GFSSP Training Course Lectures

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Thermal & Fluids Analysis Workshop

NASA/Ames Research Center & San Jose University
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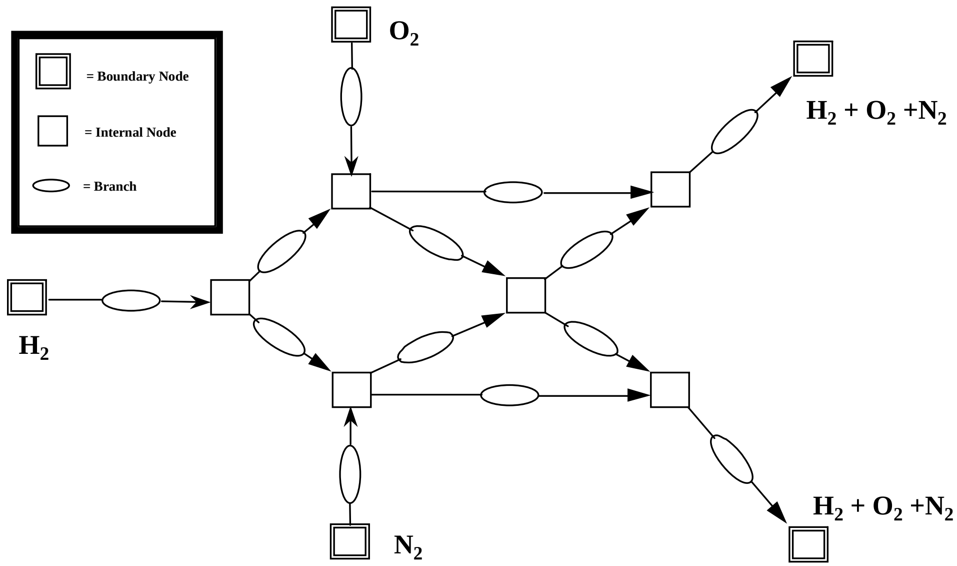
INTRODUCTION & OVERVIEW



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

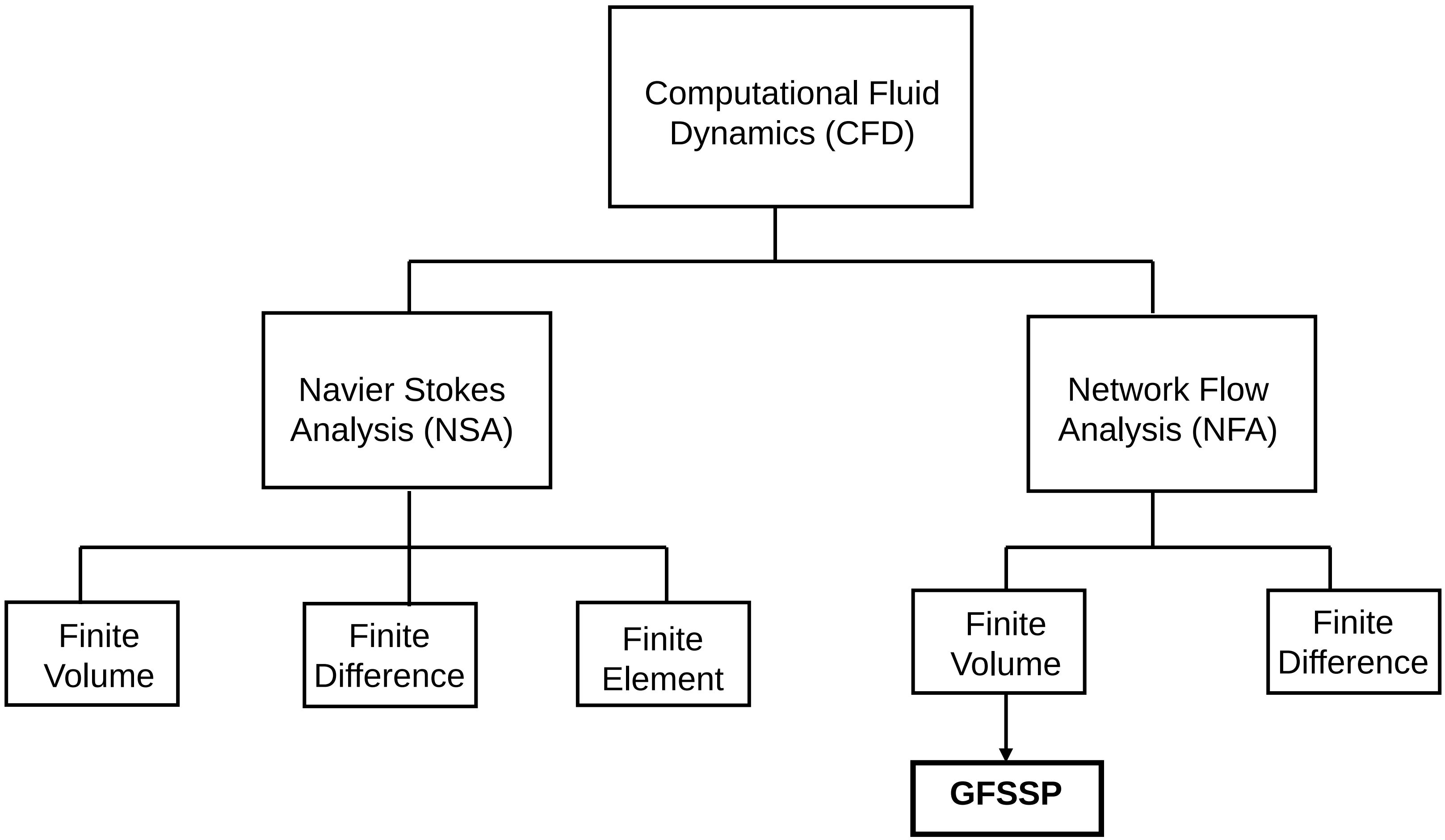
DEVELOPMENT HISTORY

- 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

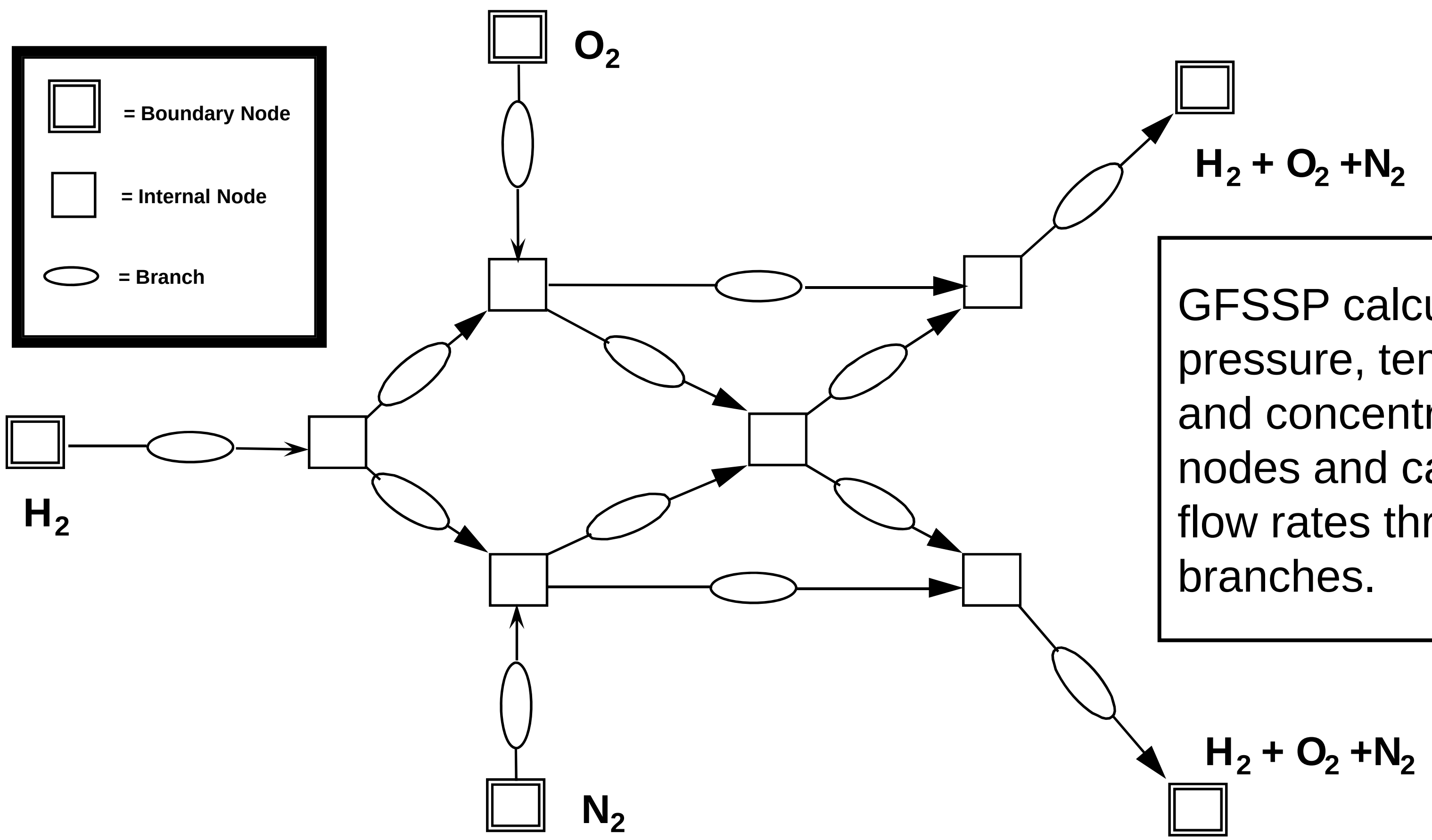
- Suitable for detailed flow analysis within a component
- Requires fine grid resolution to accurately model transport processes
- Used after after preliminary design

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

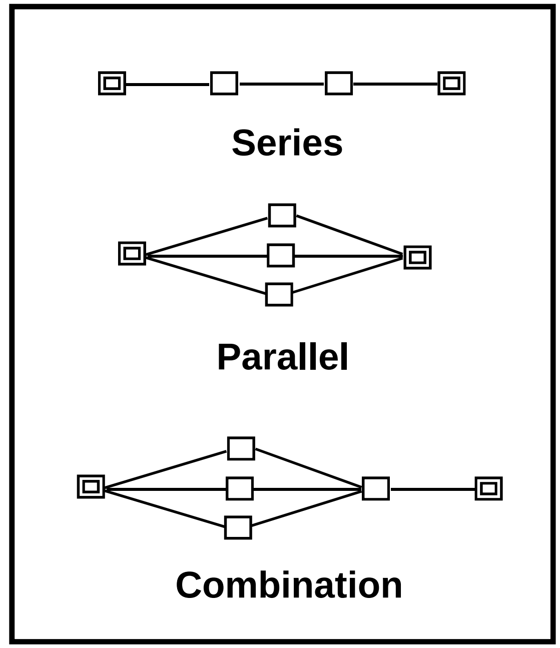
GFSSP FLOW CIRCUIT



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

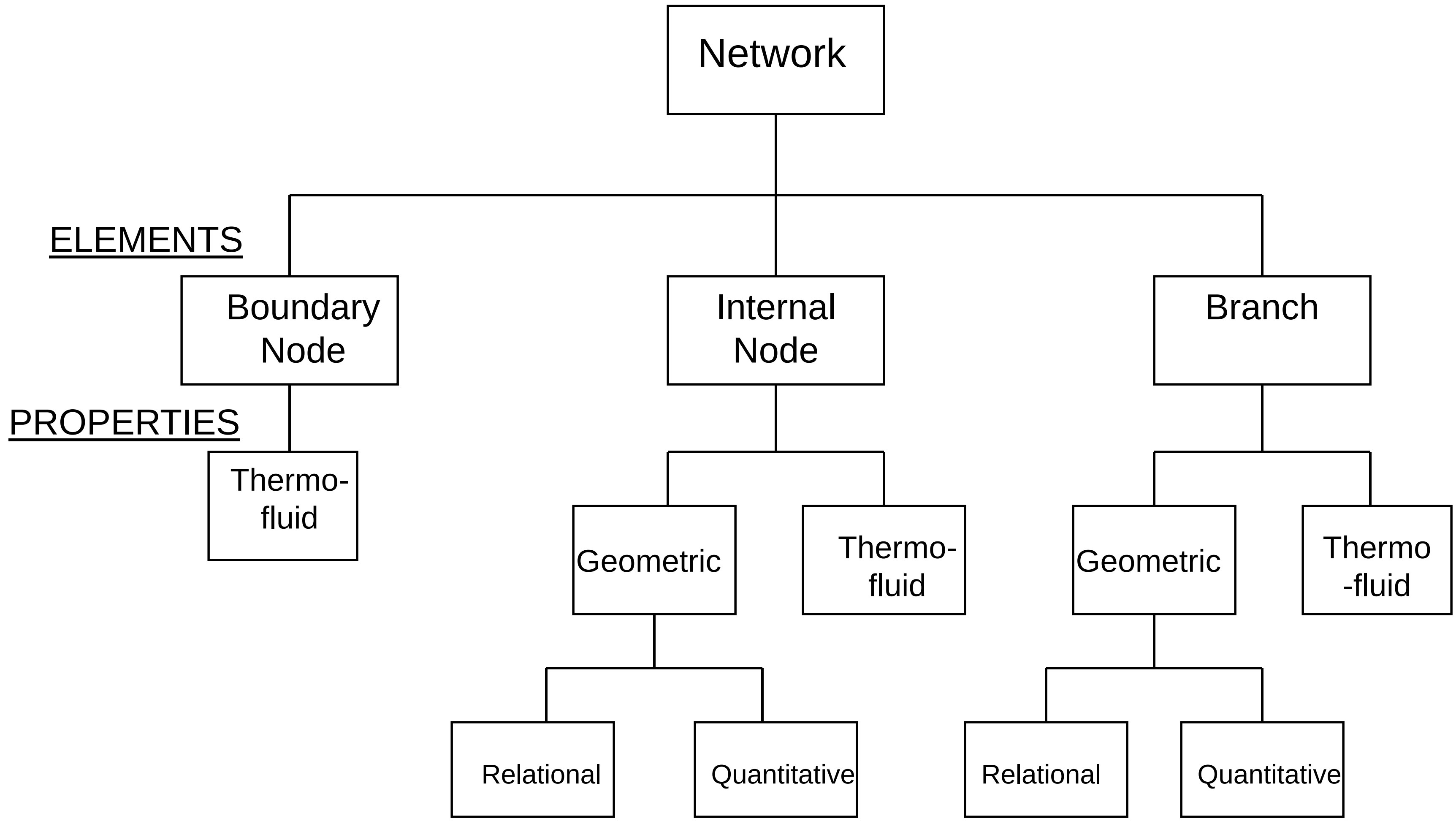
UNITS AND SIGN CONVENTIONS

- 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	
Specific Heats	Equilibrium Thermodynamic Relations
Viscosity	[GASP, WASP & GASPAK Property Programs]
Thermal Conductivity	
Flow Resistance Factor	Empirical Relations

