period of oscillation [a=4L/λ]

- Time step for each test case is so chosen that Courant number is less than unity
- Courant Number = Length of Branch/(Sound Speed X Time Step)

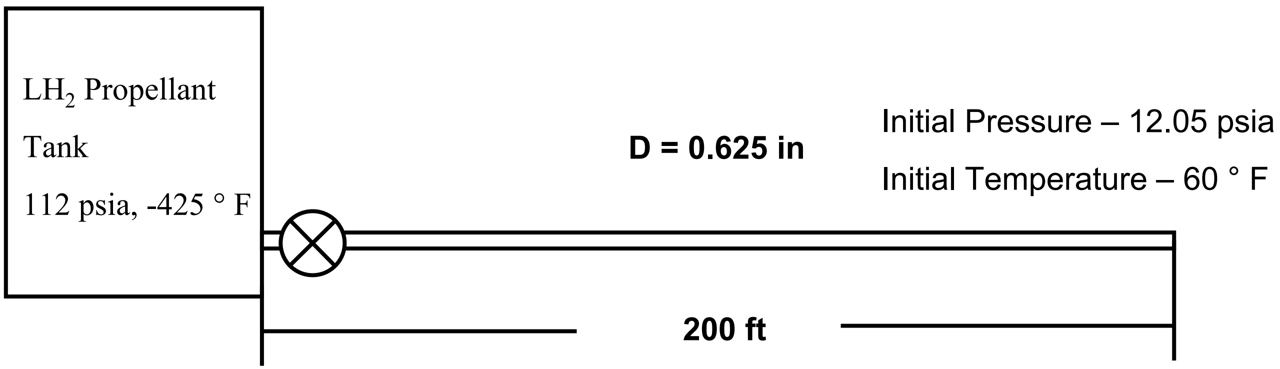
# COMPARISON BETWEEN GFSSP & MOC SOLUTION FOR THREE FLUIDS

| Fluid | Flowrate (lb/s) | Velocity (ft/s) | Friction Factor (Used in MOC solution) | Sound Speed (ft/s) | Max. Pressure rise above supply pressure (psi) | | Period of Oscillation (sec) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | MOC | GFSSP | MOC | GFSSP |
| Water | 0.071 | 3.34 | 0.0347 | 4892 | 214 | 204 | 0.33 | 0.33 |
| Oxygen | 0.0963 | 4.35 | 0.0196 | 2455 | 136 | 126 | 0.65 | 0.65 |
| Hydrogen | 0.0278 | 19.01 | 0.0157 | 3725 | 61 | 45 | 0.43 | 0.43 |

# COMPARISON BETWEEN GFSSP & MOC SOLUTION



# PROBLEM DESCRIPTION
## Rapid Valve Opening




| Time (sec) | Area ($in^2$) |
|---|---|
| 0.00 | 0.0 |
| 0.01 | 0.0088 |
| 0.02 | 0.1767 |
| 0.03 | 0.2651 |
| 0.04 | 0.3534 |
| 0.05 | 0.4418 |