MATHEMATICAL FORMULATION - 3

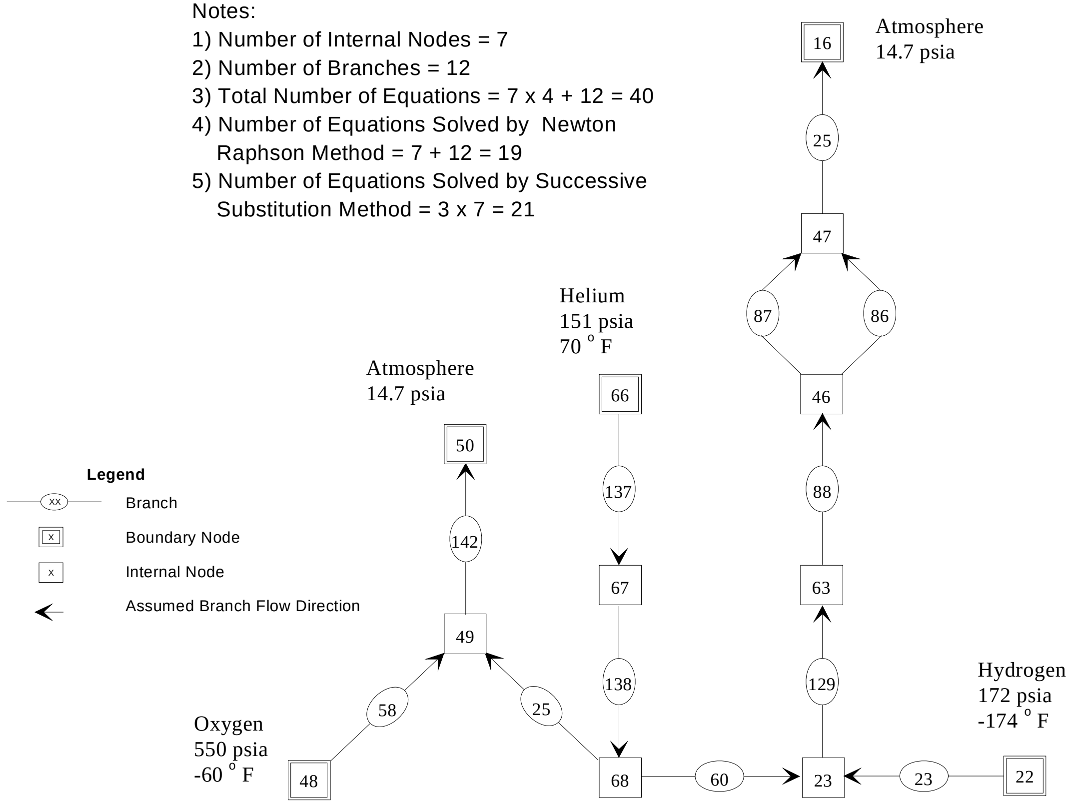
BOUNDARY CONDITIONS

- 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

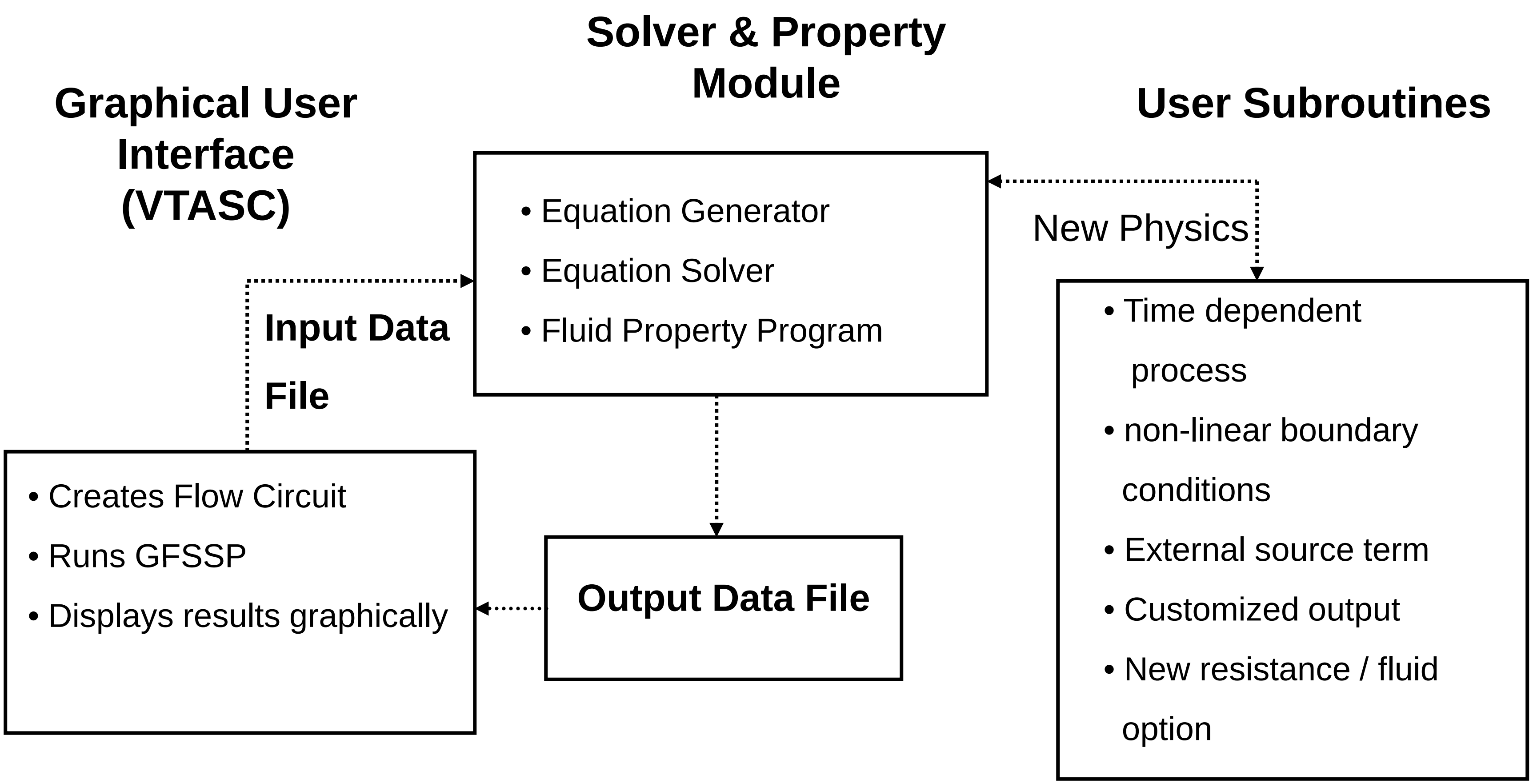
MATHEMATICAL FORMULATION - 3

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

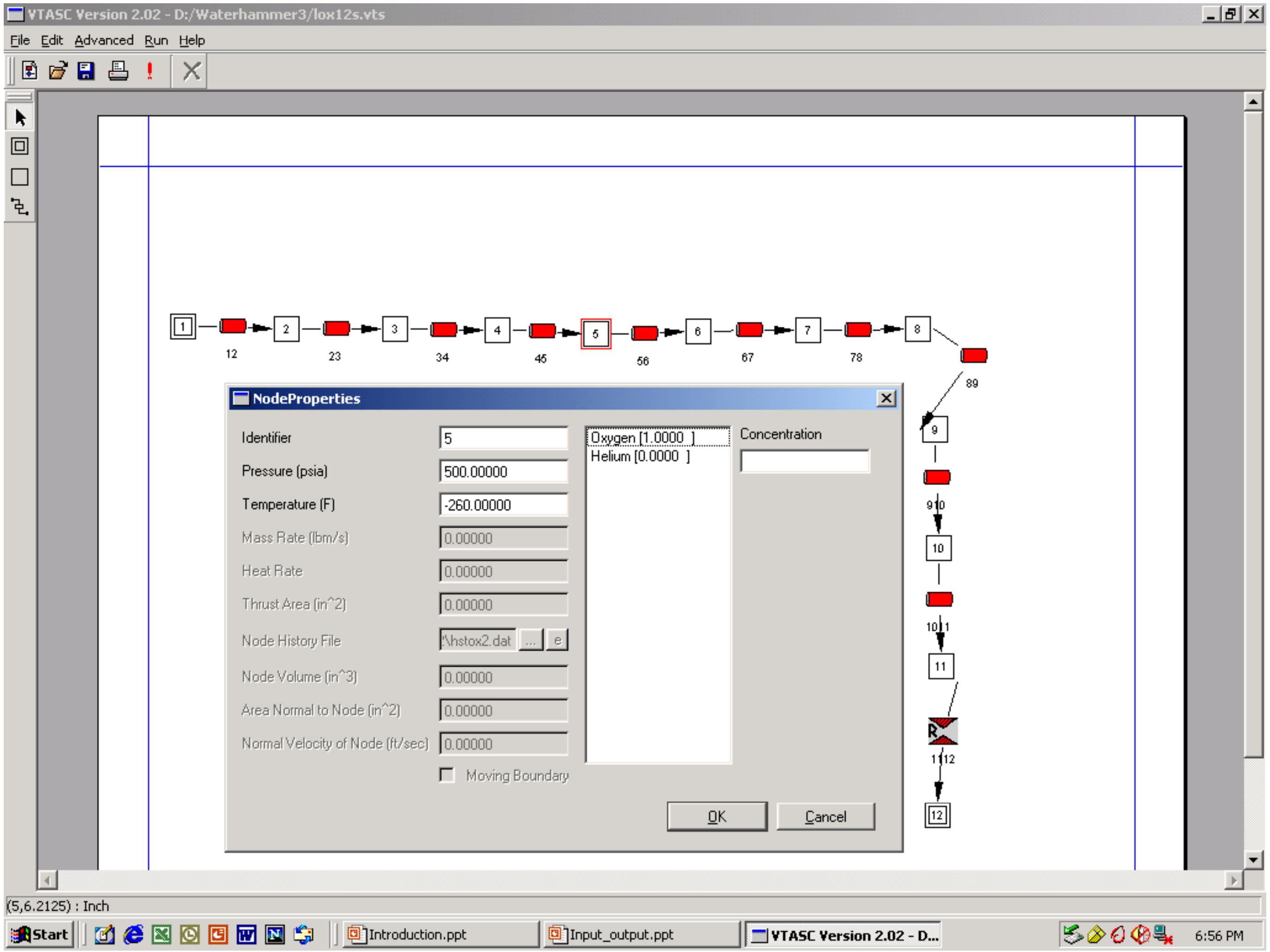


PROGRAM STRUCTURE



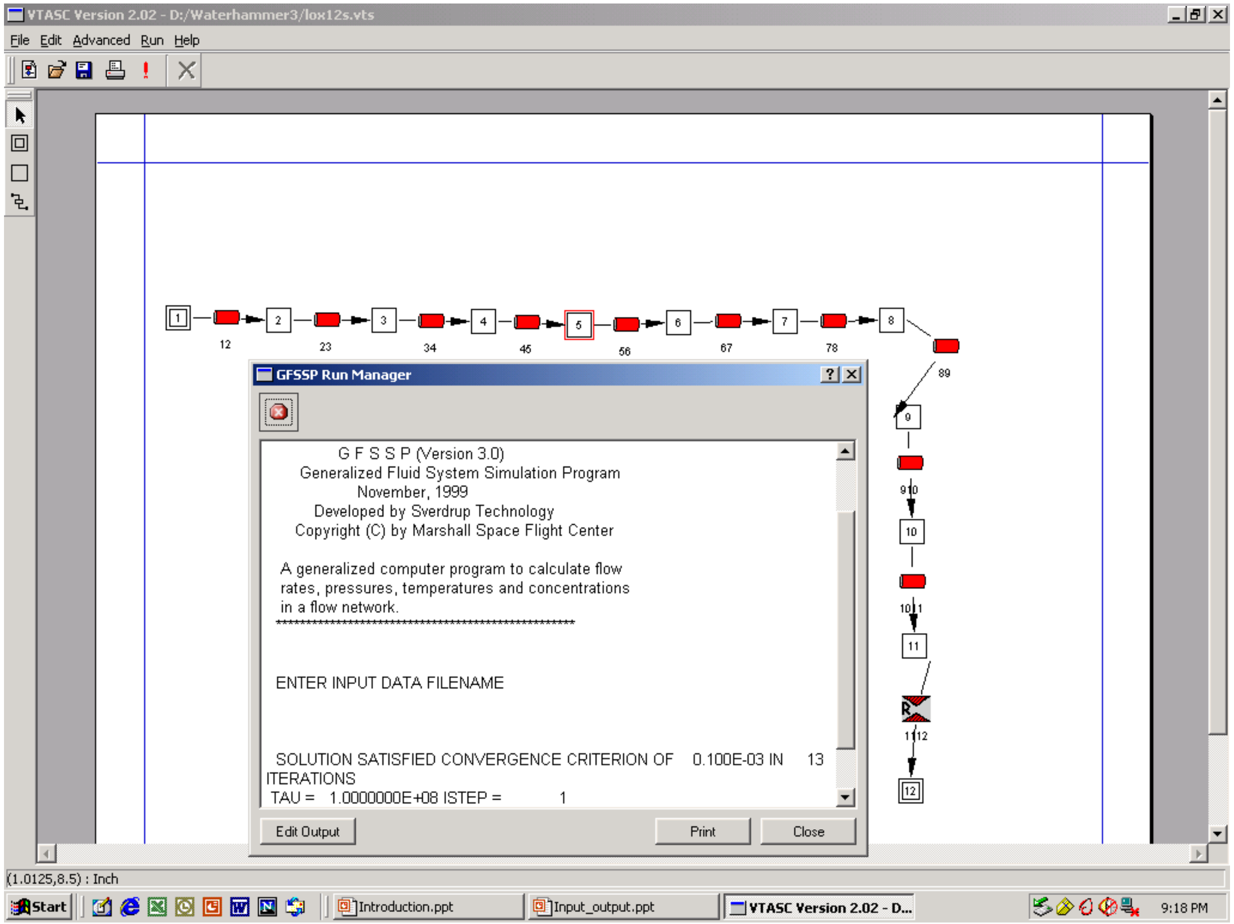
GRAPHICAL USER INTERFACE - 1

MODEL BUILDING



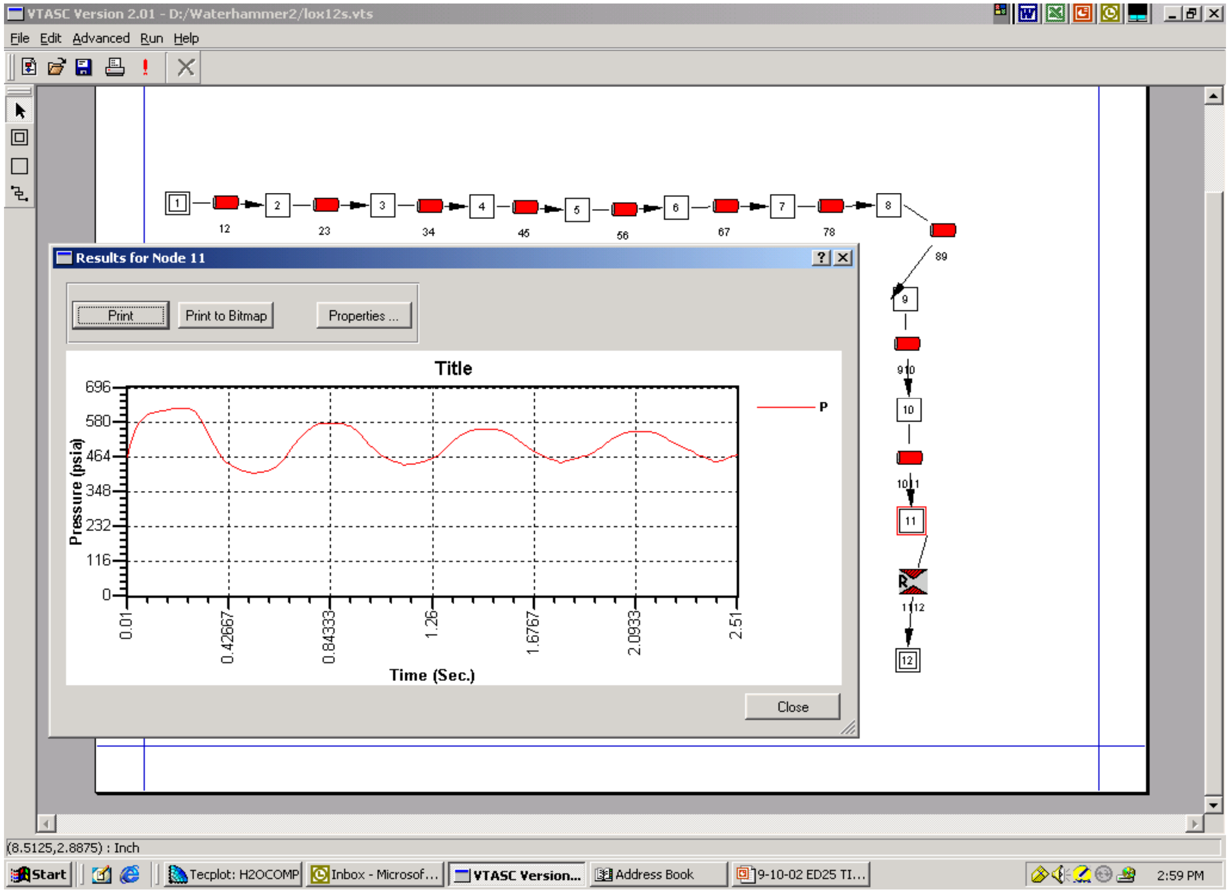
GRAPHICAL USER INTERFACE - 2

MODEL RUNNING

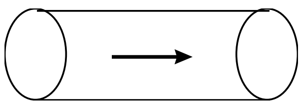


GRAPHICAL USER INTERFACE - 3

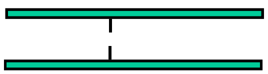
MODEL RESULTS



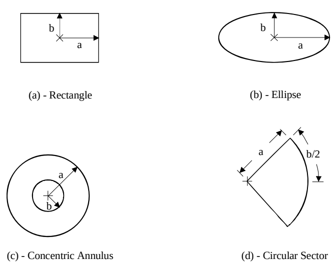
RESISTANCE & FLUID OPTIONS - 1



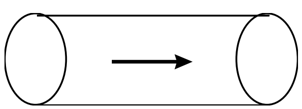
1. Pipe Flow



2. Flow Through a Restriction

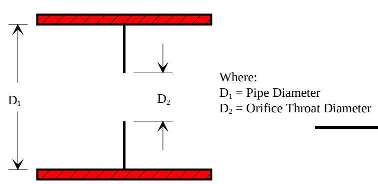


3. Non-Circular Duct



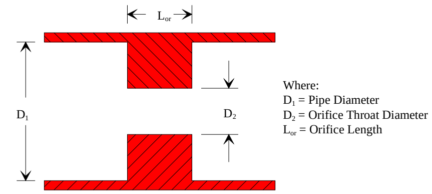
4. Pipe Flow with Entrance & Exit Losses

Thin Sharp Orifice



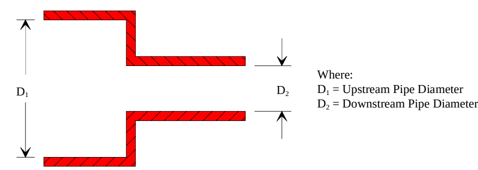
5. Thin, Sharp Orifice

Thick Orifice



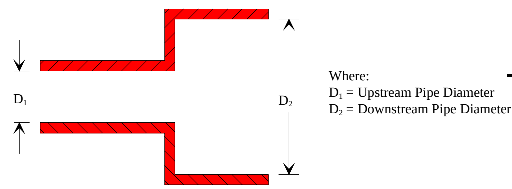
6. Thick Orifice

Square Reduction



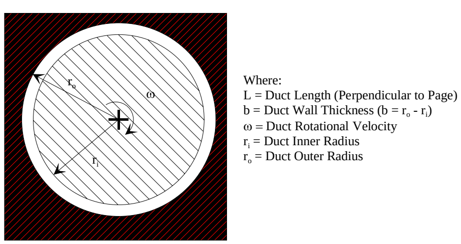
7. Square Reduction

Square Expansion



8. Square Expansion

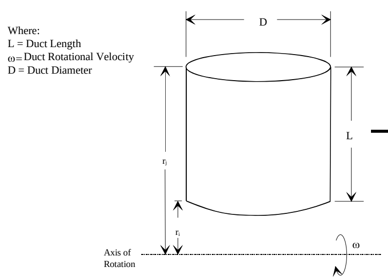
Rotating Annular Duct



9. Rotating Annular Duct

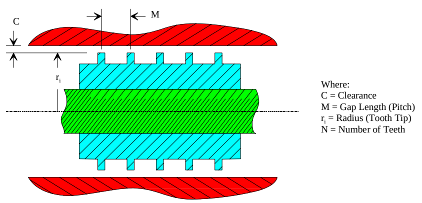
RESISTANCE & FLUID OPTIONS -2

Rotating Radial Duct

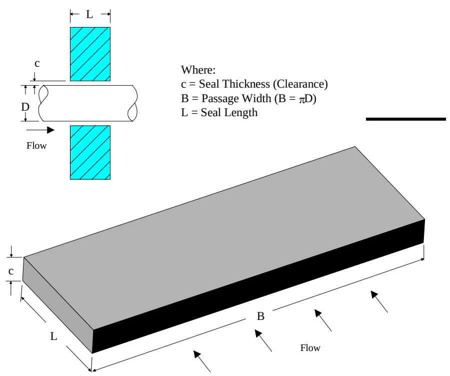


10. Rotating Radial Duct

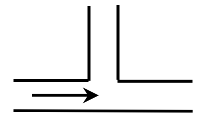
Labyrinth Seal



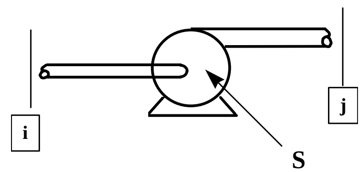
11. Labyrinth Seal



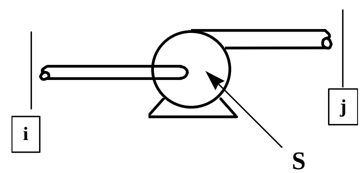
12. Face Seal



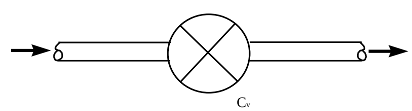
13. Common Fittings & Valves



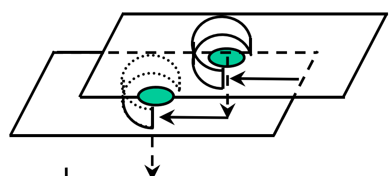
14. Pump Characteristics



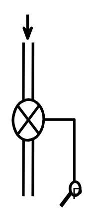
15. Pump Power



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

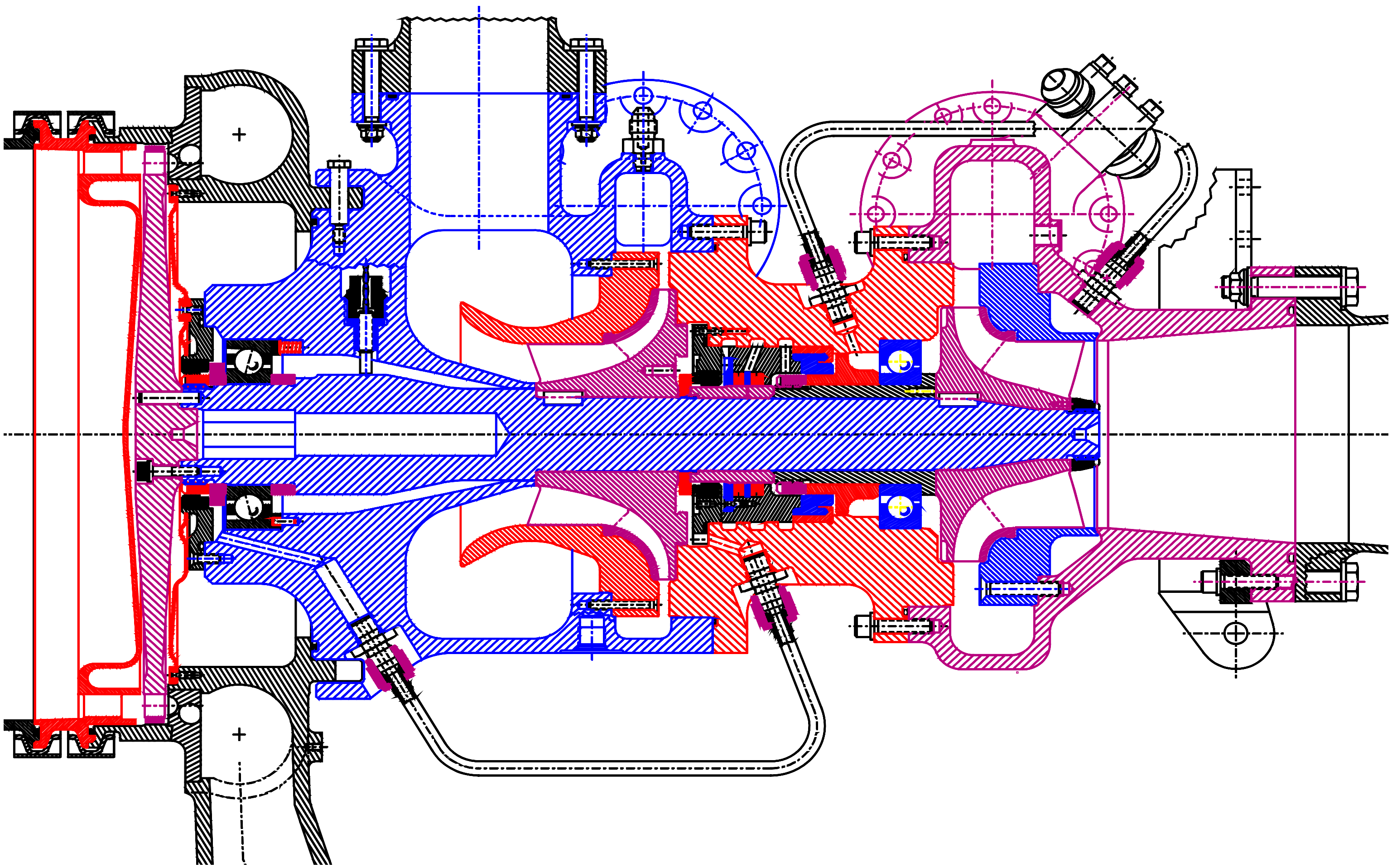
Index	Fluid	Index	Fluid
1	HELIUM	18	HYDROGEN SULFIDE
2	METHANE	19	KRYPTON
3	NEON	20	PROPANE
4	NITROGEN	21	XENON
5	CO	22	R-11
6	OXYGEN	23	R12
7	ARGON	24	R22
8	CO_2	25	R32
9	PARAHYDROGEN	26	R123
10	HYDROGEN	27	R124
11	WATER	28	R125
12	RP-1	29	R134A
13	ISOBUTANE	30	R152A
14	BUTANE	31	NITROGEN TRIFLUORIDE
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

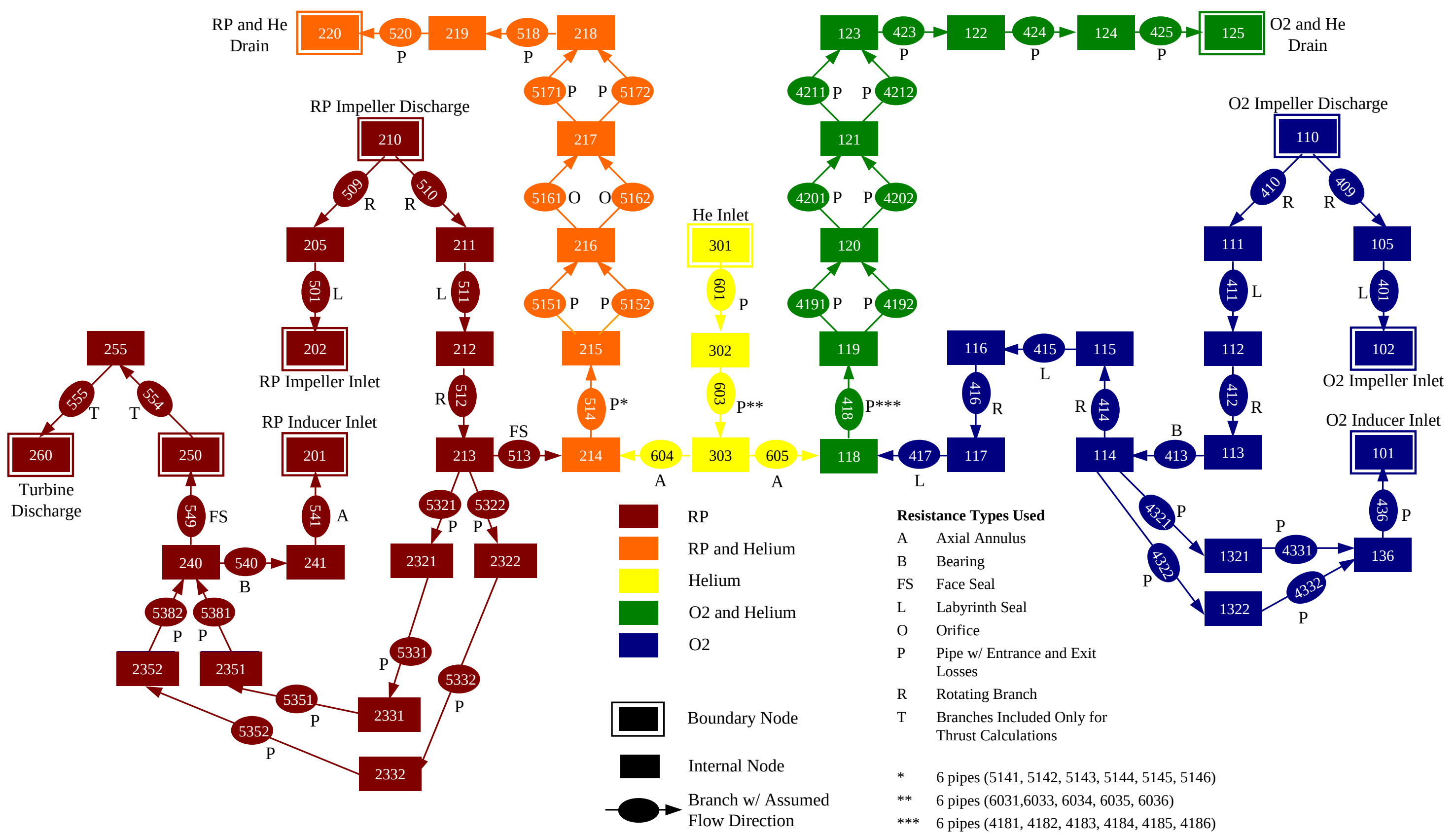
APPLICATIONS - 1

FASTRAC TURBOPUMP



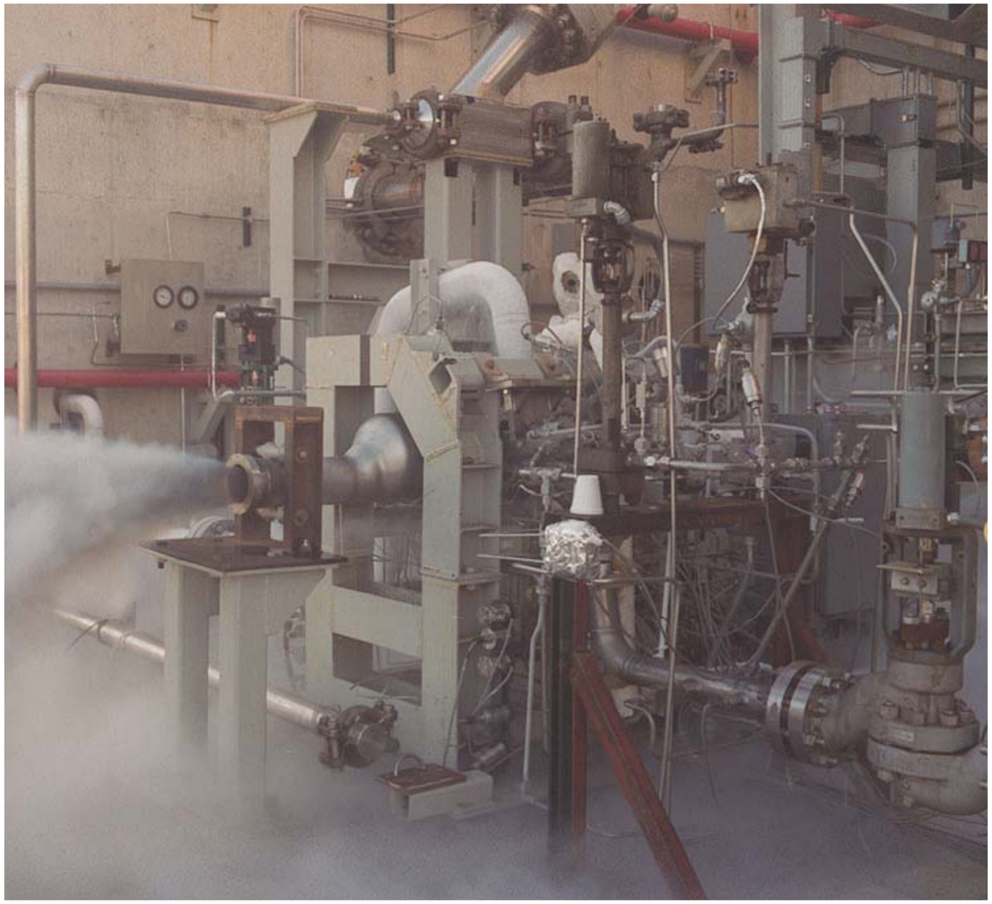
APPLICATIONS - 2

GFSSP Model of the Fastrac Turbopump



APPLICATIONS - 3

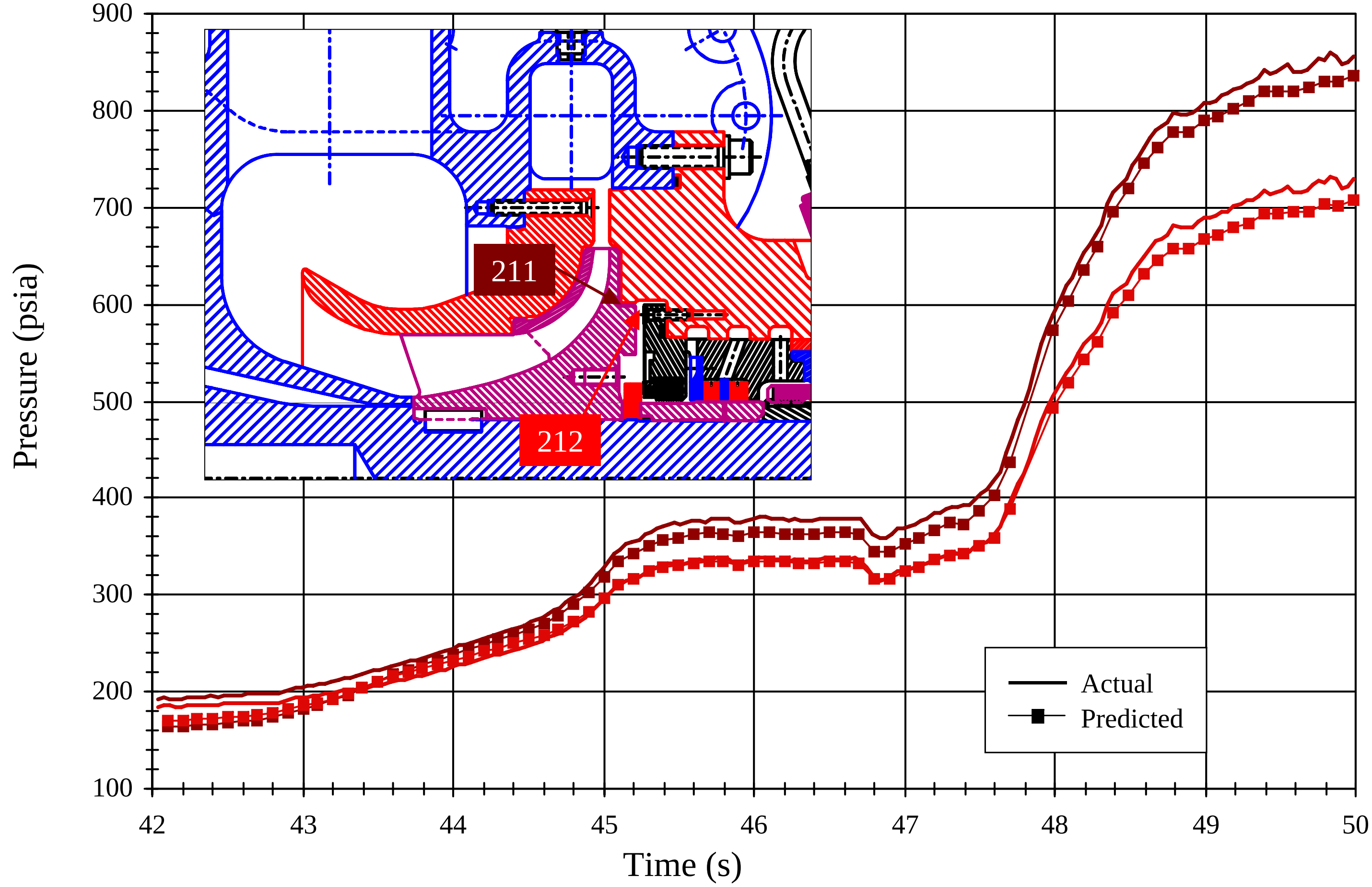
Turbopump Test to 20000 RPM with Gas Generator



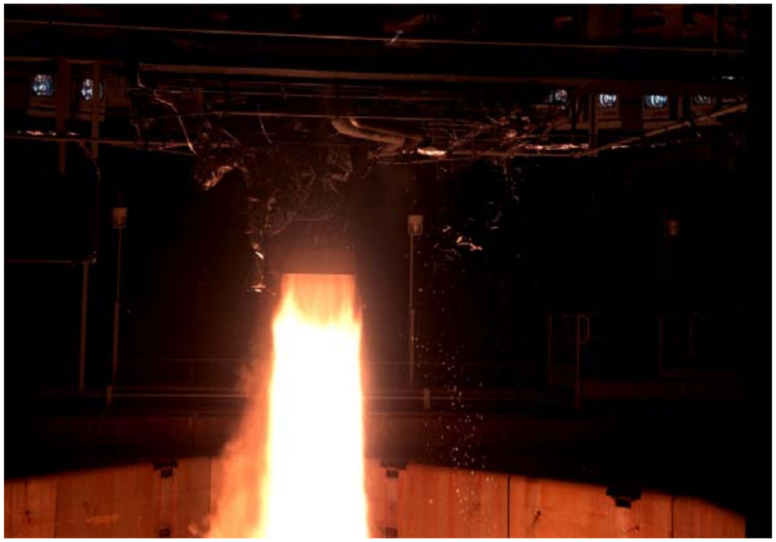
APPLICATIONS - 4

Fastrac Turbopump Model Results

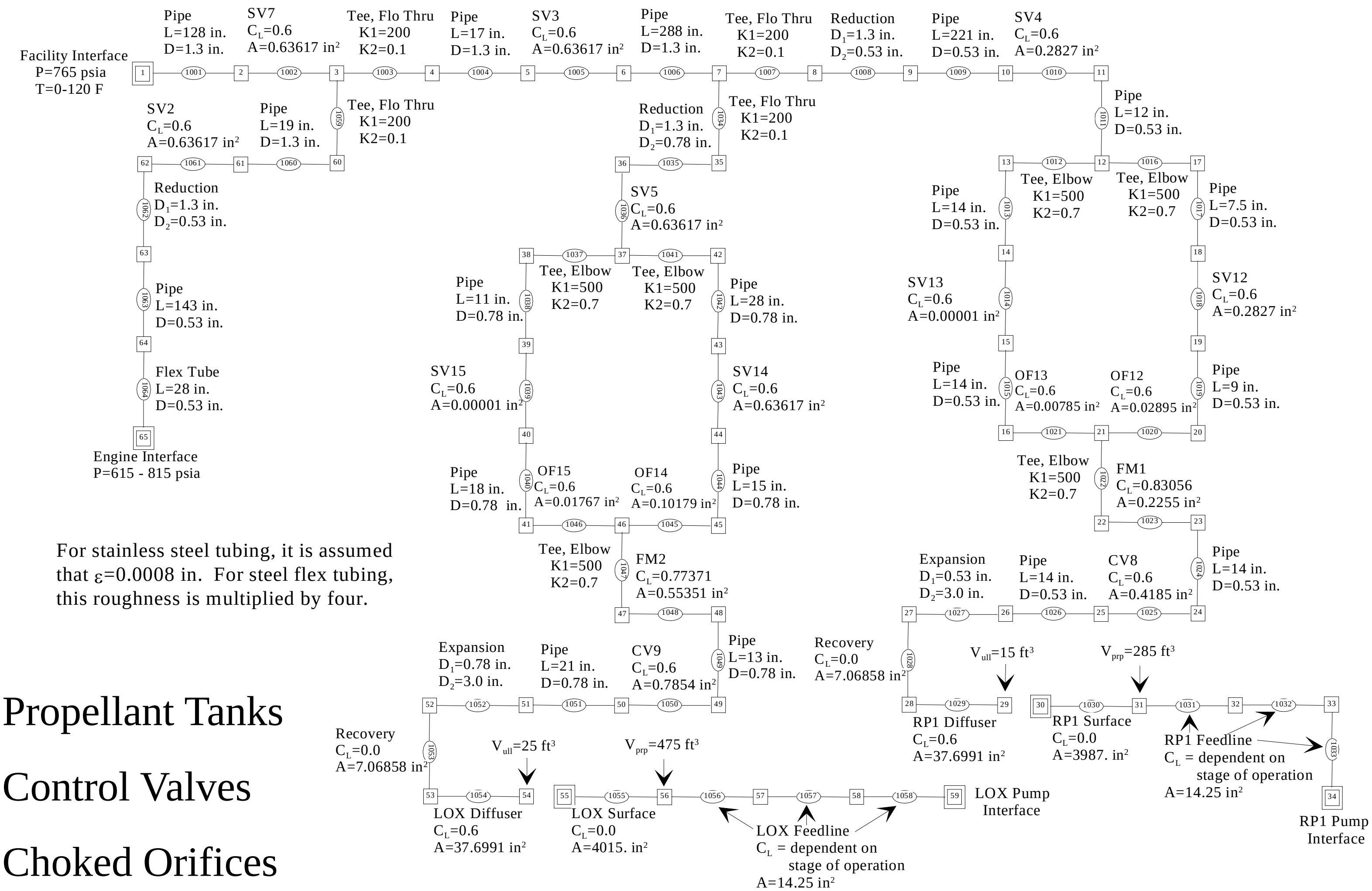
Pressure history comparison at RP-1 Impeller back face [Labyrinth seal inlet (211) and outlet (212)]



APPLICATIONS - 5



GFSSP Model of PTA Helium Pressurization System

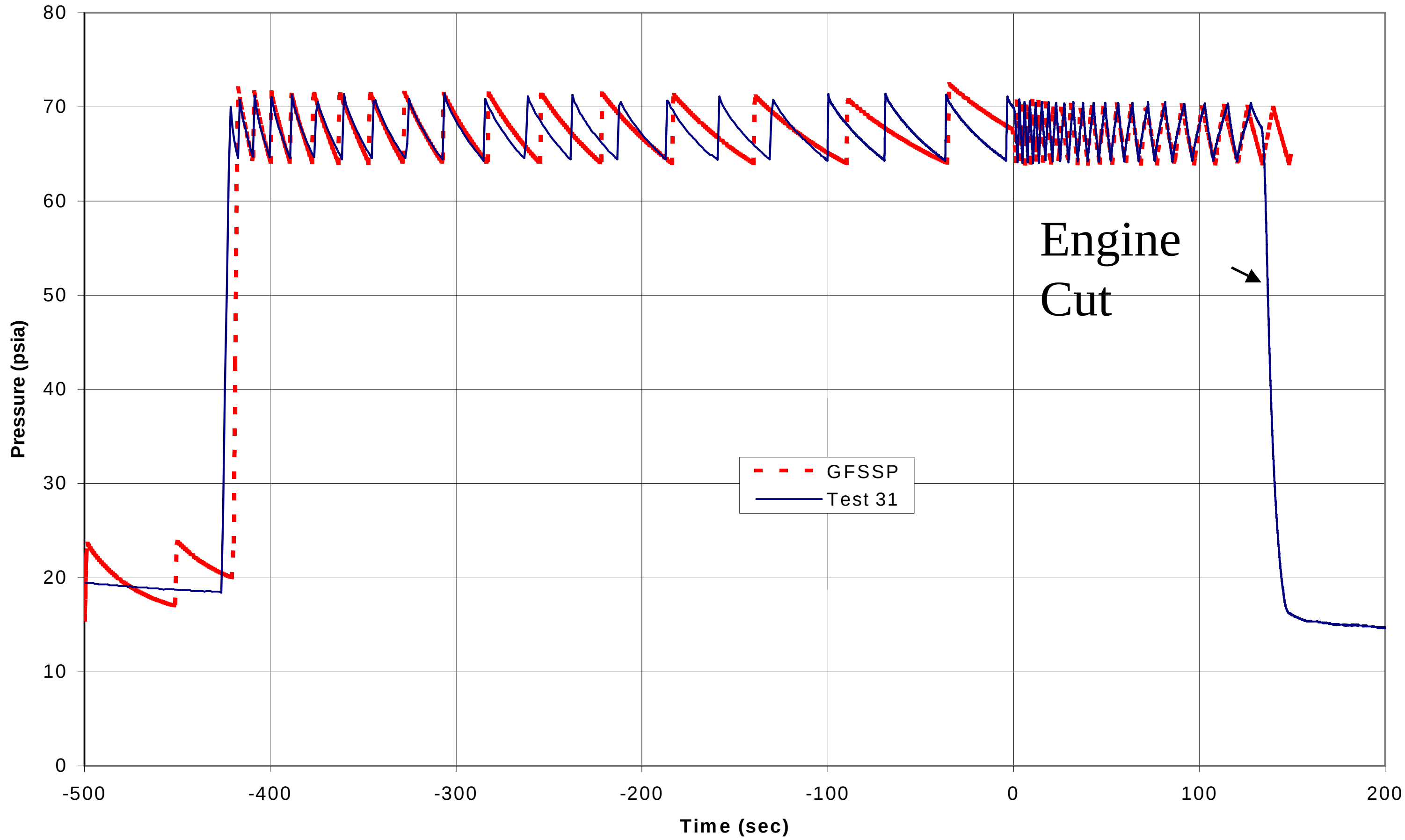


For stainless steel tubing, it is assumed that ε=0.0008 in. For steel flex tubing, this roughness is multiplied by four.