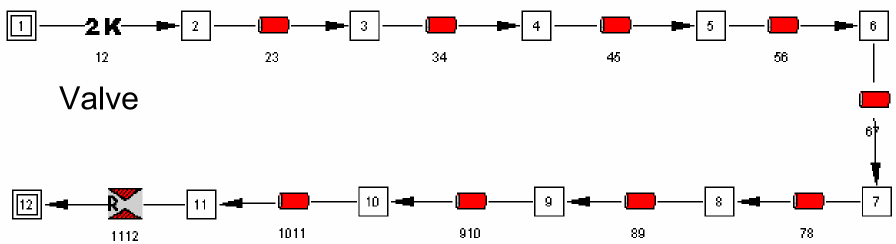
**Objectives of Analysis:**

- **Maximum Pressure**
- **Time to reach steady-state**

# GFSSP Model

LH$_2$ Propellant Tank

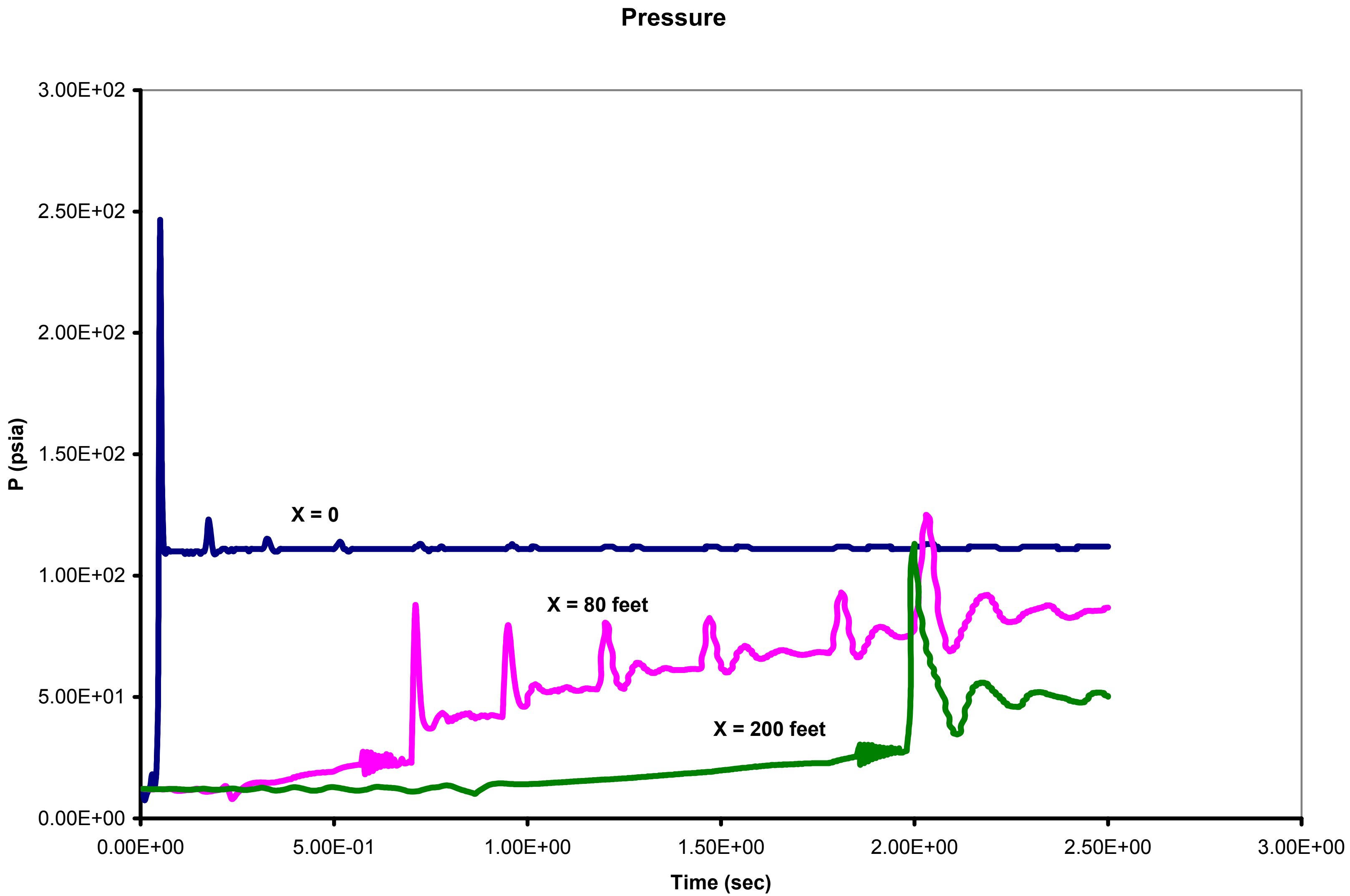