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

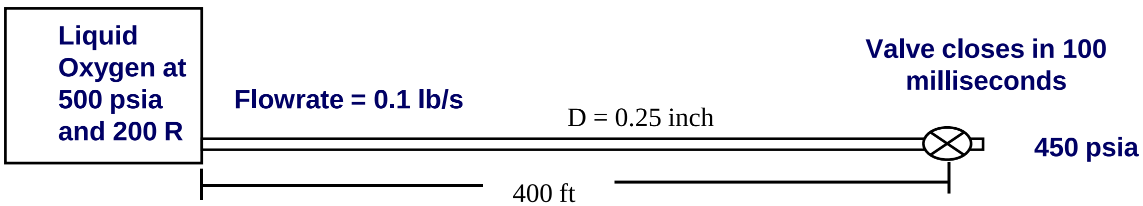
APPLICATIONS - 7

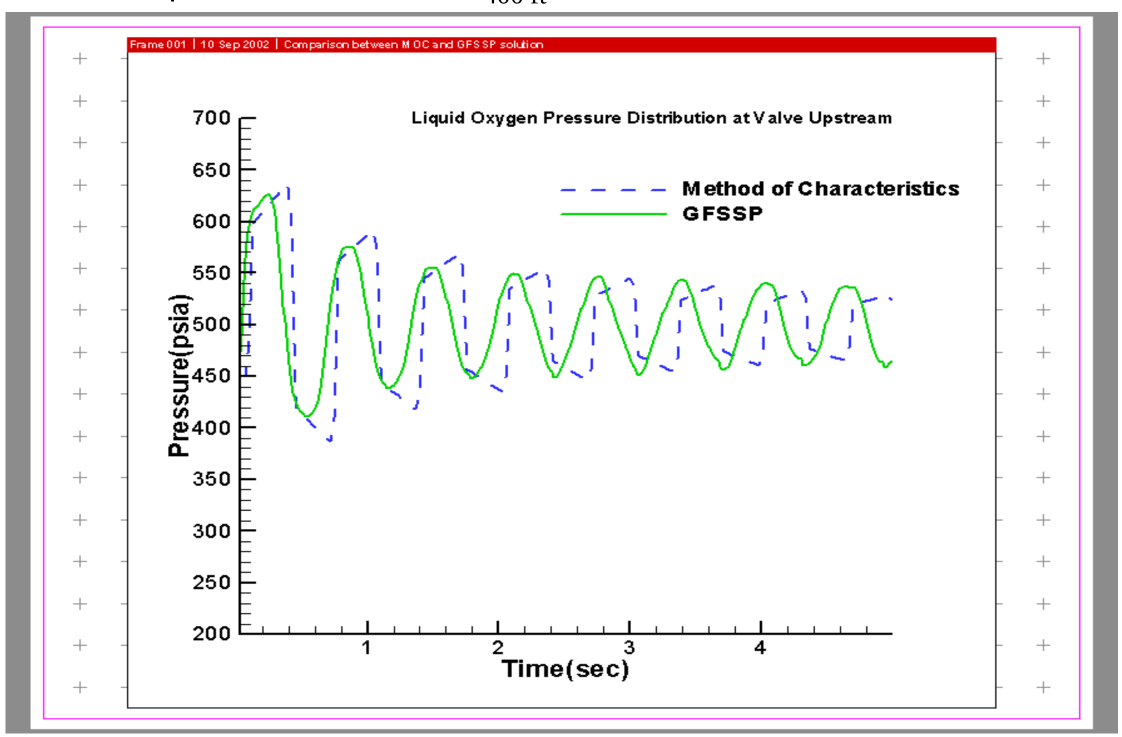
Comparison of LOX Ullage Pressure with Test Data



APPLICATIONS - 8

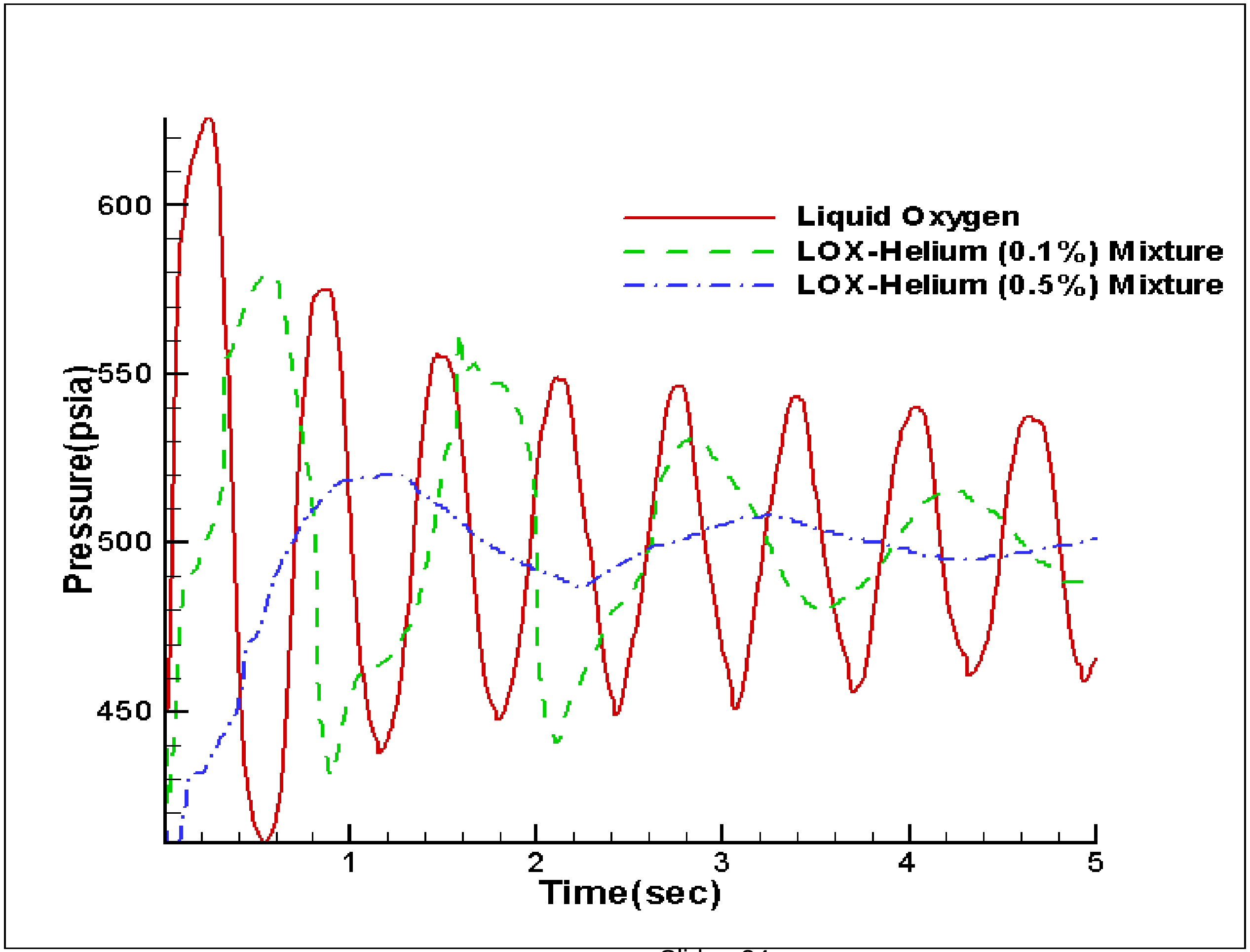
Verification of Fluid Transient Computation





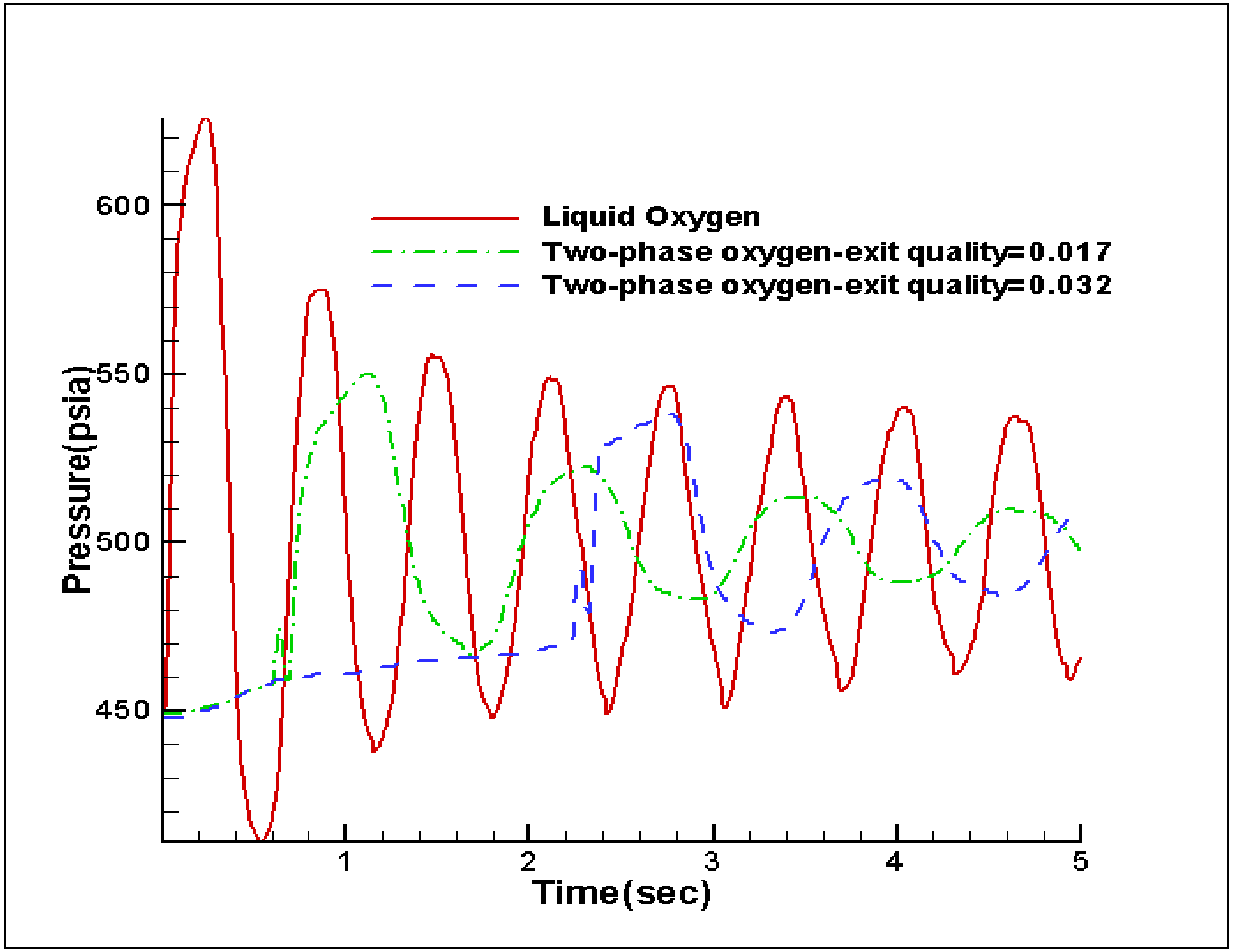
APPLICATIONS - 9

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

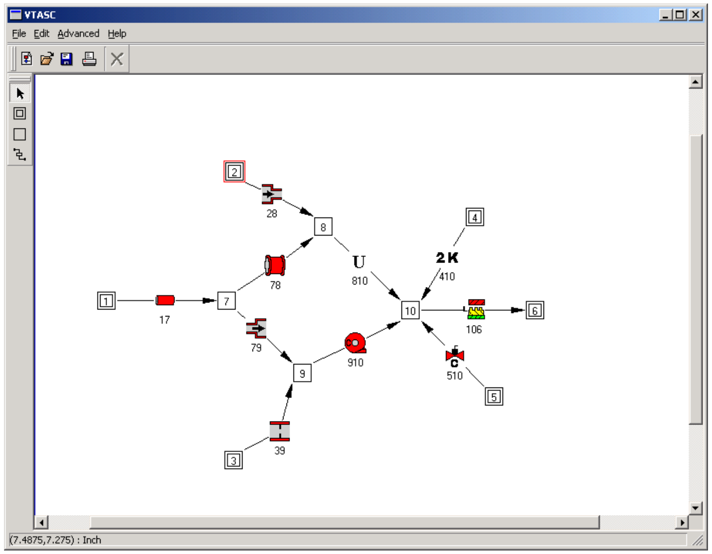
SUMMARY – 2

- 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



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

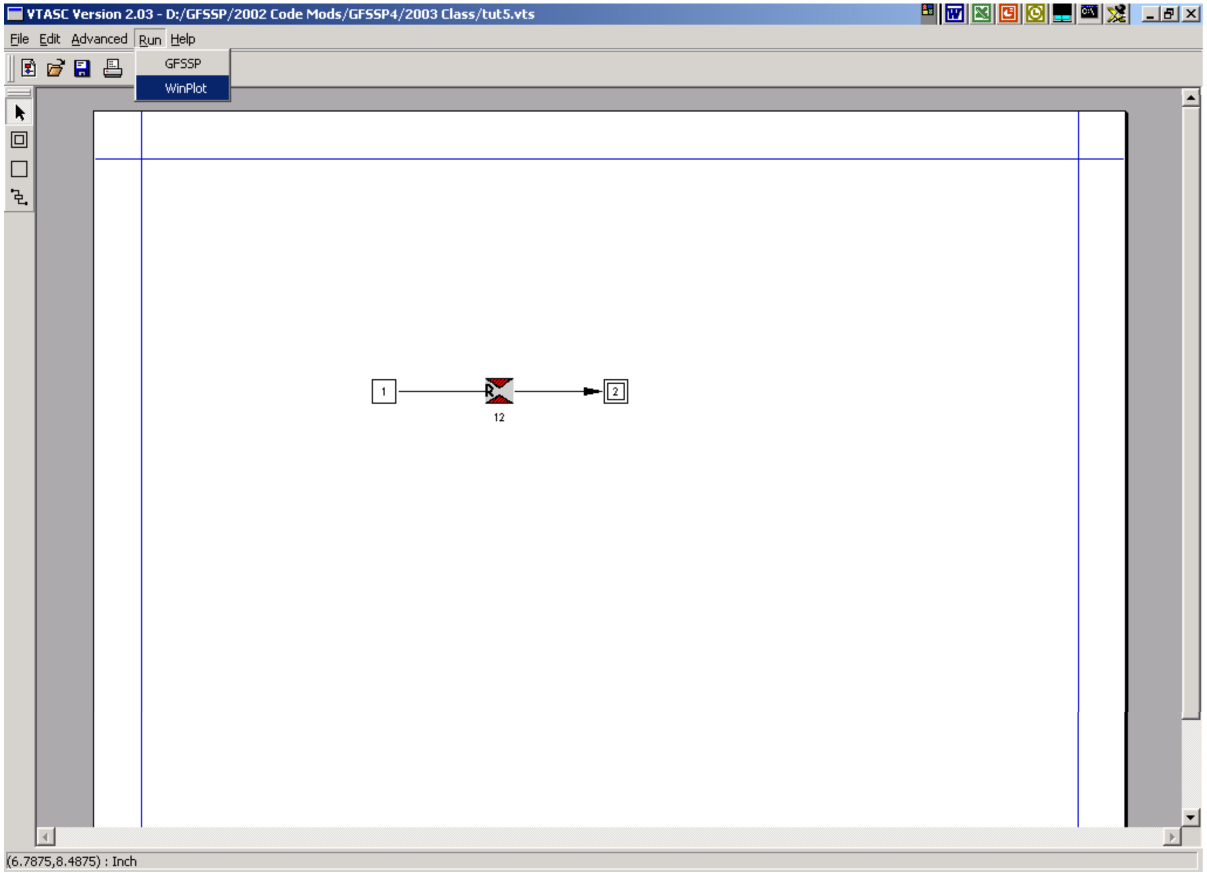
BACKGROUND -2

- 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

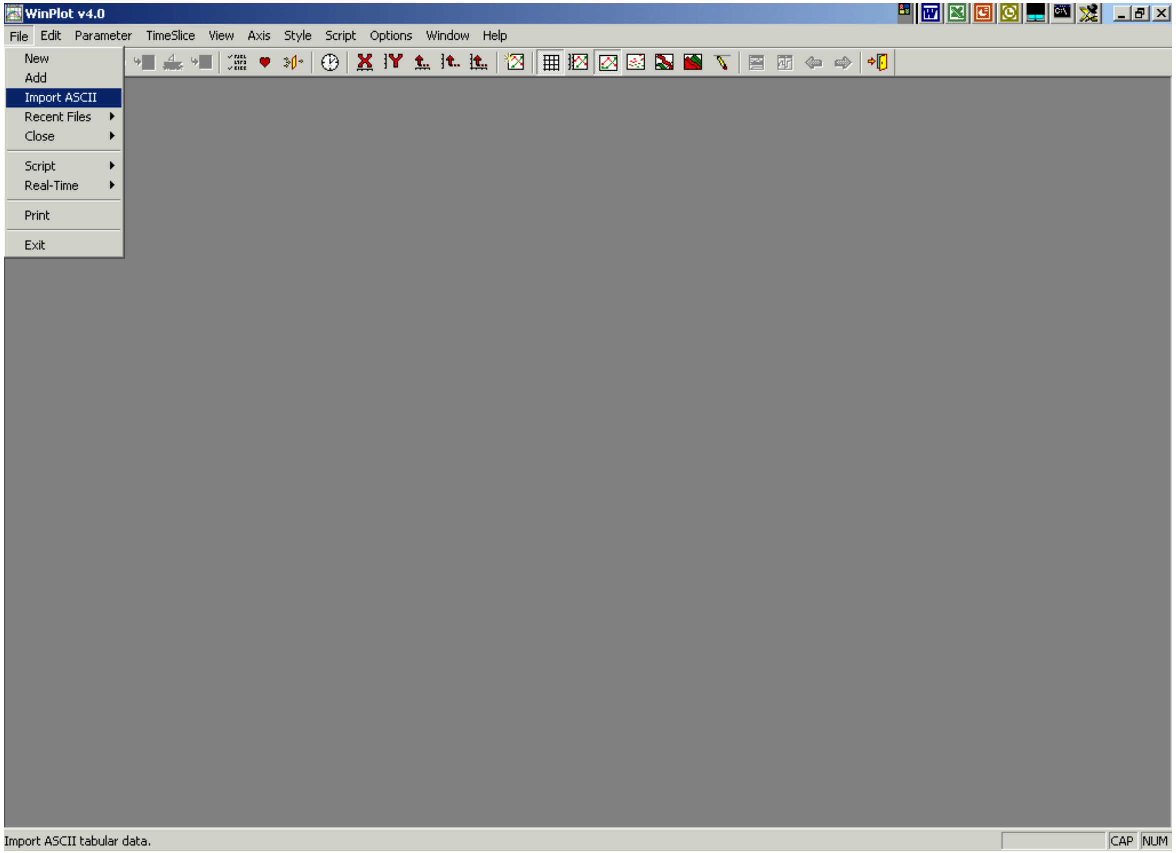
- Post-processing capability allows quick study of results
  - Pushbutton access to GFSSP output file
  - Point and click access to output at each node and branch
  - Built-in plotting capability for transient cases
  - Capable of plotting through Winplot
- Cross platform operation
  - Program written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

CREATING A CHART IN WINPLOT -1



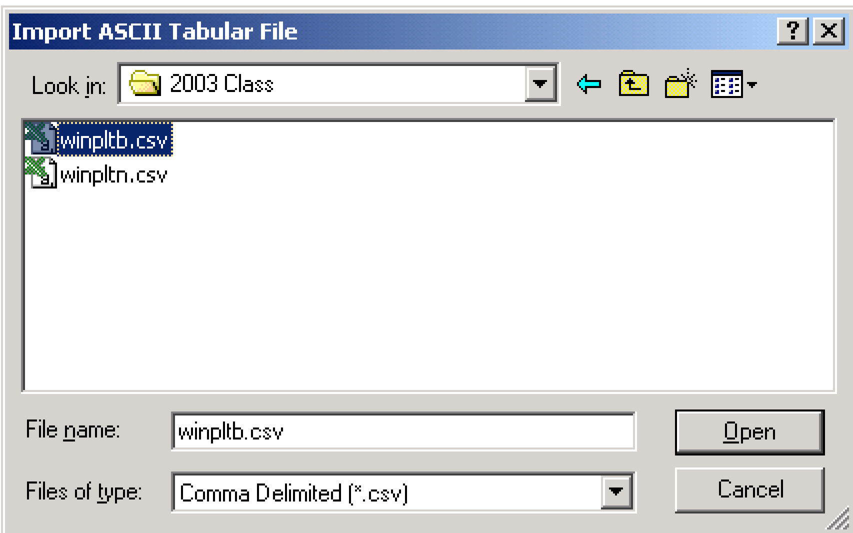
•After completing a model run, select Winplot from the VTASC Run Menu