112 psia, -425 ° F



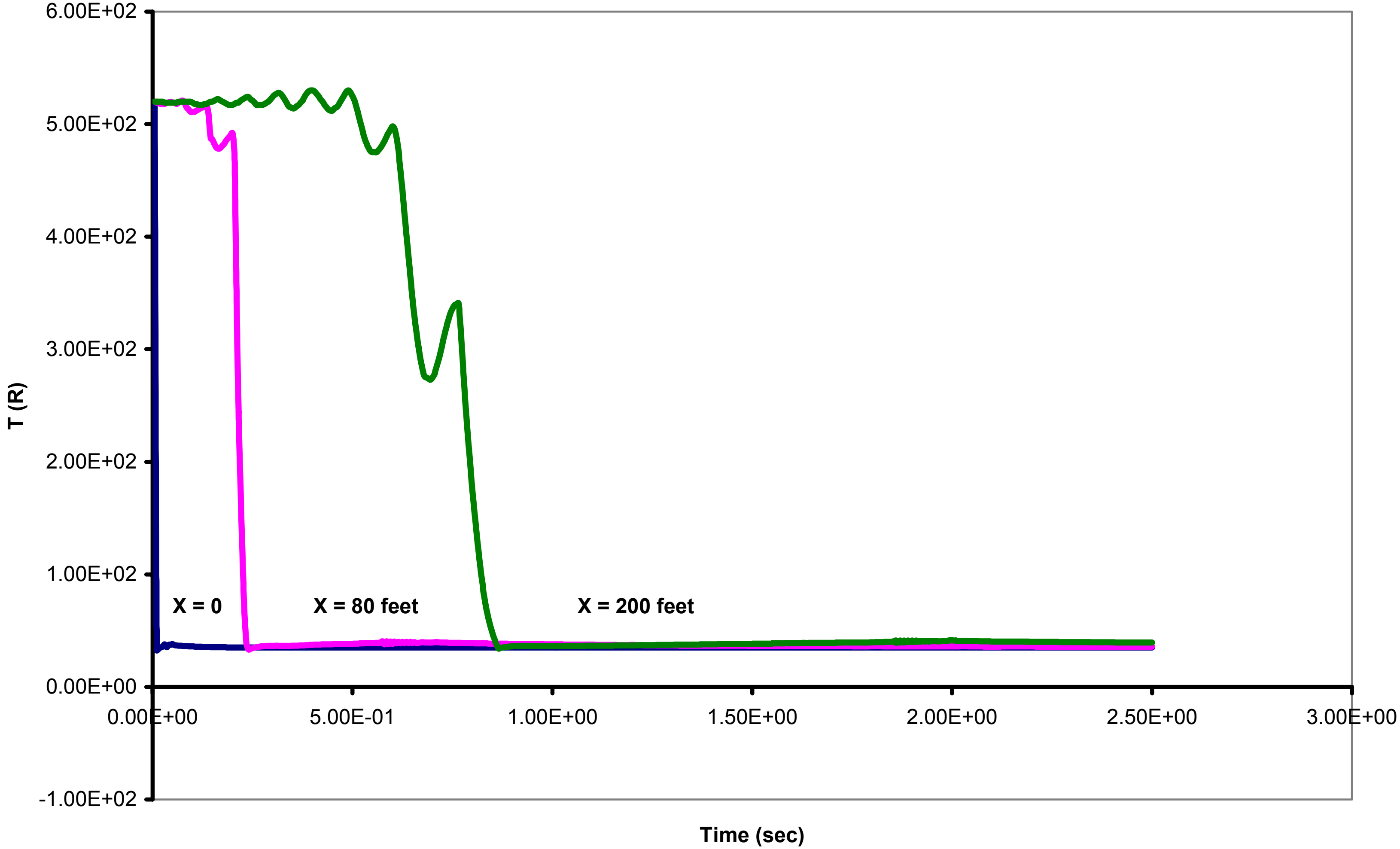

Valve

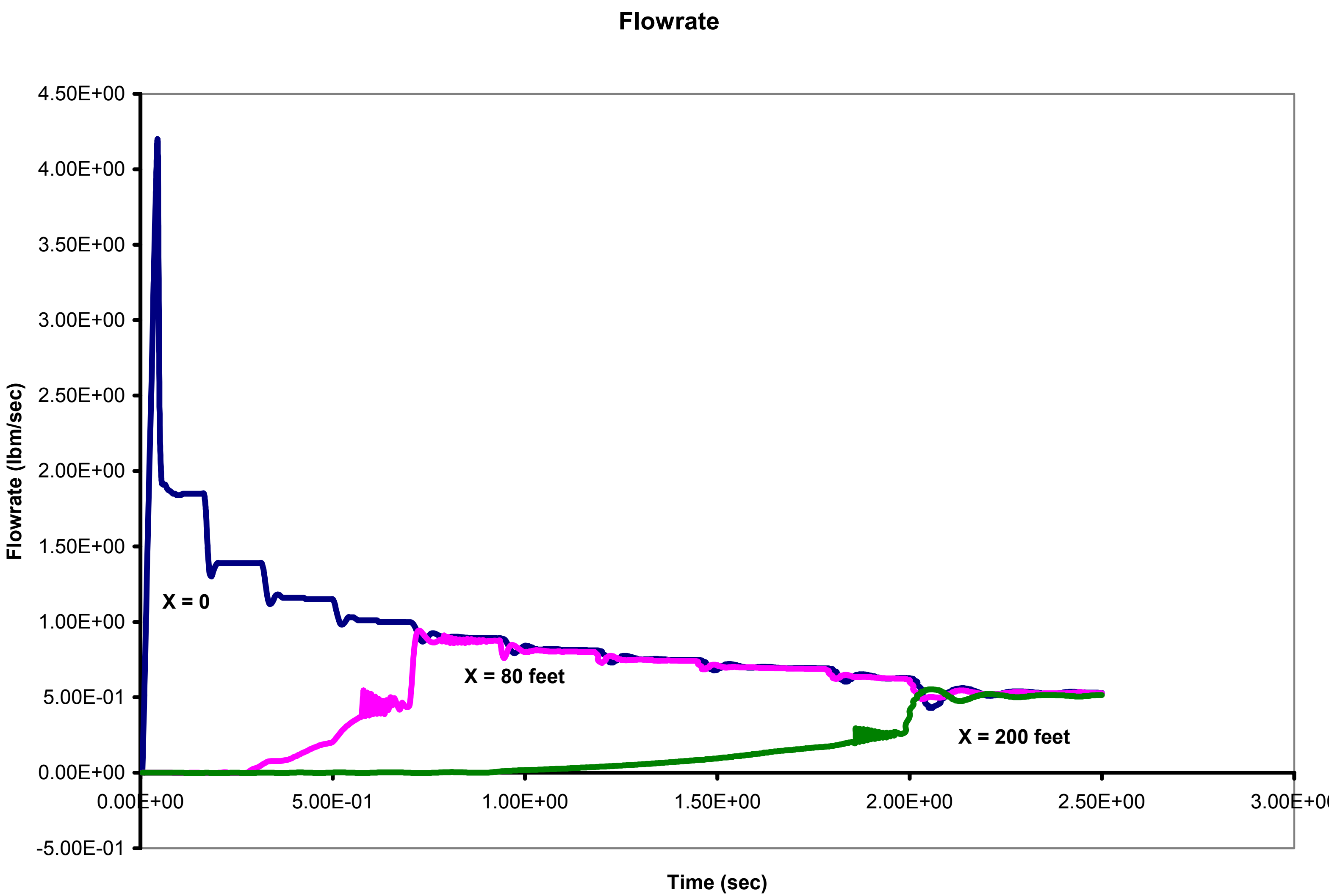
Orifice

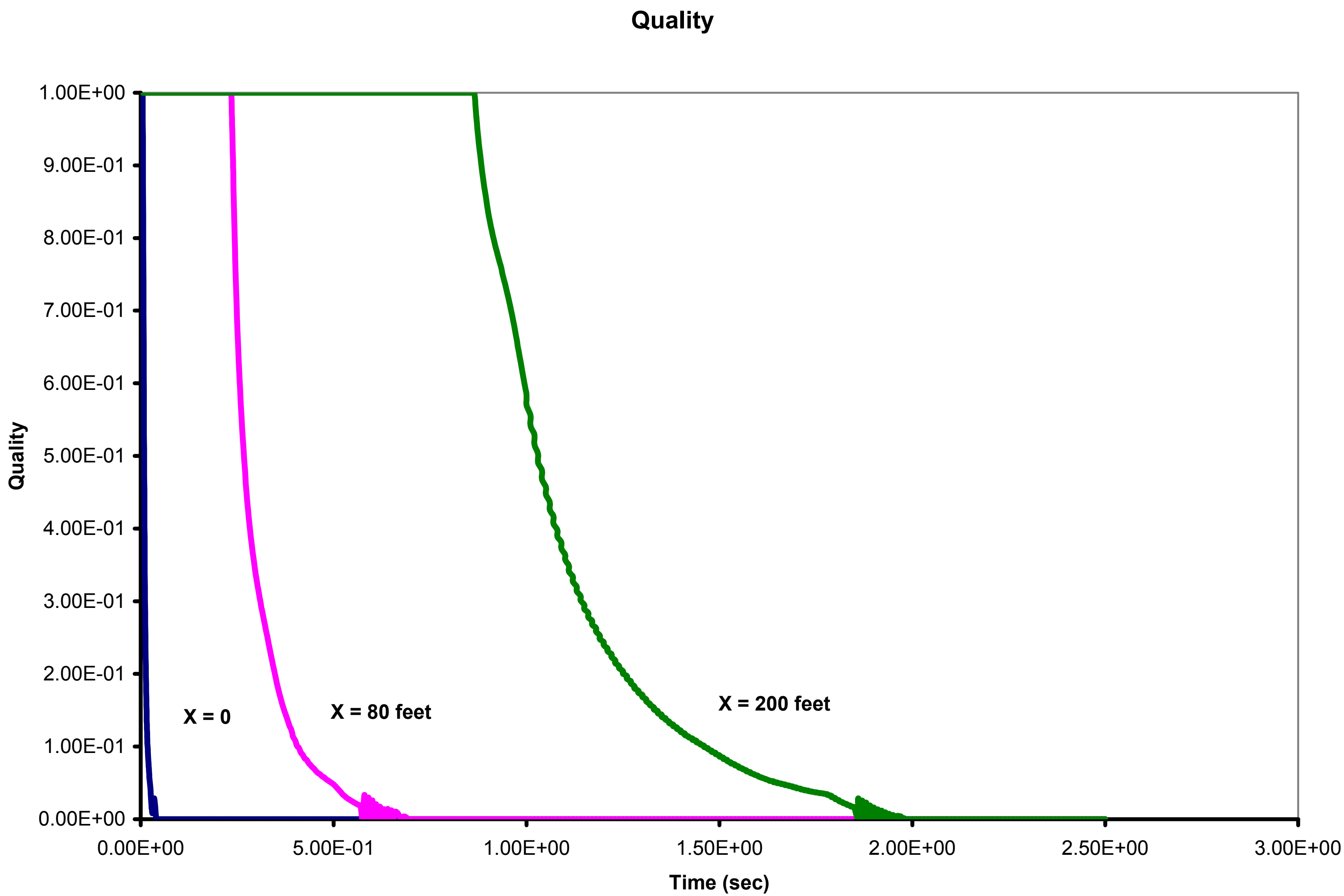
- Valve closing sequence is coded in BNDUSER