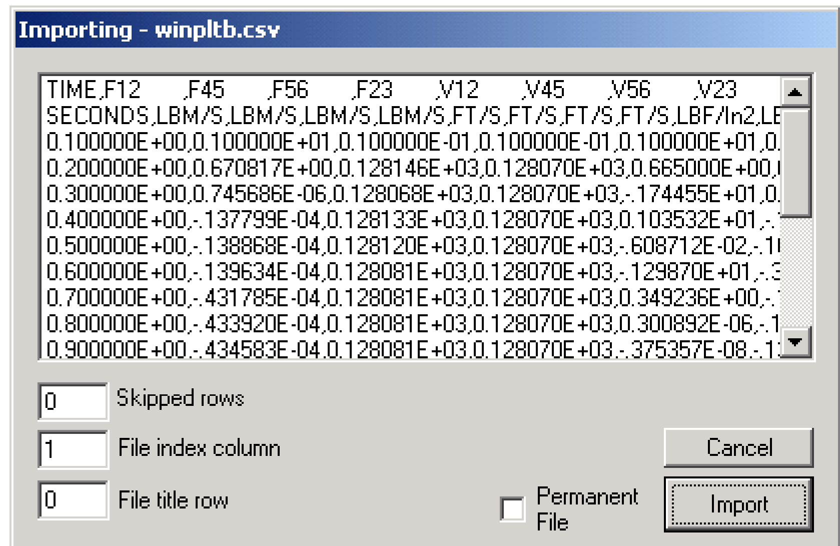
CREATING A CHART IN WINPLOT -2



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

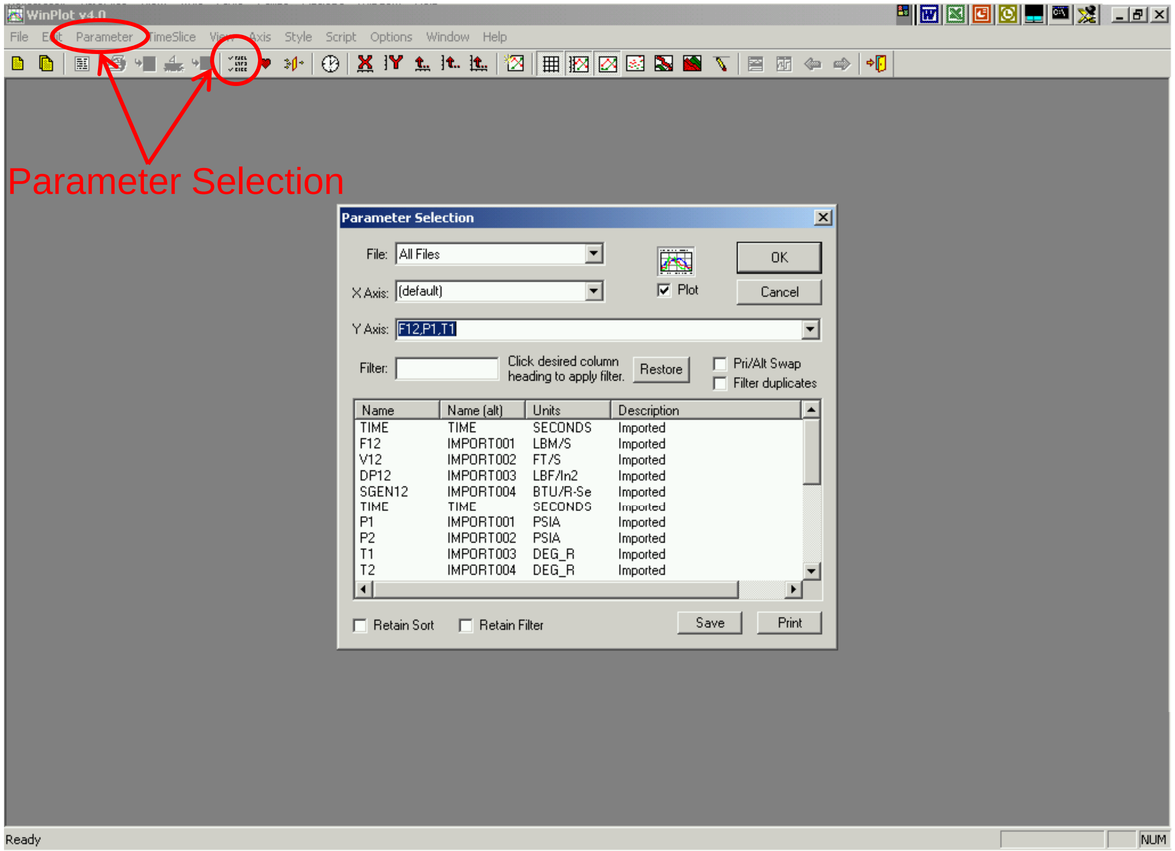
CREATING A CHART IN WINPLOT -3





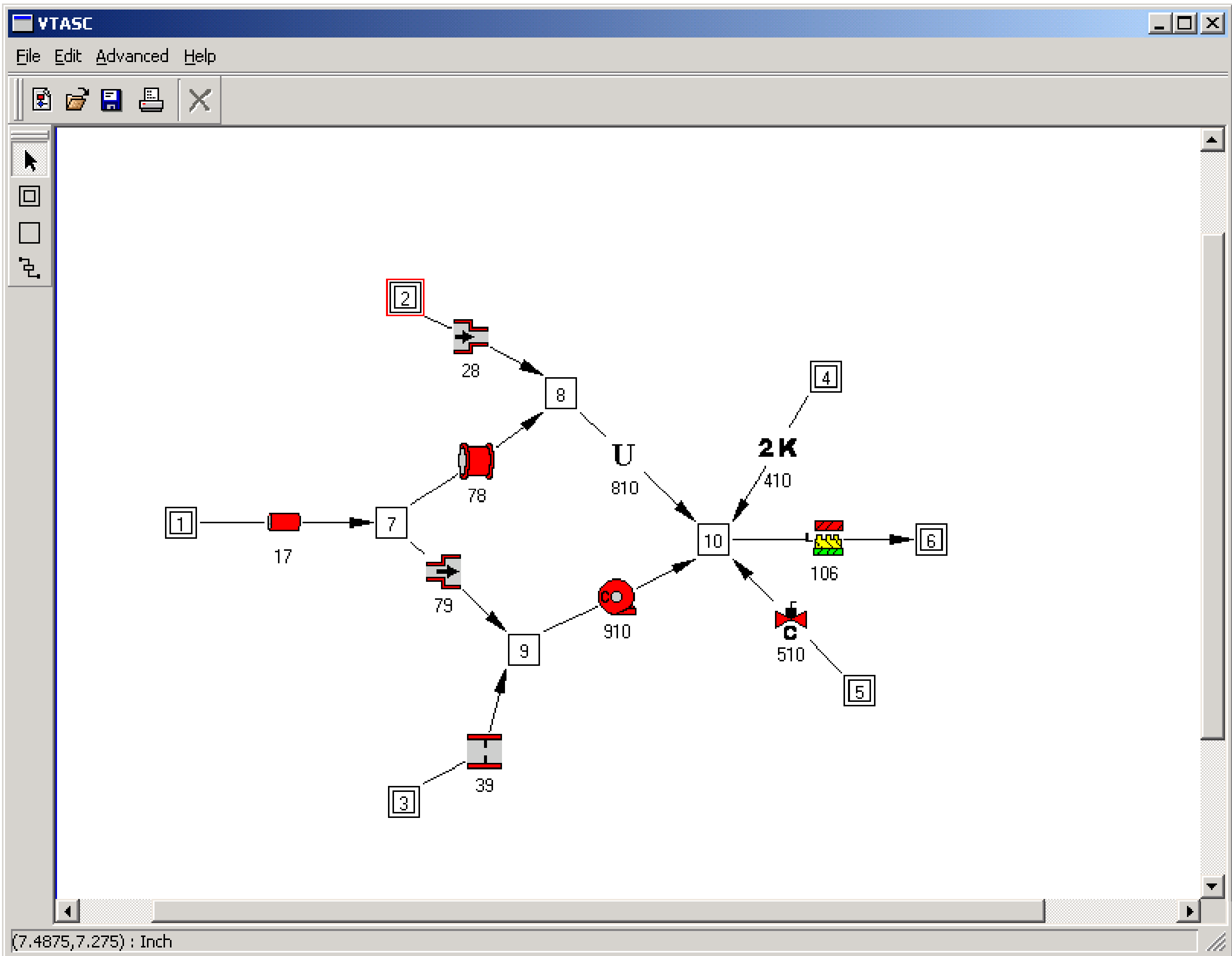
- Use the Browse window to select the files you wish to import
- The default GFSSP Winplot files are “winpltb.csv” & “winpltn.csv”
- Selecting a file opens the Importing window. Click Import.

CREATING A CHART IN WINPLOT -4

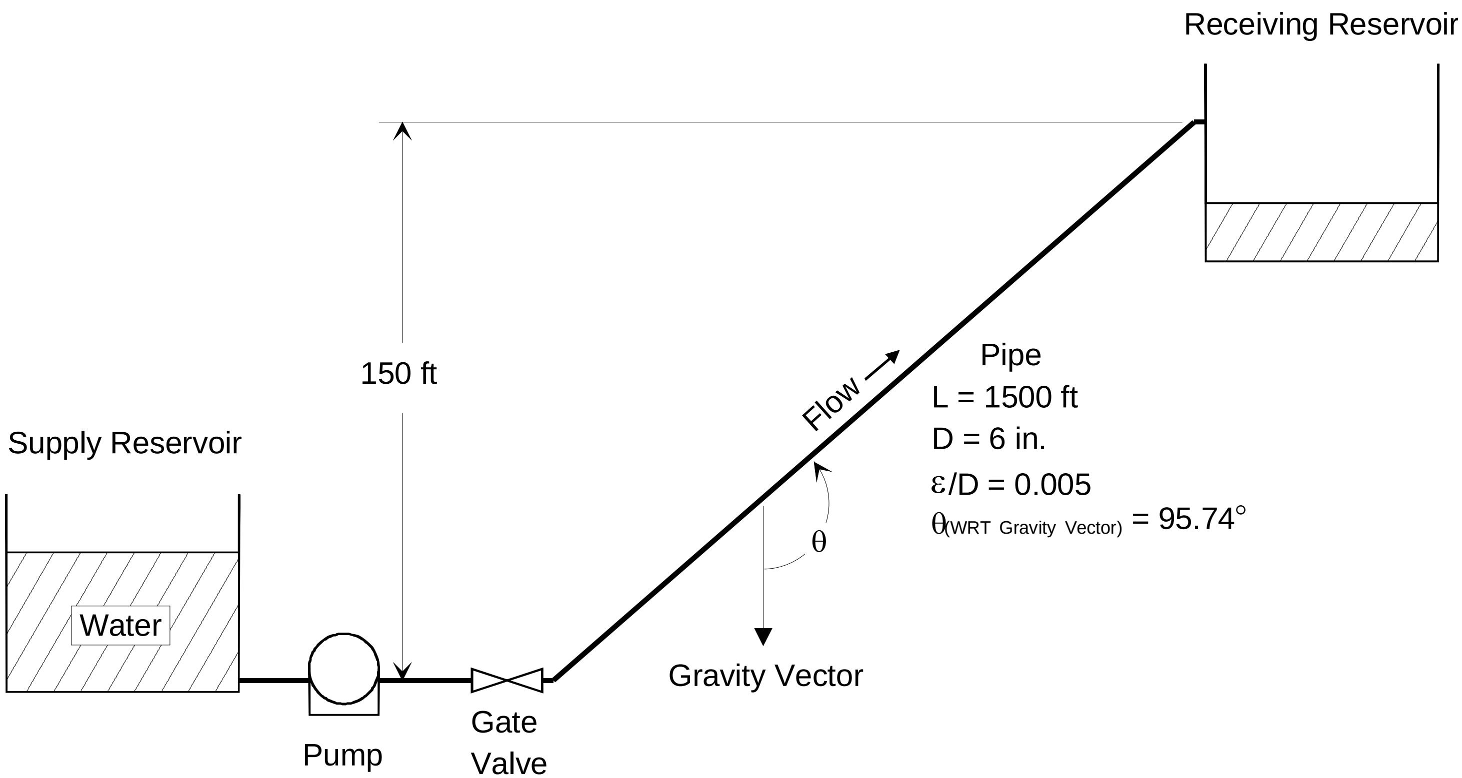


•From the Parameter Selection window, select the data you wish to plot

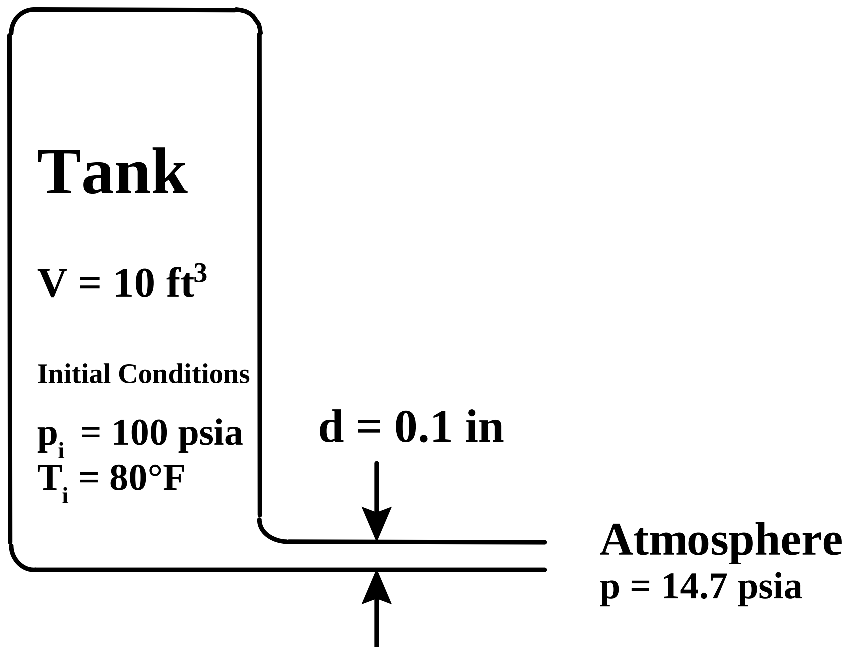
DEMONSTRATION



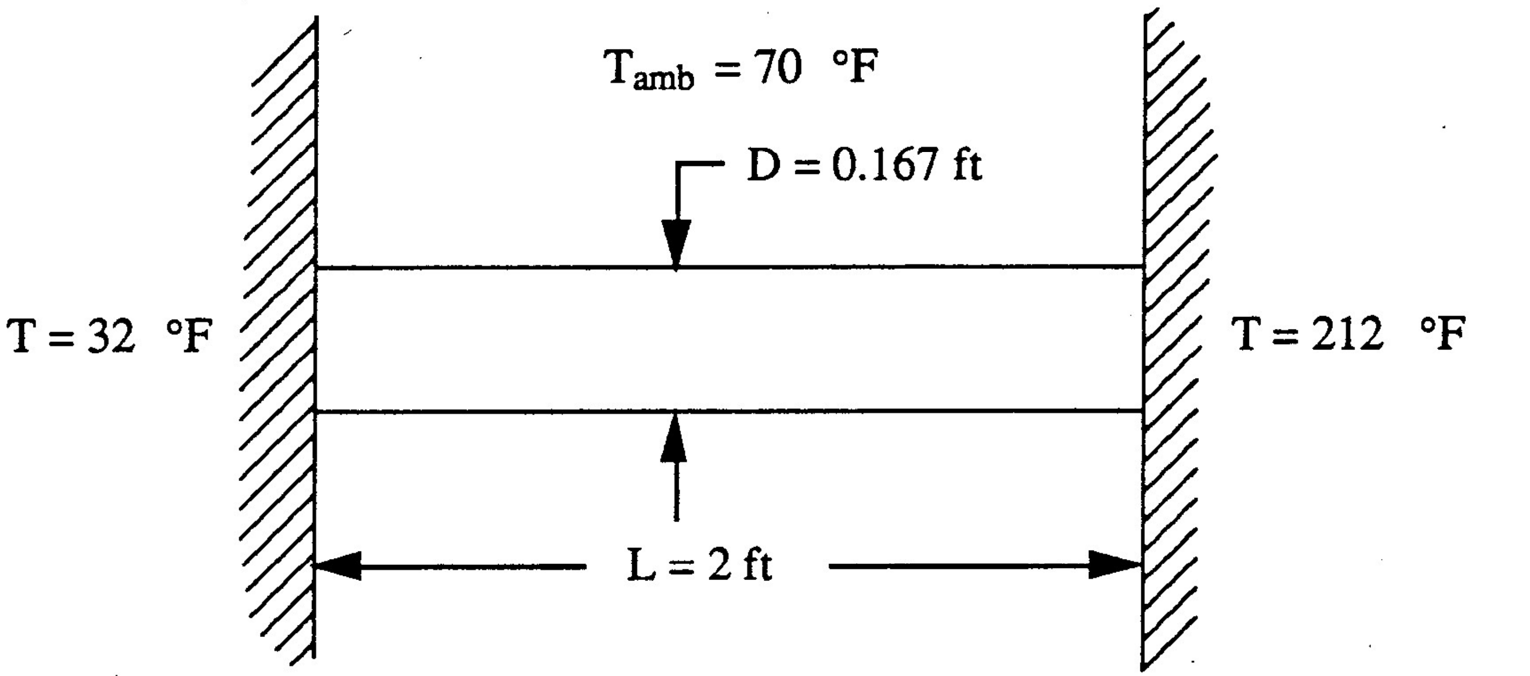
VTASC DEMONSTRATION PROBLEMS -1



VTASC DEMONSTRATION PROBLEMS -2



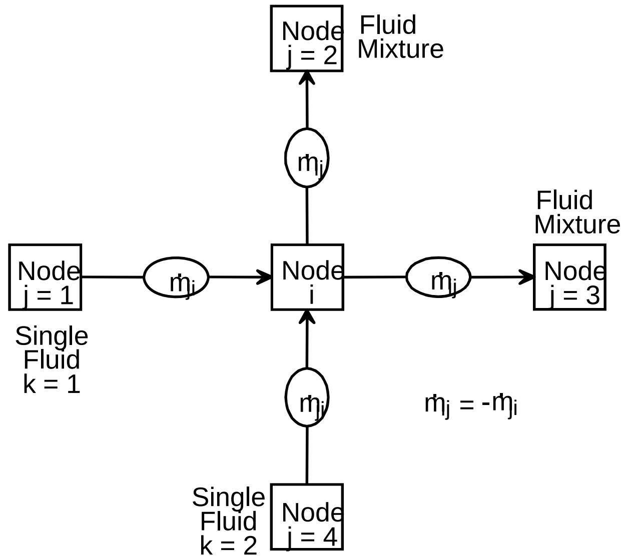
VTASC DEMONSTRATION PROBLEMS -3



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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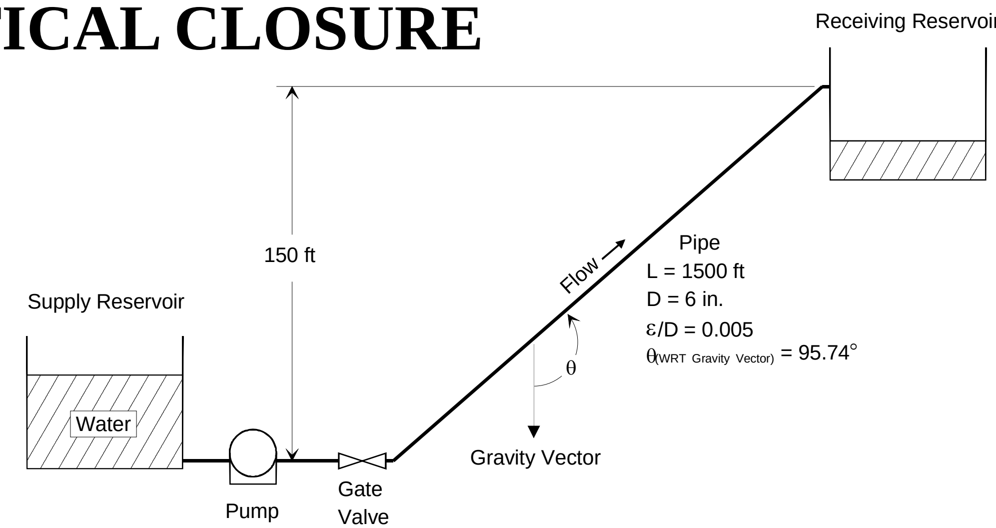
Content

- Mathematical Closure
- Governing Equations
- Solution Procedure

MATHEMATICAL CLOSURE



Problem of a Steady State Flow Network

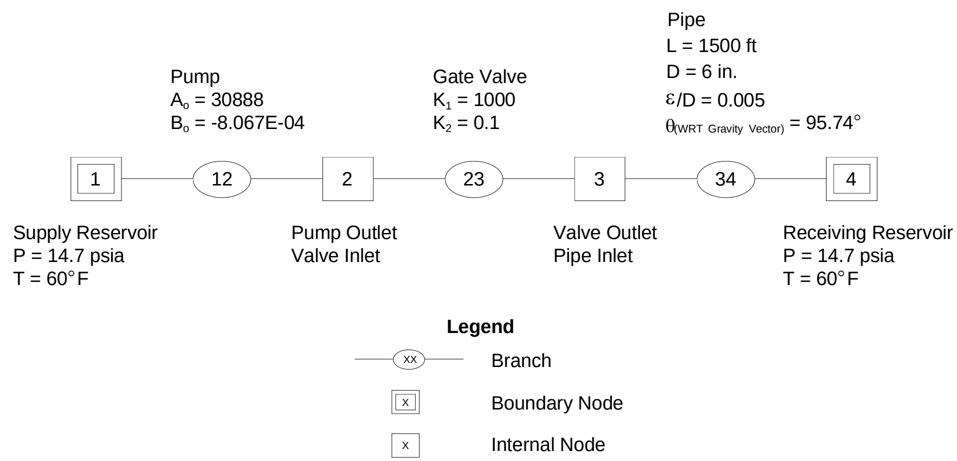
- **Given** : Pressures and Temperatures at Boundary Nodes
- **Find** : Pressures and Temperatures at Internal Nodes and Flowrates in Branches

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

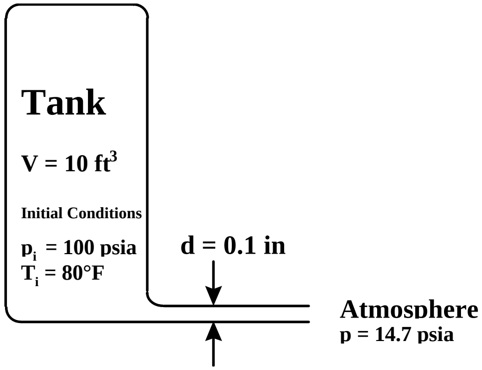
Primary Variables

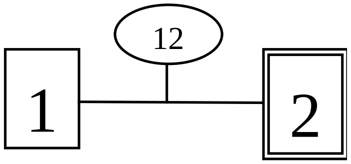
$$p_1(\tau), T_1(\tau), m_1(\tau), \dot{m}(\tau)$$

Secondary Variables

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

- **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.