Pressure
P (psia)
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
X = 0
X = 80 feet
X = 200 feet
0.00E+00
5.00E-01
1.00E+00
1.50E+00
2.00E+00
2.50E+00
3.00E+00
Time (sec)

## Temperature




Flowrate
Flowrate (lbm/sec)
Time (sec)
4.50E+00
4.00E+00
3.50E+00
3.00E+00
2.50E+00
2.00E+00
1.50E+00
1.00E+00
5.00E-01
0.00E+00
-5.00E-01
0.00E+00
5.00E-01
1.00E+00
1.50E+00
2.00E+00
2.50E+00
3.00E+00
X = 0
X = 80 feet
X = 200 feet


Quality
1.00E+00
9.00E-01
8.00E-01
7.00E-01
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Quality
X = 0
X = 80 feet
X = 200 feet
0.00E+00
5.00E-01
1.00E+00
1.50E+00
2.00E+00
2.50E+00
3.00E+00
Time (sec)

# CONCLUSIONS

- GFSSP has been used to compute fluid transient following rapid valve closure and opening
- GFSSP predictions have been compared with MOC solution:
  - Maximum pressure and frequency compares well
  - Discrepancies exist in damping rate and shape of the pressure curve
- Demonstrations have been made for
  - Sudden opening of cryogenic propellant in long pipeline
- Time step must satisfy Courant condition
- Predictions in all demonstration calculations show physical realism

# Conjugate Heat Transfer

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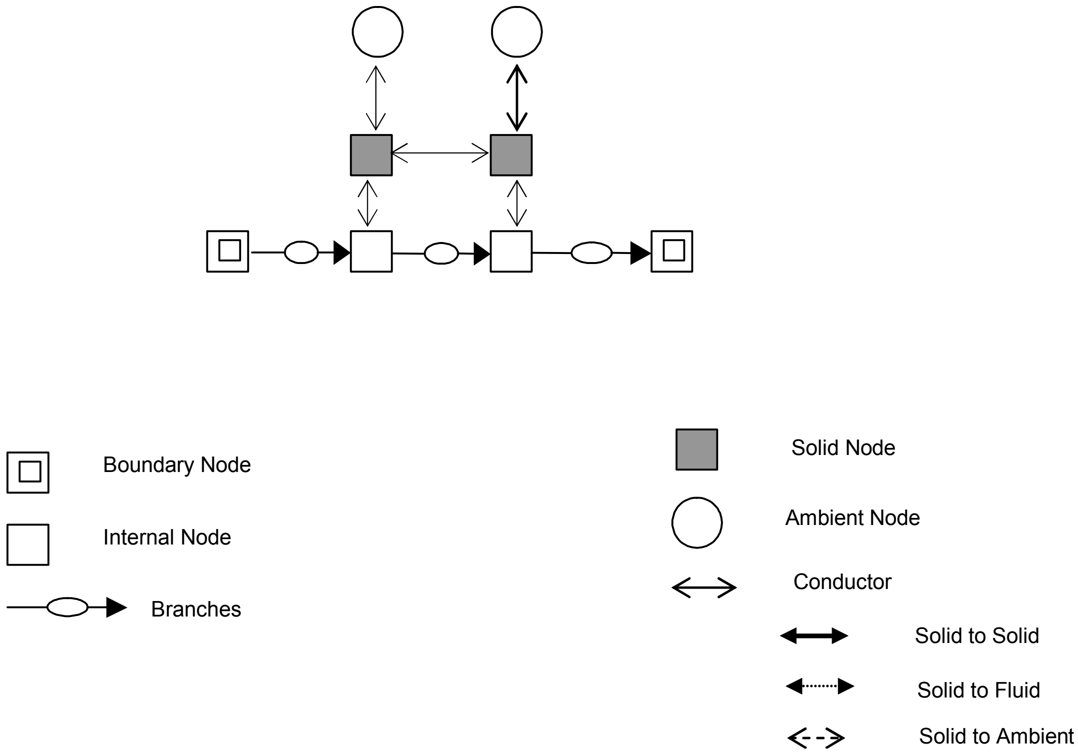
# Conjugate Heat Transfer