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

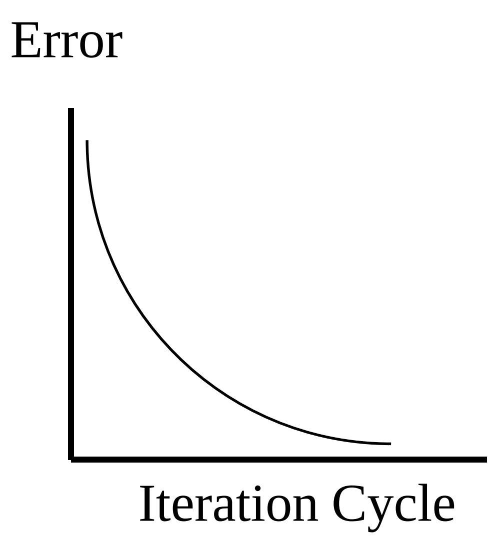
p – Pressure

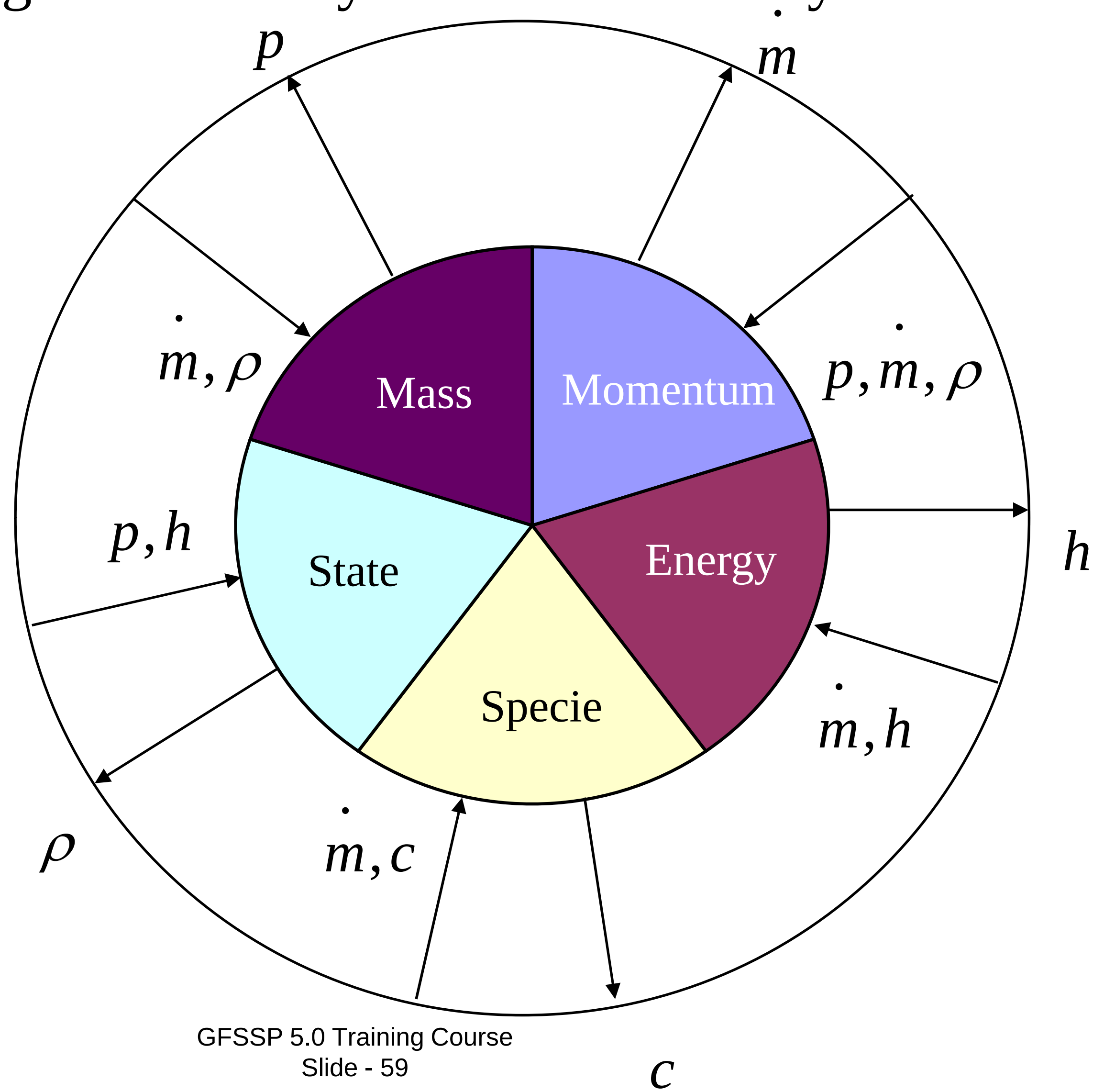
$\dot{m}$ - Flowrate

h - Enthalpy

c - Concentration

ρ - Density

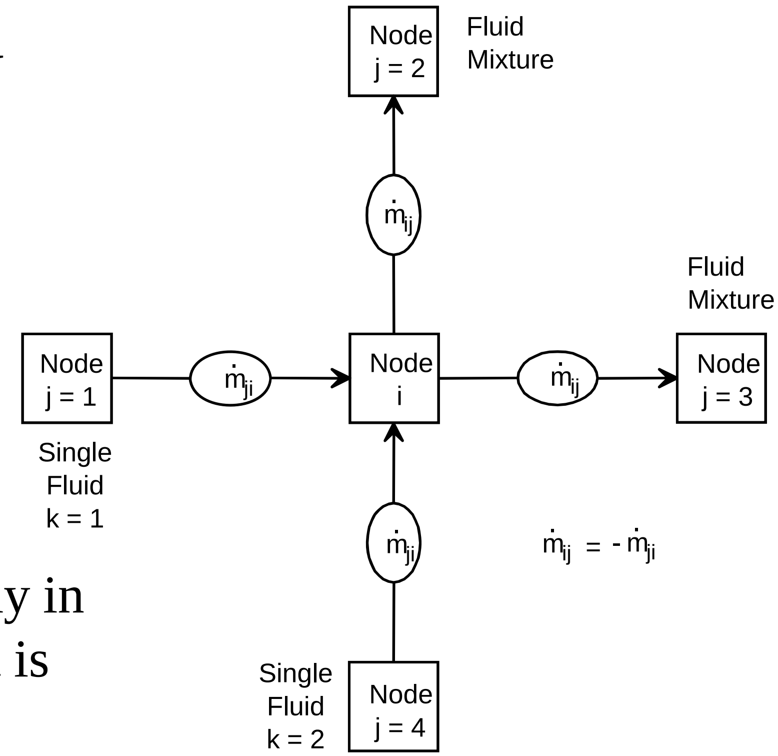




GOVERNING EQUATIONS

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

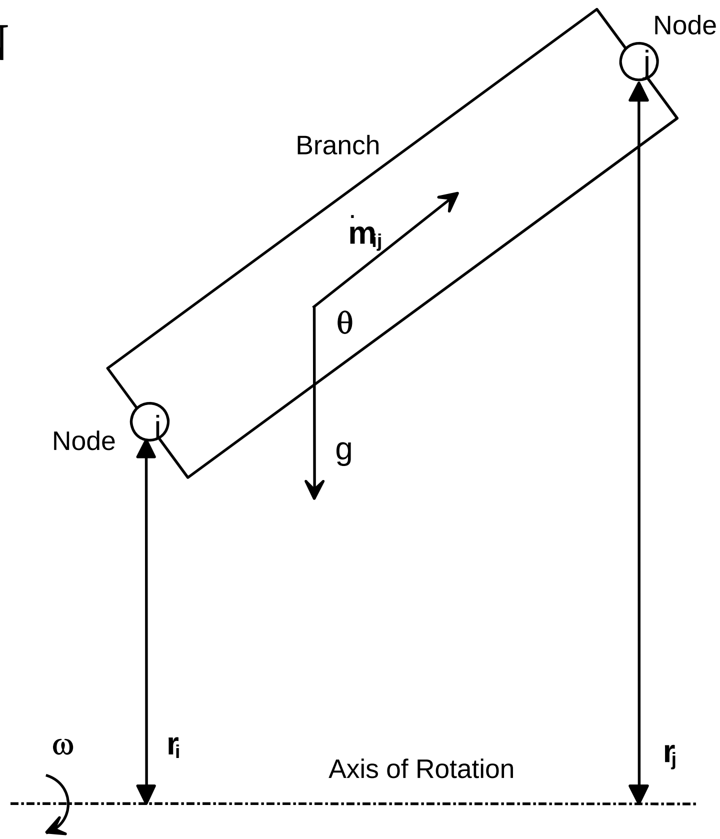
MOMENTUM CONSERVATION EQUATION

- Represents Newton's Second Law of Motion

Mass x Acceleration = Forces

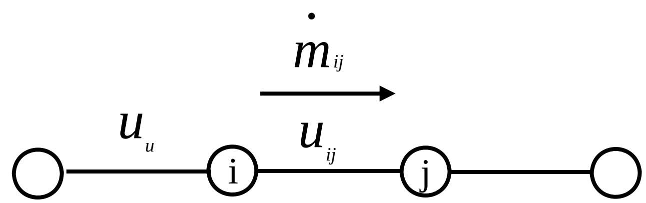
- Unsteady
- Longitudinal Inertia
- Transverse Inertia

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



MOMENTUM CONSERVATION EQUATION

Mass x Acceleration Terms in GFSSP



<u>Unsteady</u>

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

<u>Longitudinal Inertia</u>

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

MOMENTUM CONSERVATION EQUATION

Force Terms in GFSSP

Pressure

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

Gravity

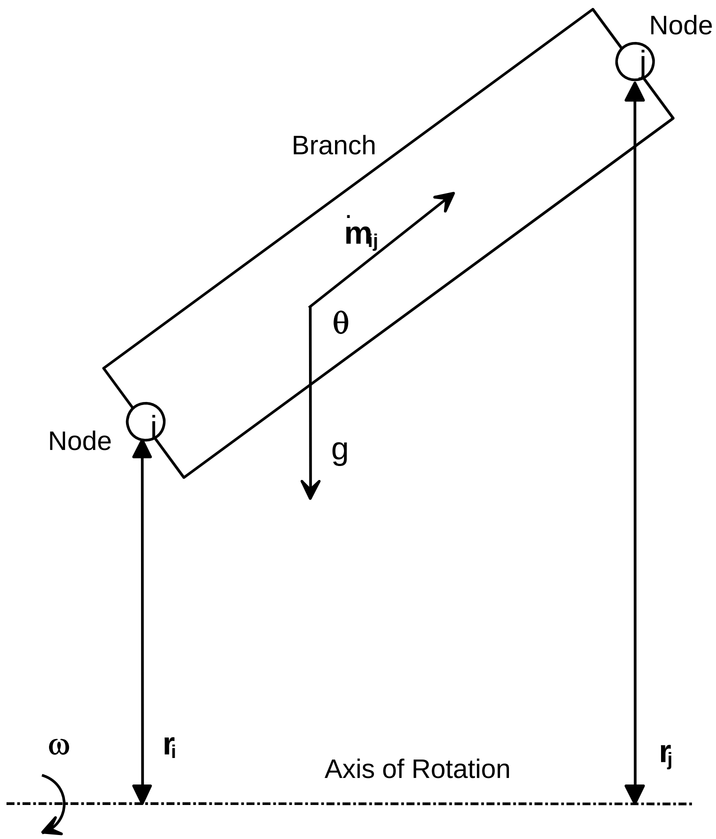
$$\frac{\rho g V Cos\theta}{g_c}$$

Friction

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

Centrifugal

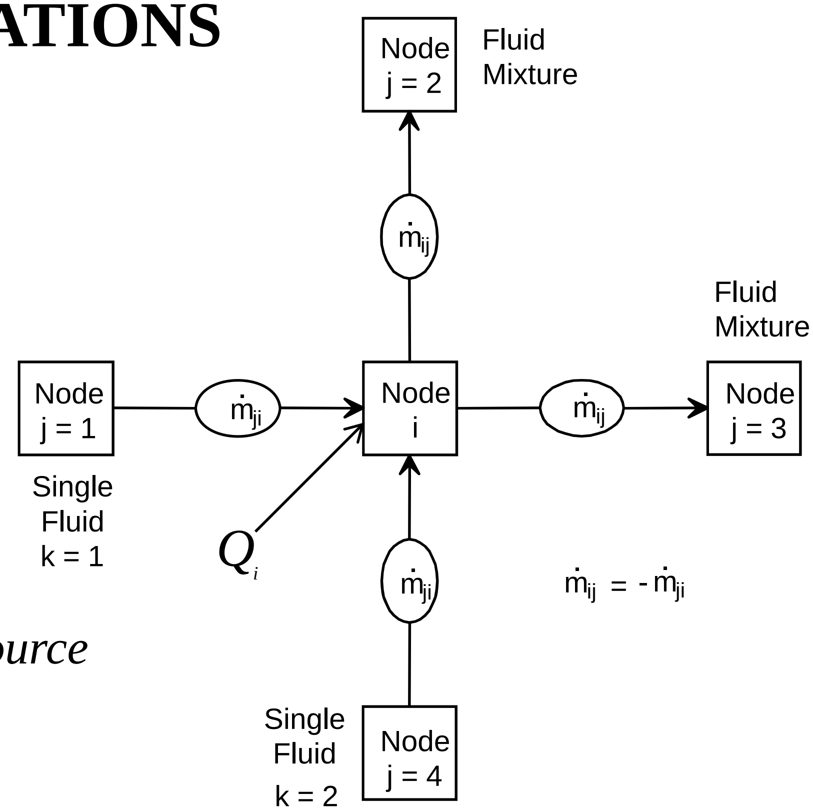
$$\frac{\rho K_{rot}^2 \omega^2 A}{g_c}$$



GOVERNING EQUATIONS

ENERGY CONSERVATION EQUATION

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



<u>Enthalpy Equation</u>

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

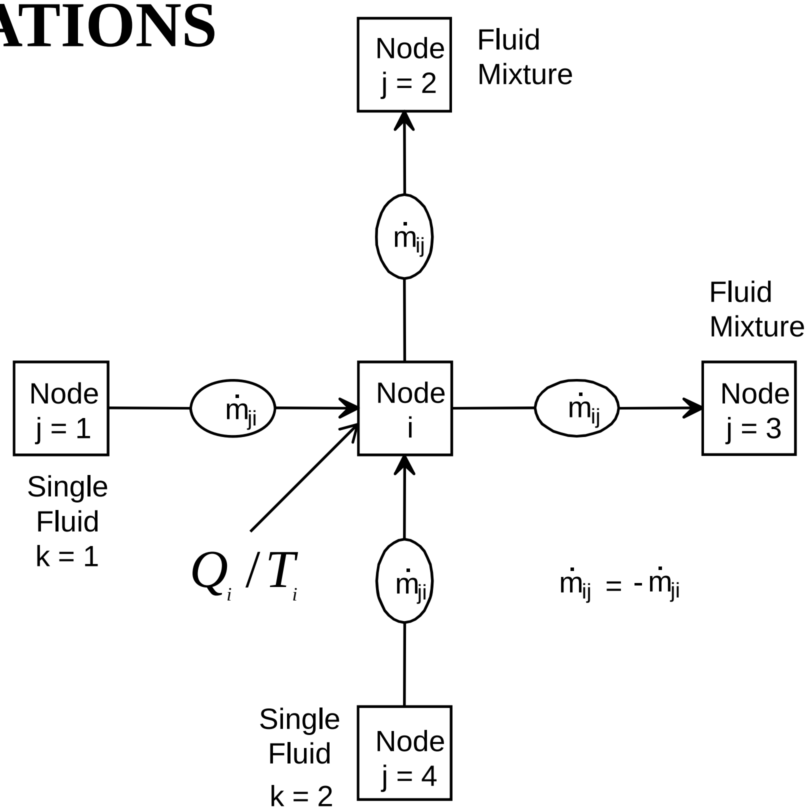
ENERGY CONSERVATION EQUATION

Entropy Equation

Rate of Increase of Entropy =

Entropy Inflow - Entropy Outflow +

Entropy Generation + Entropy Source



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

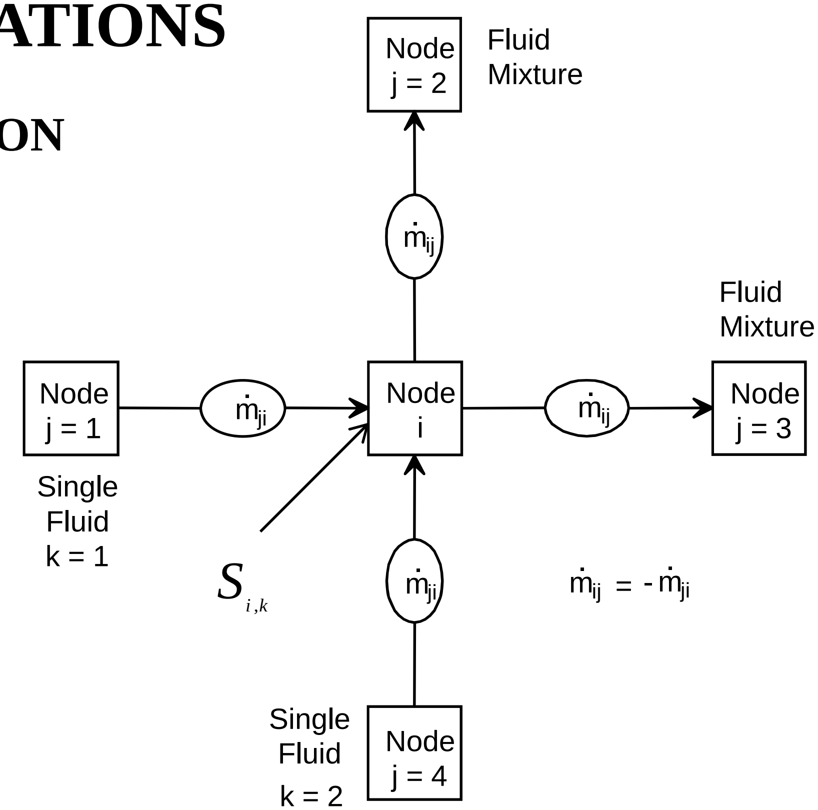
GOVERNING EQUATIONS

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

$$\rho_i = \frac{p_i}{z_i R_i T_i} \qquad R_i = \sum_{k=1}^{k=n} x_k R_k$$

- Compressibility Factor of Mixture is Mole average of Individual Components

$$z_i = \sum_{k=1}^{k=n} x_k z_k \qquad z_k = \frac{p_i}{\rho_k R_k T_k}$$

GOVERNING EQUATIONS

Mixture Property Relation

<u>Thermophysical Properties</u>

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

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

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

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

GOVERNING EQUATIONS

Mixture Property Relation

Temperature

• Mixture Temperature is calculated from Energy Conservation Equation

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

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

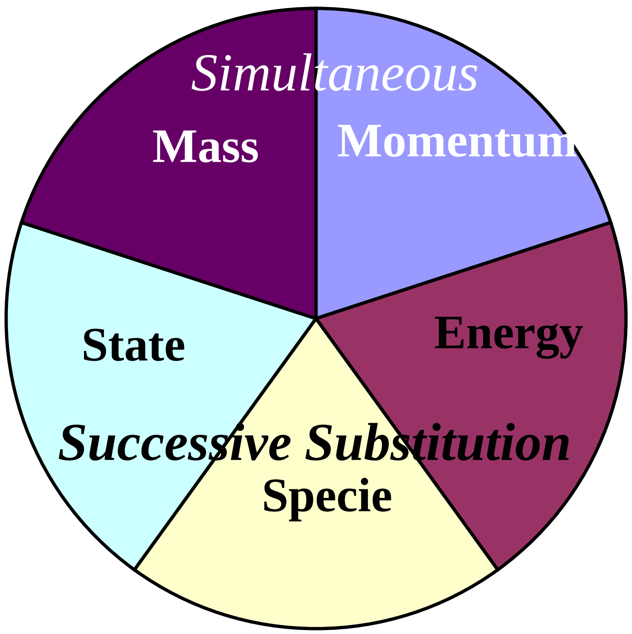
- **SASS is a combination of successive substitution and Newton-Raphson method**
- **Mass conservation and flowrate equations are solved by Newton-Raphson method**
- **Energy Conservation and concentration equations are solved by successive substitution method**
- **Underlying principle for making such 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, Δ_{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

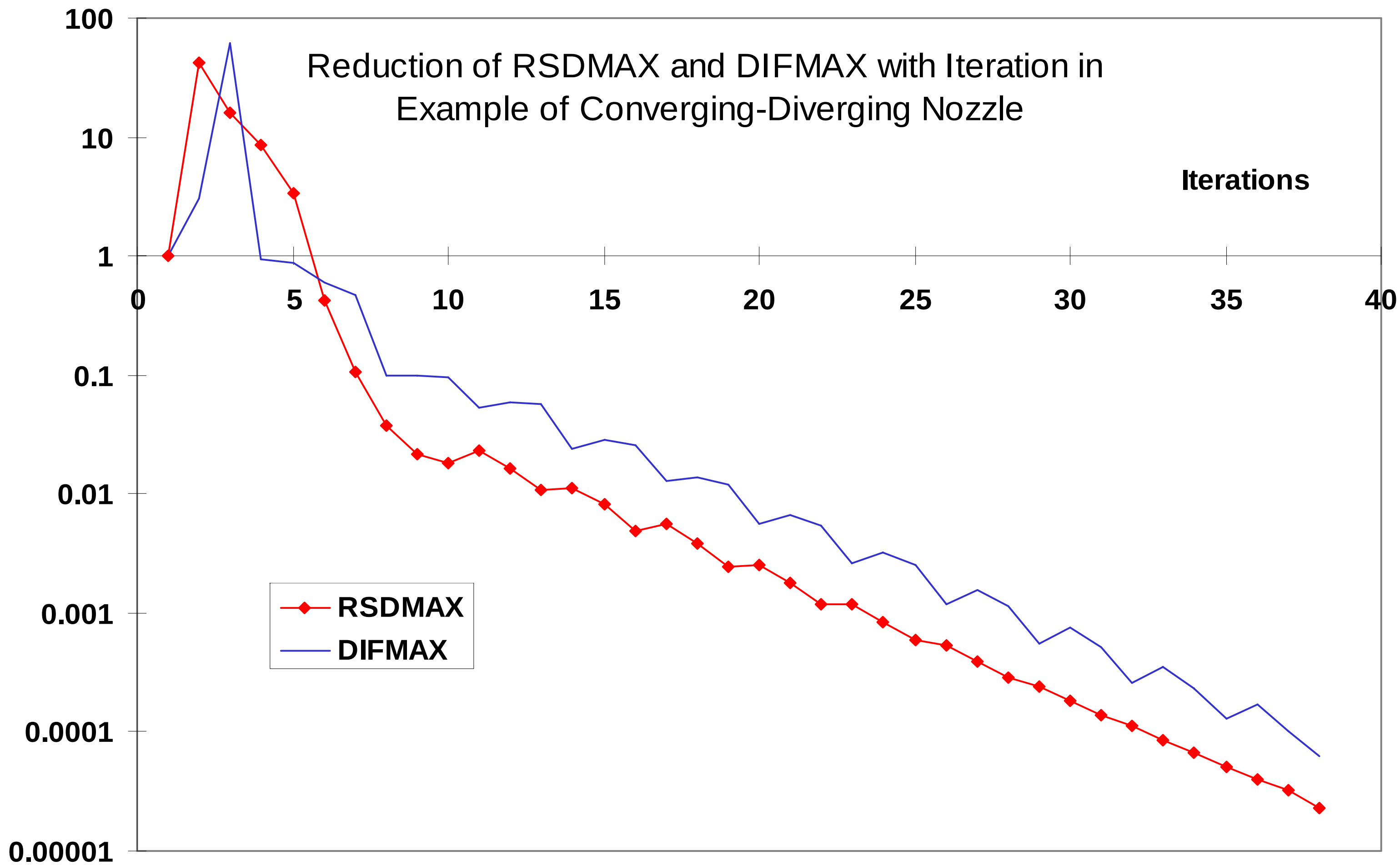
CONVERGENCE

Non-Simultaneous Option

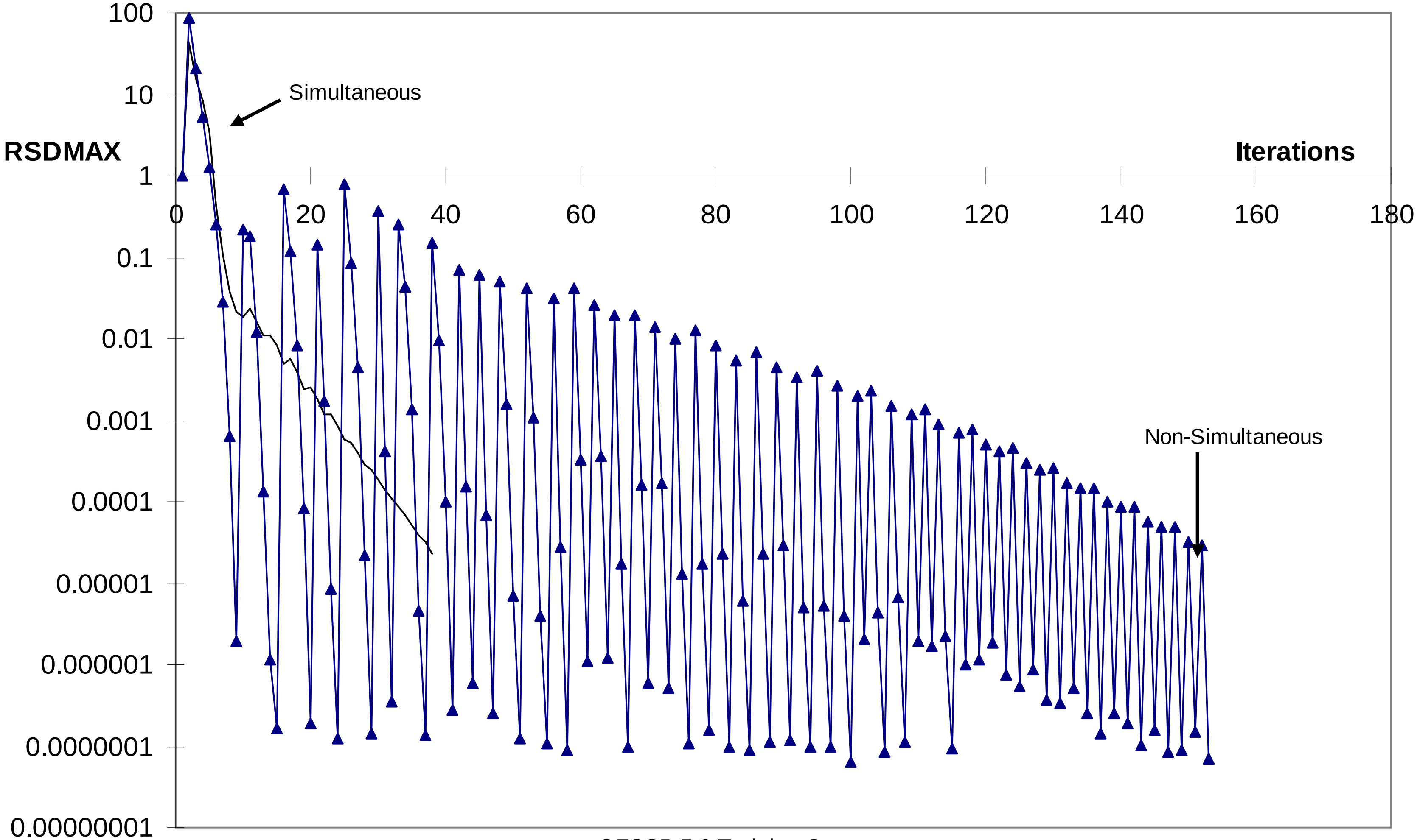
- Inner & Outer Iteration Loop
  - Mass, Momentum and Equation of state is solved in inner iteration loop by NR scheme
  - Energy and Specie conservation equations are solved in outer iteration loop by SS scheme
  - Convergence of NR scheme is determined by Δ_{max}
  - Convergence of SS scheme is determined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

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

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

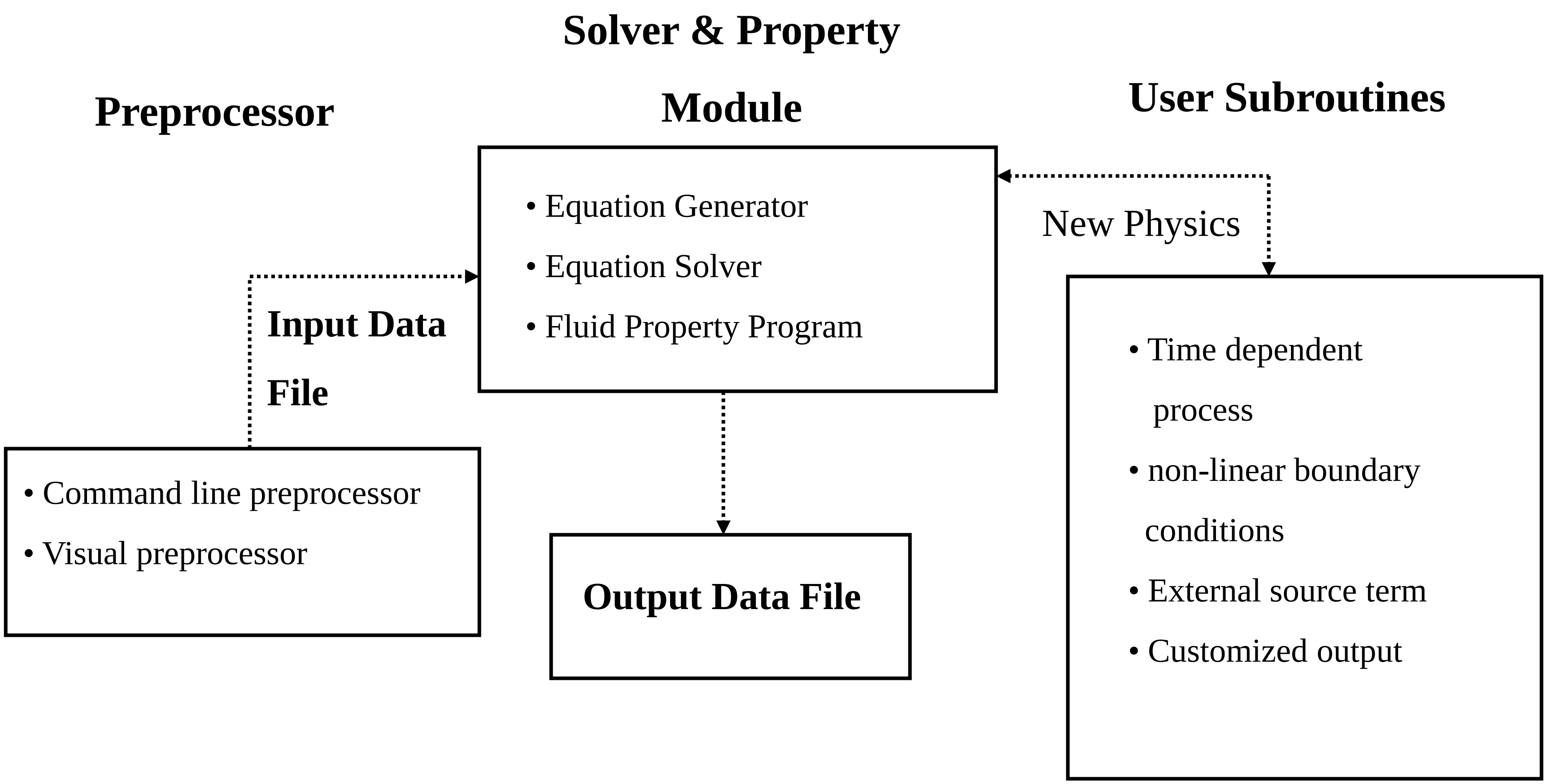
- The subroutines do not have any code but includes the common block

- 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
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

Solver Module/function		**User Subroutine/**function
ENTHALPY/ ENTROPY Generates and solves the energy conservation equation	⟷	**SORCEQ** Allows user to provide an external heat source
MASSC Generates and solves the specie conservation equation	⟷	**SORCEC** Allows user to provide an external specie source
RESIST Calculates the flow resistance coefficient	⟷	**KFUSER** Allows user to define new resistance options
DENSITY Calculates the fluid properties	⟷	**PRPUSER** Allows user to define new fluid properties
PRINT Generates the Output files	⟷	**PRNUSER** 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

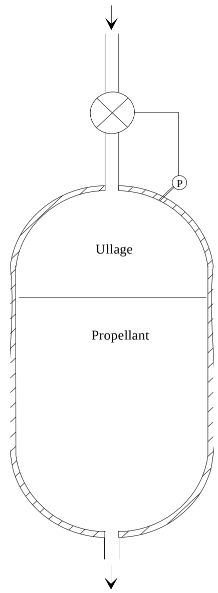
NODE & BRANCH INDEX

- 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

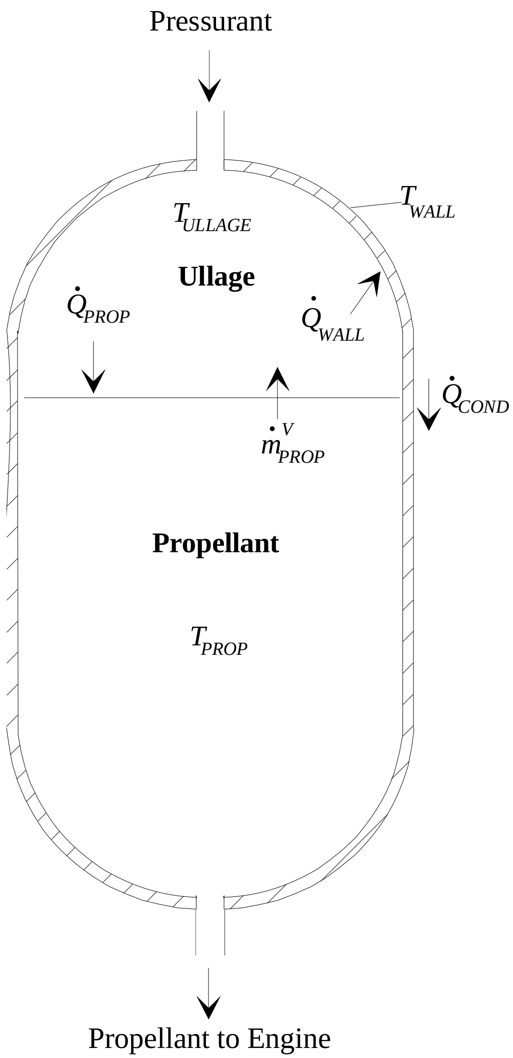
TANK PRESSURIZATION



TANK PRESSURIZATION

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

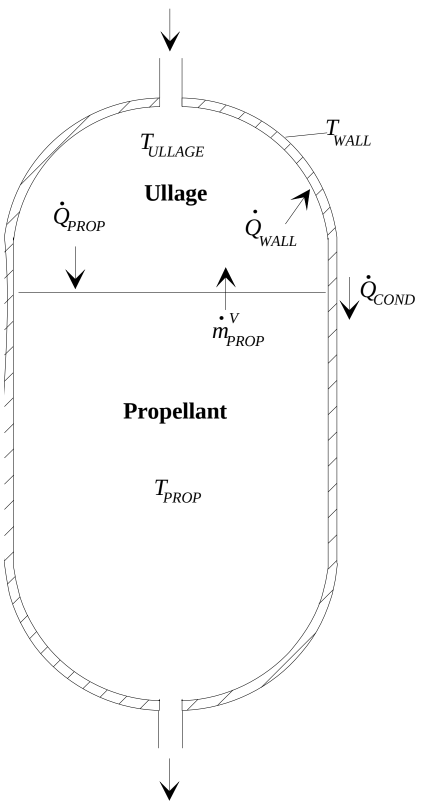
- Predict the propellant conditions leaving the tank



TANK PRESSURIZATION

ADDITIONAL PHYSICAL PROCESSES

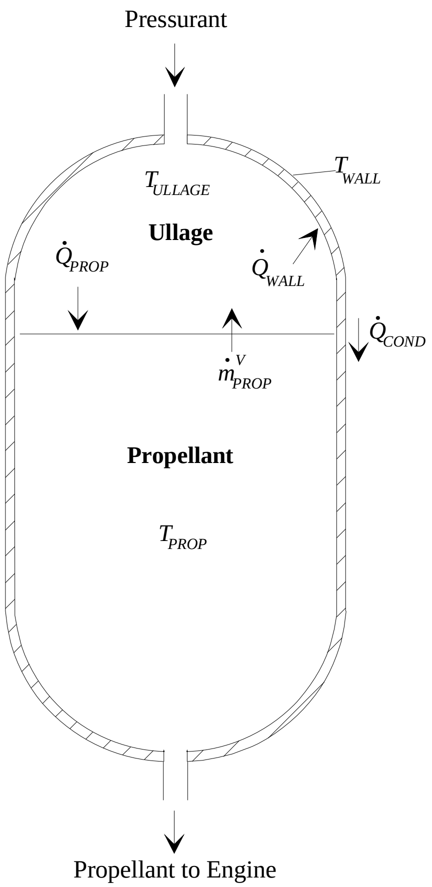
- Change in ullage and propellant volume.
- Change in gravitational head in the tank.
- Heat transfer from pressurant to propellant.
- Heat transfer from pressurant to the tank wall.
- Heat conduction between the pressurant exposed tank surface and the propellant exposed tank surface.
- Mass transfer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



TANK PRESSURIZATION
CALCULATION STEPS

For each time step calculate

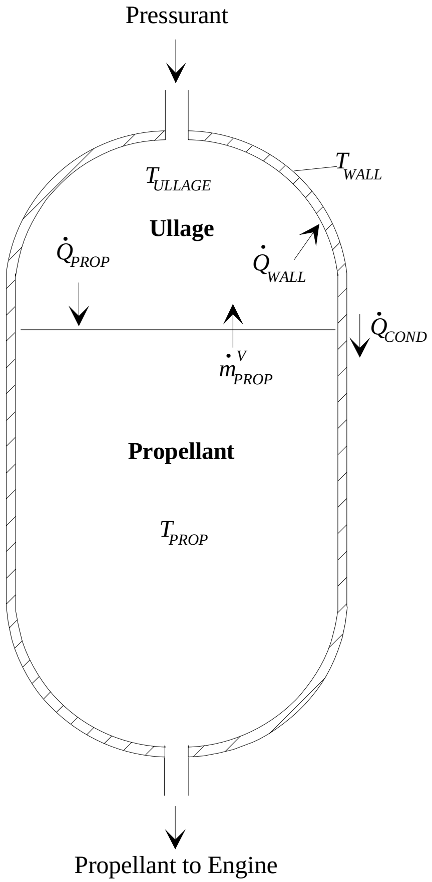
- Ullage and Propellant Volumes
- Tank Bottom Pressure
- Heat Transfer between pressurant and propellant and pressurant and wall
- Wall Temperature
- Mass Transfer from propellant to ullage