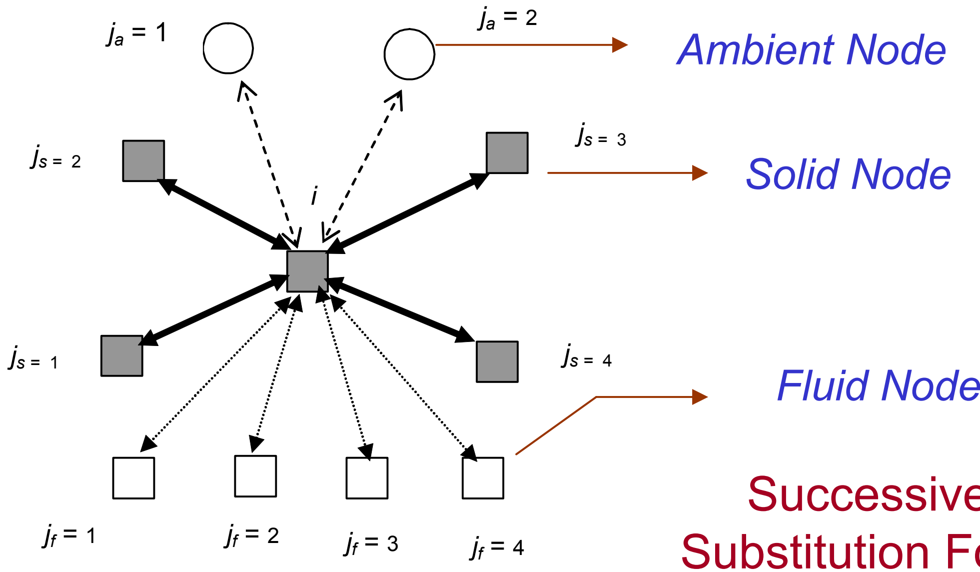


# Mathematical Closure

| **Unknown Variables** | **Available Equations to Solve** |
|---|---|
| 1. Pressure | 1. Mass Conservation Equation |
| 2. Flowrate | 2. Momentum Conservation Equation |
| 3. Fluid Temperature | 3. Energy Conservation Equation of Fluid |
| 4. Solid Temperature | 4. Energy Conservation Equation of Solid |
| 5. Specie Concentrations | 5. Conservation Equations for Mass Fraction of Species |
| 6. Mass | 6. Thermodynamic Equation of State |

# Heat Conduction Equation






## Conservation Equation

$$\frac{\partial}{\partial \tau}\left(mC_pT_s^i\right) = \sum_{j_s=1}^{n_{ss}} \dot{q}_{ss} + \sum_{j_f=1}^{n_{sf}} \dot{q}_{sf} + \sum_{j_a=1}^{n_{sa}} \dot{q}_{sa} + \dot{S}_i$$

$$\dot{q}_{ss} = k_{ij_s} A_{ij_s} / \delta_{ij_s} \left(T_s^{j_s} - T_s^i\right)$$

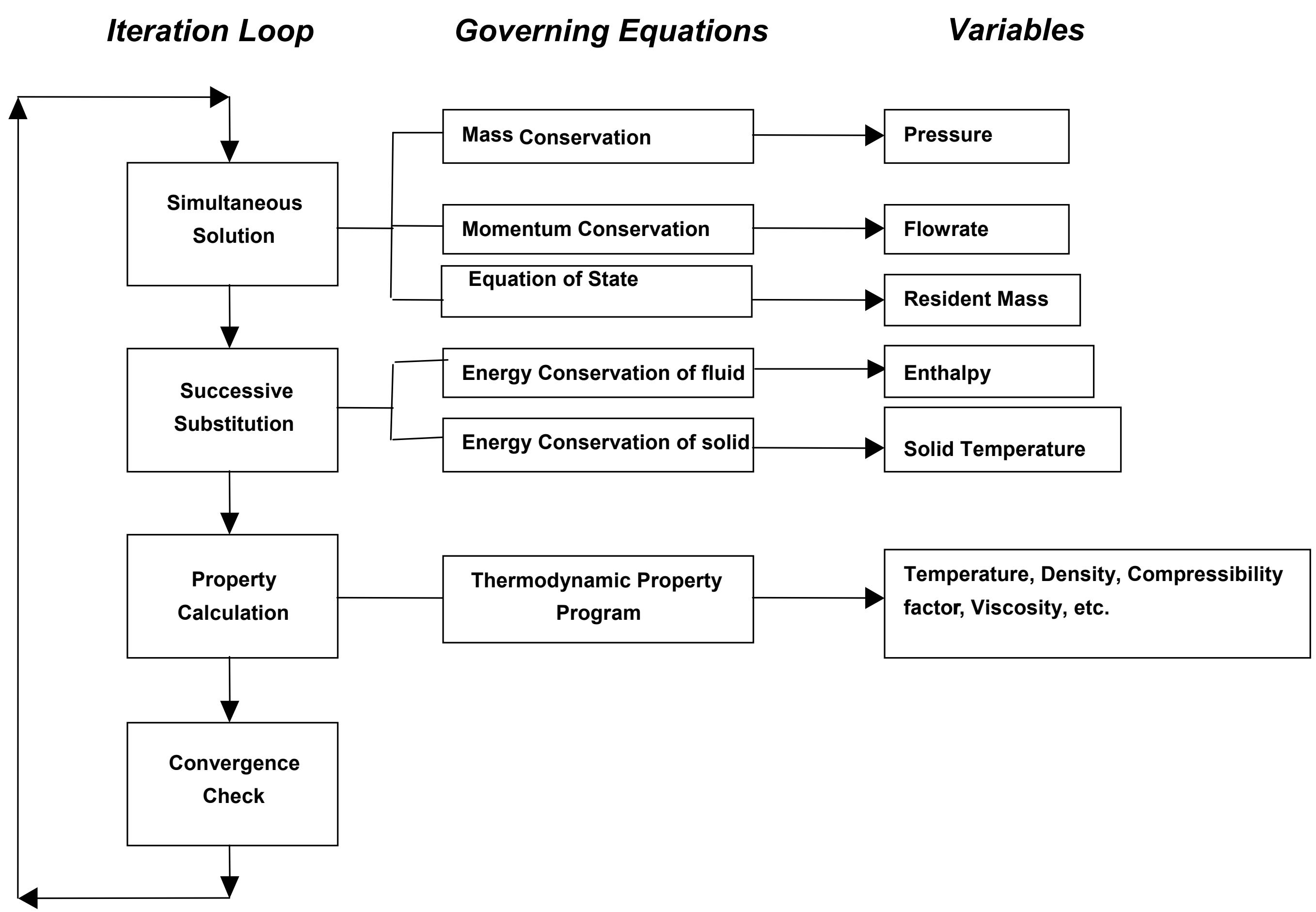
$$\dot{q}_{sf} = h_{ij_f} A_{ij_f} \left(T_f^{j_f} - T_s^i\right)$$

$$\dot{q}_{sa} = h_{ij_a} A_{ij_a} \left(T_a^{j_a} - T_s^i\right)$$

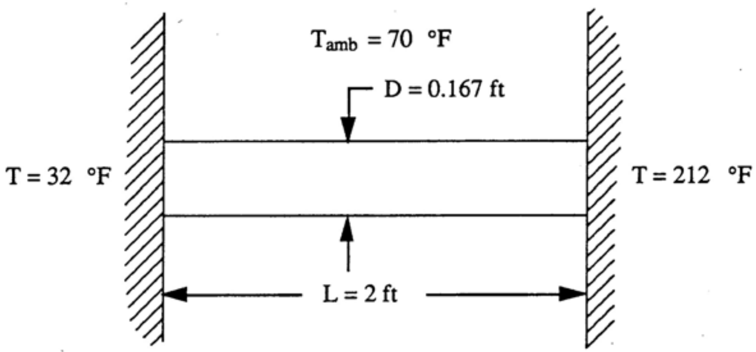
## Successive Substitution Form

$$T_s^i = \frac{\sum_{j_s=1}^{n_{ss}} C_{ij_s} T_s^{j_s} + \sum_{j_f=1}^{n_{sf}} C_{ij_f} T_f^{j_f} + \sum_{j_a=1}^{n_{sa}} C_{ij_a} T_a^{j_a} + \frac{\left(mC_p\right)_m}{\Delta\tau} T_{s,m}^i + \dot{S}}{\frac{mC_p}{\Delta\tau} + \sum_{j_s=1}^{n_{ss}} C_{ij_s} + \sum_{j_f=1}^{n_{sf}} C_{ij_f} + \sum_{j_a=1}^{n_{sa}} C_{ij_a}}$$

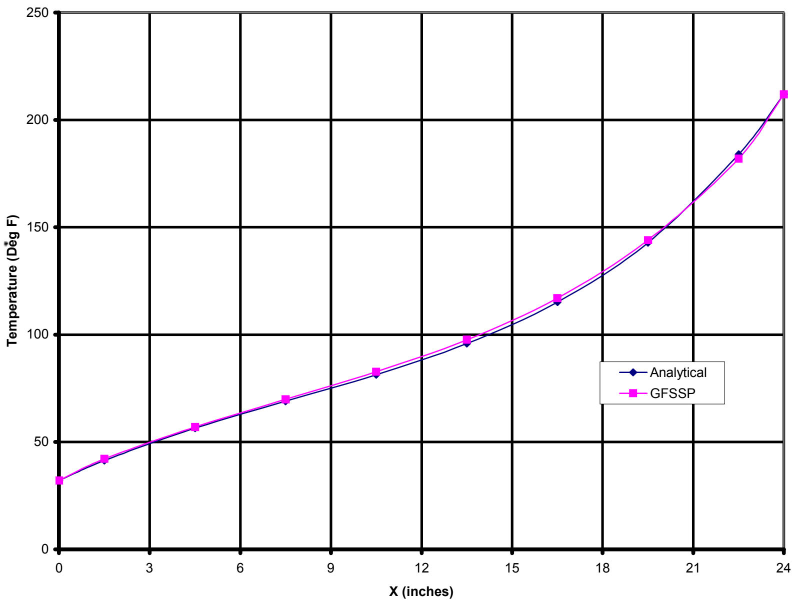
# SASS Solution Scheme



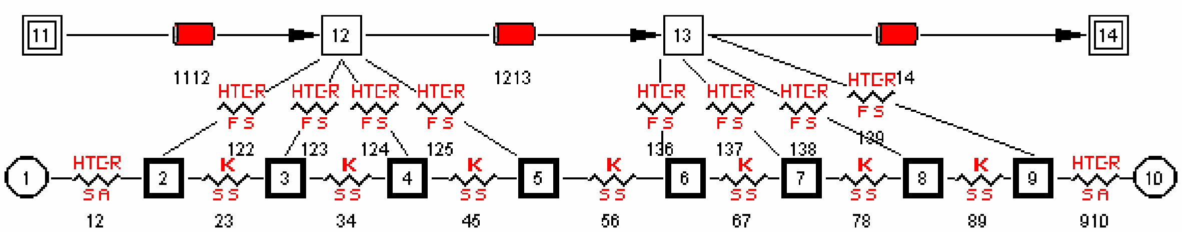
# Verification of Conjugate Heat Transfer Results




Problem Considered



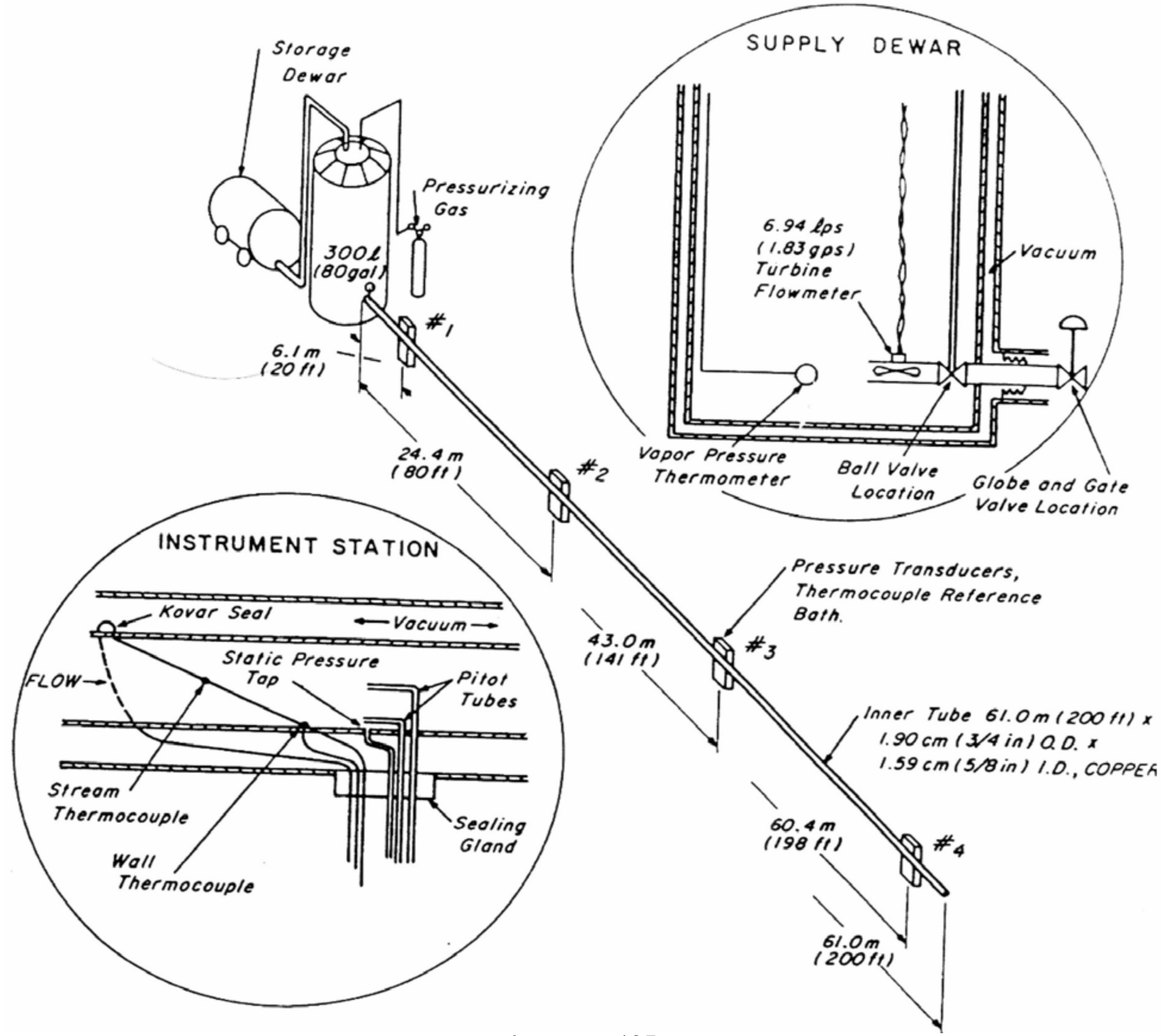

Comparison with Analytical Solution



GFSSP Model

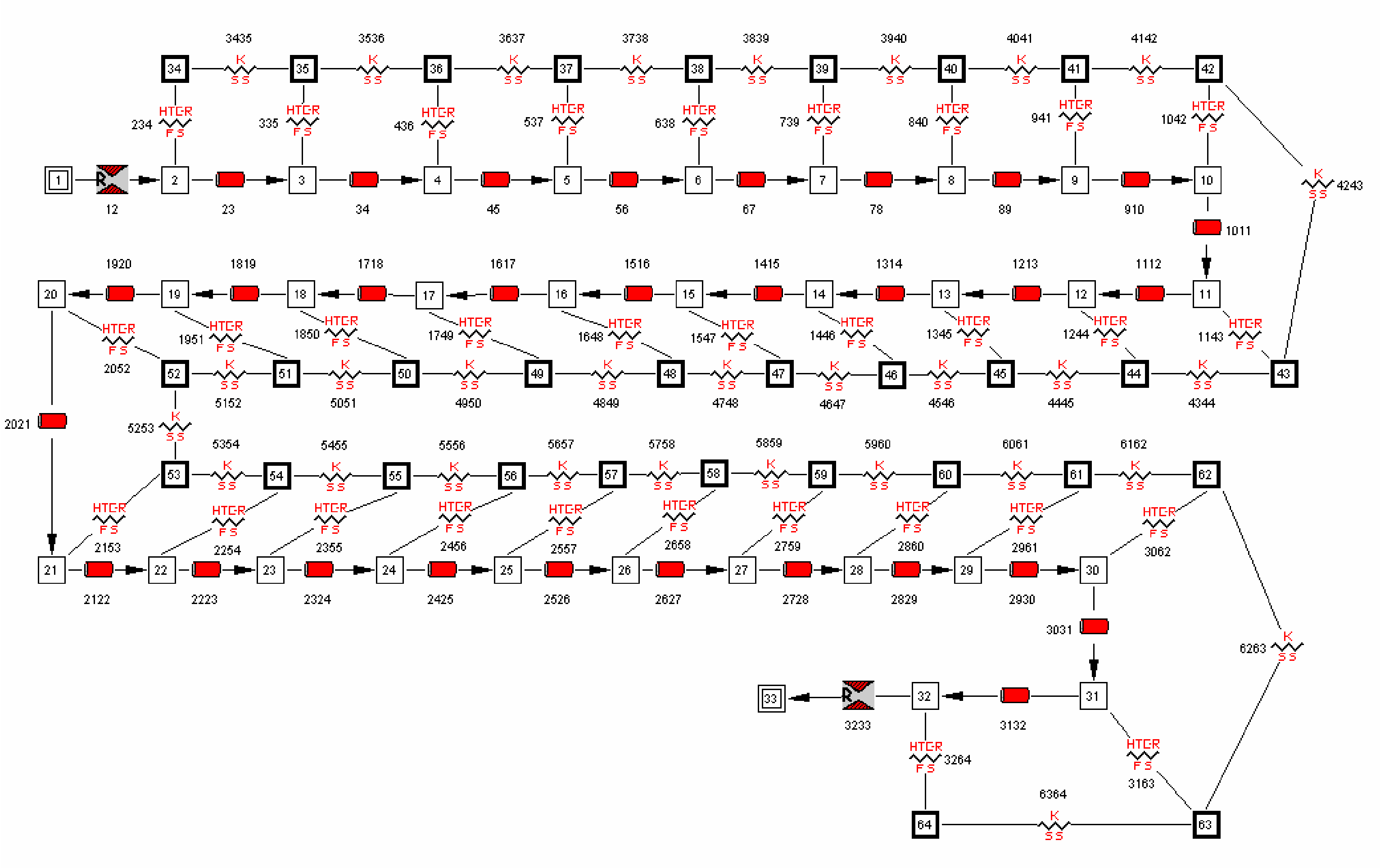
# NBS Test Set-up of Cryogenic Transfer Line





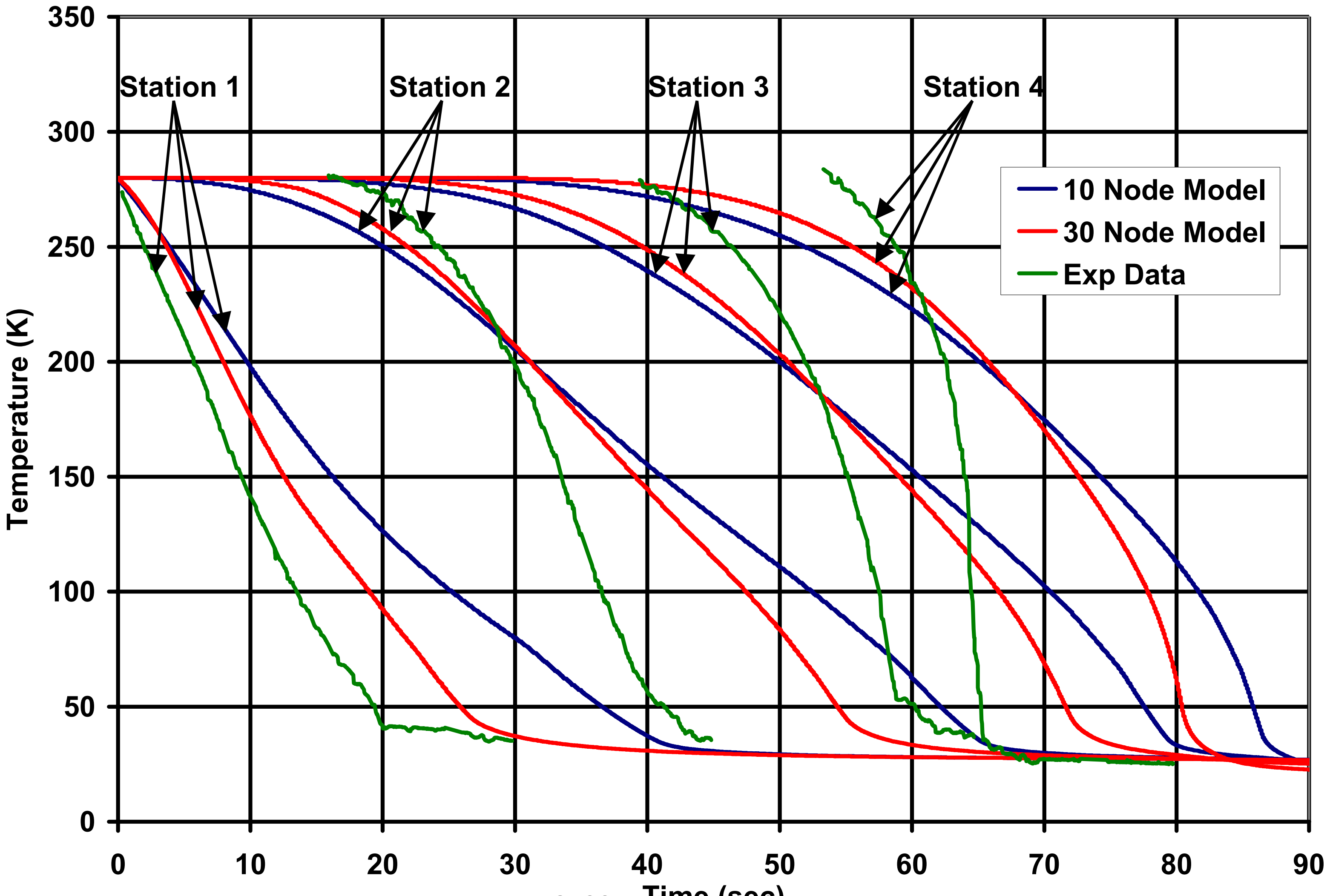
# GFSSP Model of Cryogenic Transfer Line





# Comparison with Test Data





# Summary

- **GFSSP has been extended to model conjugate heat transfer**
- **Fluid Solid Network Elements include**:
  - Fluid nodes and Flow Branches
  - Solid Nodes and Ambient Nodes
  - Conductors connecting Fluid-Solid, Solid-Solid and Solid-Ambient Nodes
- **Heat Conduction Equations are solved simultaneously with Fluid Conservation Equations for Mass, Momentum, Energy and Equation of State**
- **The extended code was verified by comparing with analytical solution for simple conduction-convection problem**
- **The code was applied to model**
  - Pressurization of Cryogenic Tank
  - Freezing and Thawing of Metal
  - Chilldown of Cryogenic Transfer Line
  - Boil-off from Cryogenic Tank