TANK PRESSURIZATION

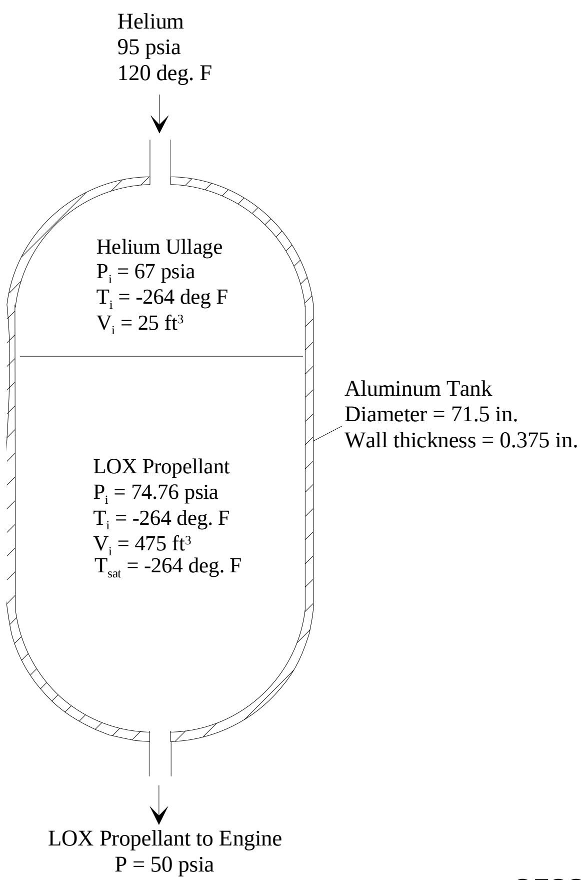
ADDITIONAL INPUT DATA FOR PRESSURIZATION

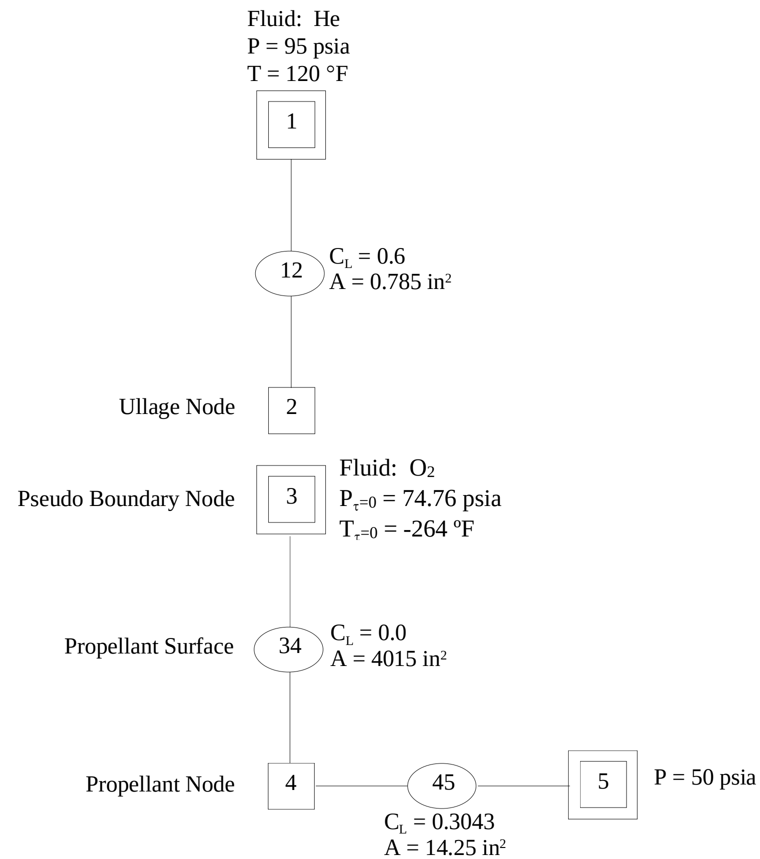
PRESS	Logical Variable to Activate the Option
NTANK	Number of Tanks in the Circuit
NODUL	Ullage Node
NODULB	Pseudo Boundary Node at interface
NODPRP	Propellant Node
IBRPRP	Branch number connecting NODULB & NODPRP
TNKAR	Tank Surface Area in Ullage at Start, in^2
TNKTH	Tank Thickness, in
TNKRHO	Tank Density, 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, ^oF



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
```

<u>Tank Input Units</u>

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 (LBM/FT^3)	EM(LBM)	CONC HE	CONC 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 (LBF-S^2/(LBM-FT)^2)	DELP (PSI)	FLOW RATE (LBM/SEC)	VELOCITY (FT/SEC)	REYN. NO.	MACH NO.	ENTROPY GEN. BTU/(R-SEC)	LOST WORK 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

Tank Output Units

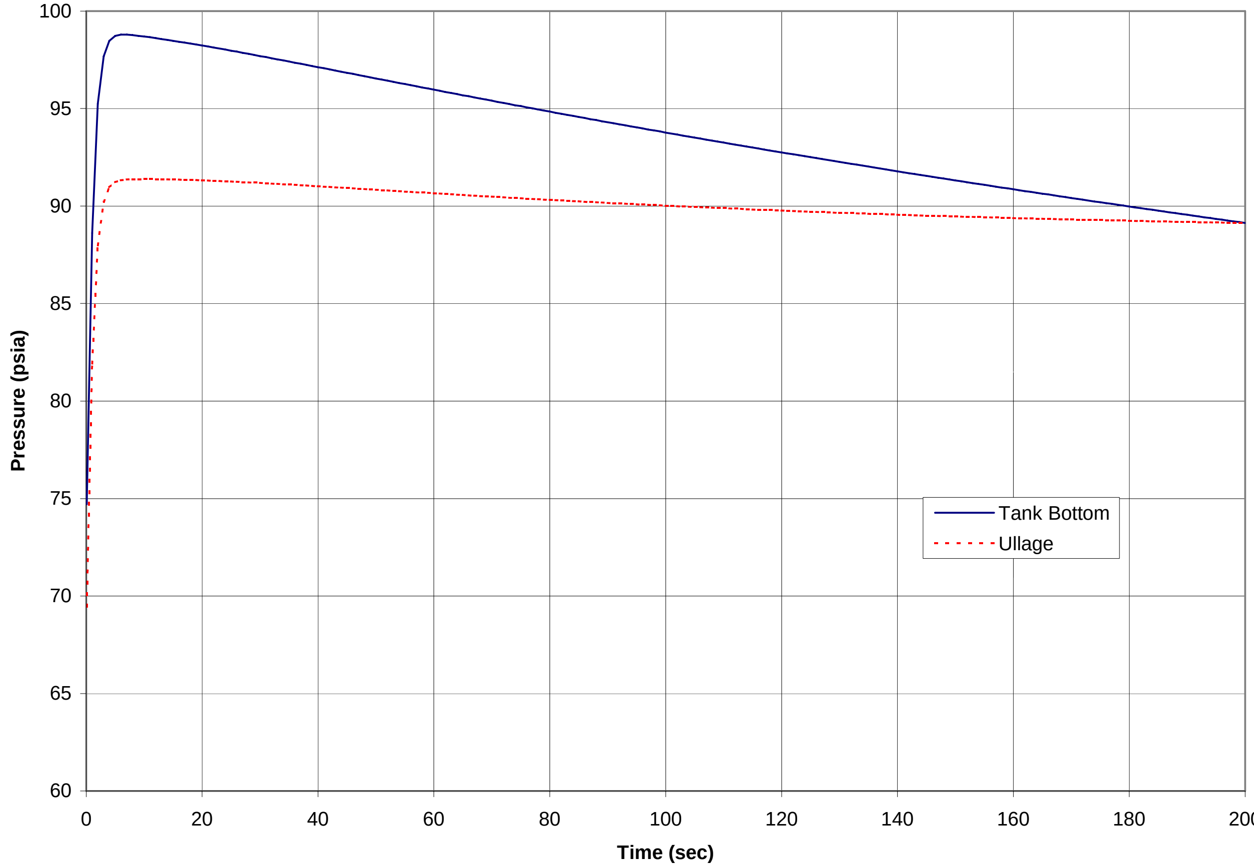
QULPROP, Btu/s
QULWAL, Btu/s
QCOND, Btu/s
TNKTM, deg. R
VOLPROP, ft^3
VOLULG, ft^3

SOLUTION SATISFIED CONVERGENCE CRITERION OF 0.100E-02 IN 5 ITERATIONS

TAU = 10.0000 ISTEP = 100

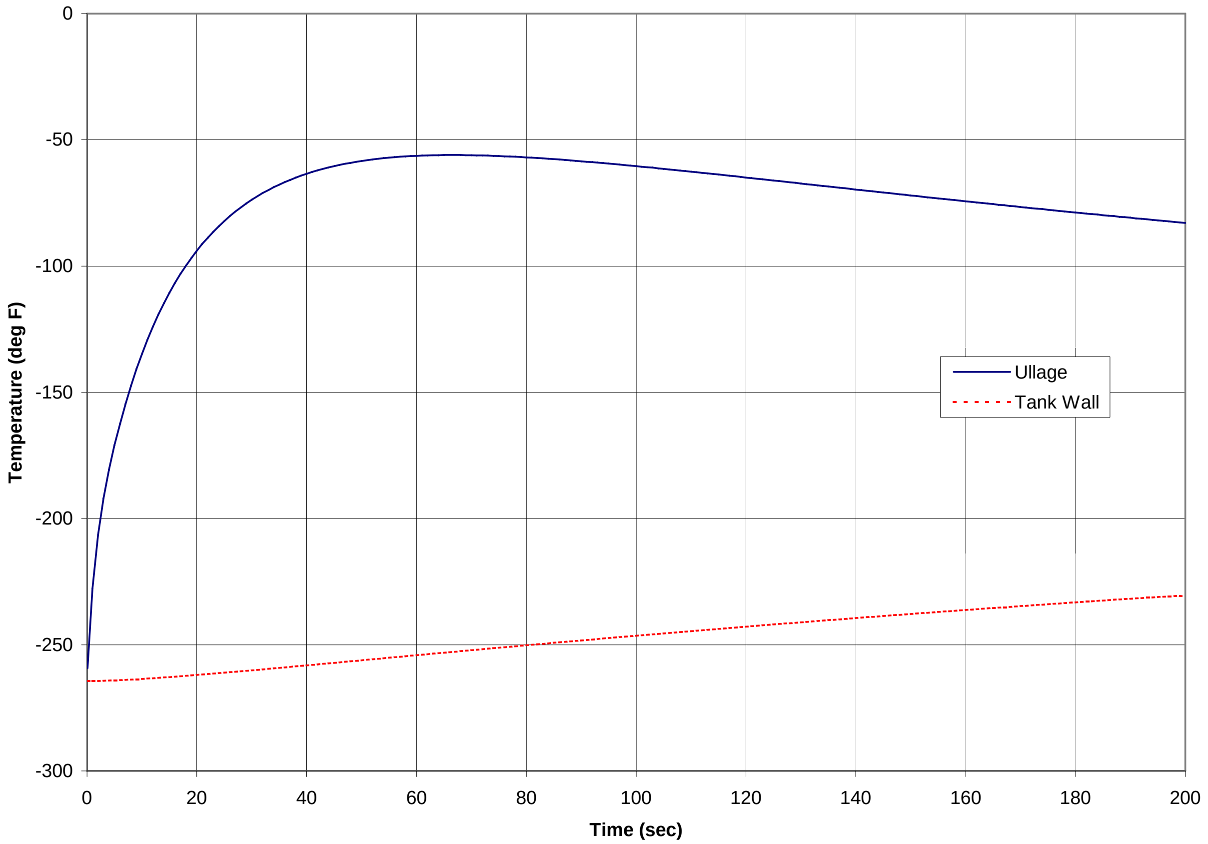
TANK PRESSURIZATION

EXAMPLE 10 ULLAGE AND TANK BOTTOM PRESSURE HISTORY



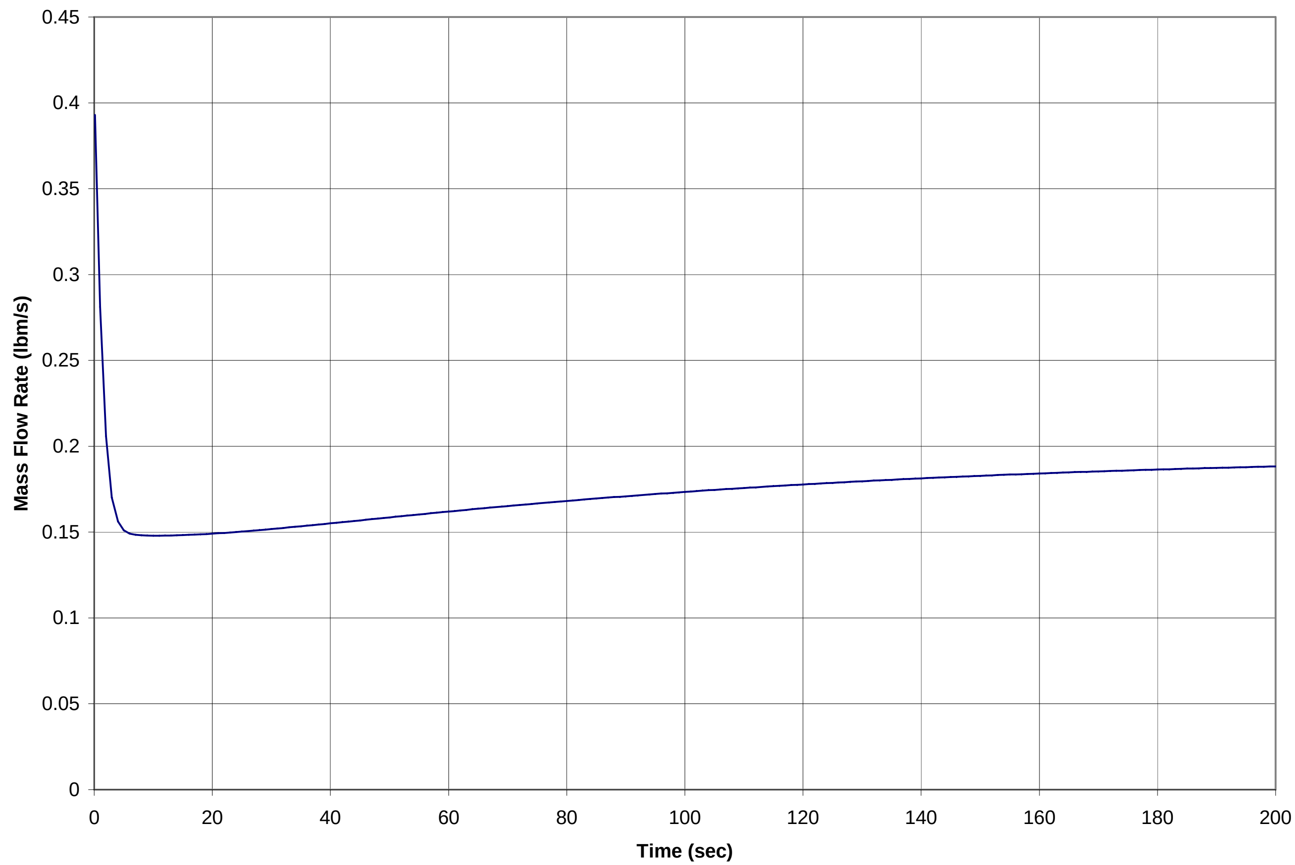
TANK PRESSURIZATION

EXAMPLE 10 ULLAGE AND TANK WALL TEMPERATURE HISTORY

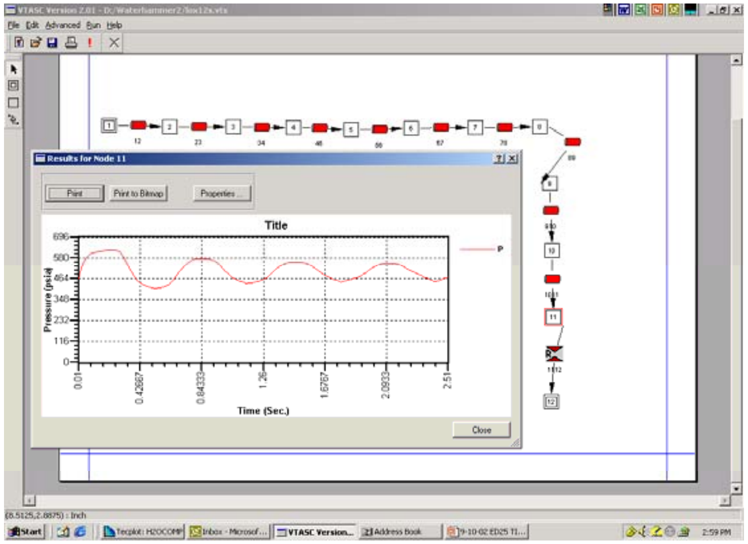


TANK PRESSURIZATION

EXAMPLE 10 HELIUM FLOW RATE HISTORY



FLUID TRANSIENT



CONTENT

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

CLASSIFICATION OF UNSTEADY FLOW

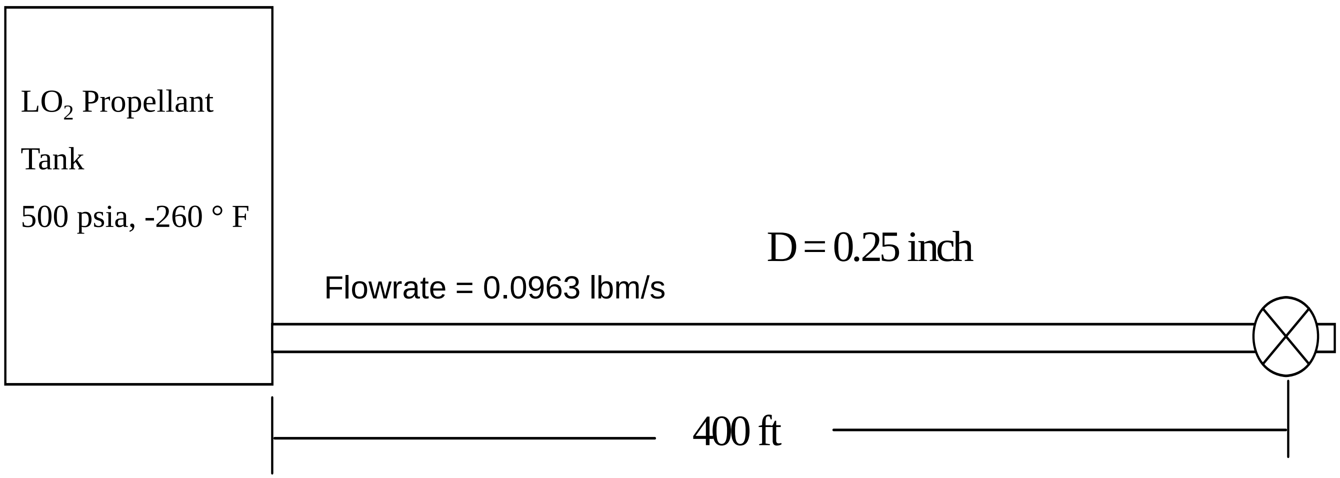
- Quasi-steady flow is a type of unsteady flow when flow changes from one steady-state situation to another steady-state situation
  - Time dependant terms in conservation equation is not activated
  - Solution is time dependant because boundary condition is time dependant
- Unsteady flow formulation 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



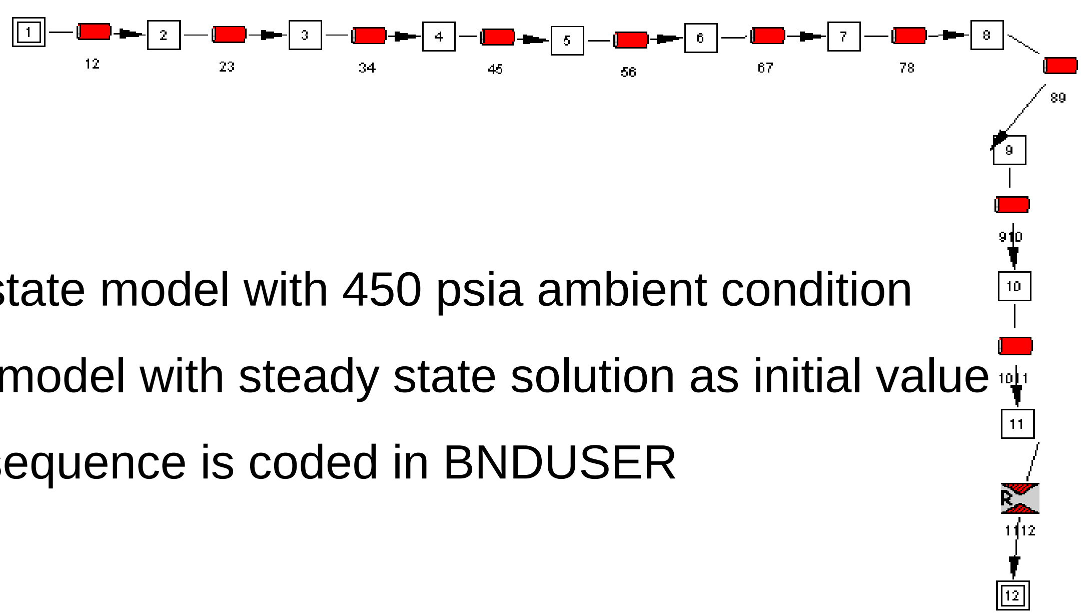
Valve Closure History

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



- 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

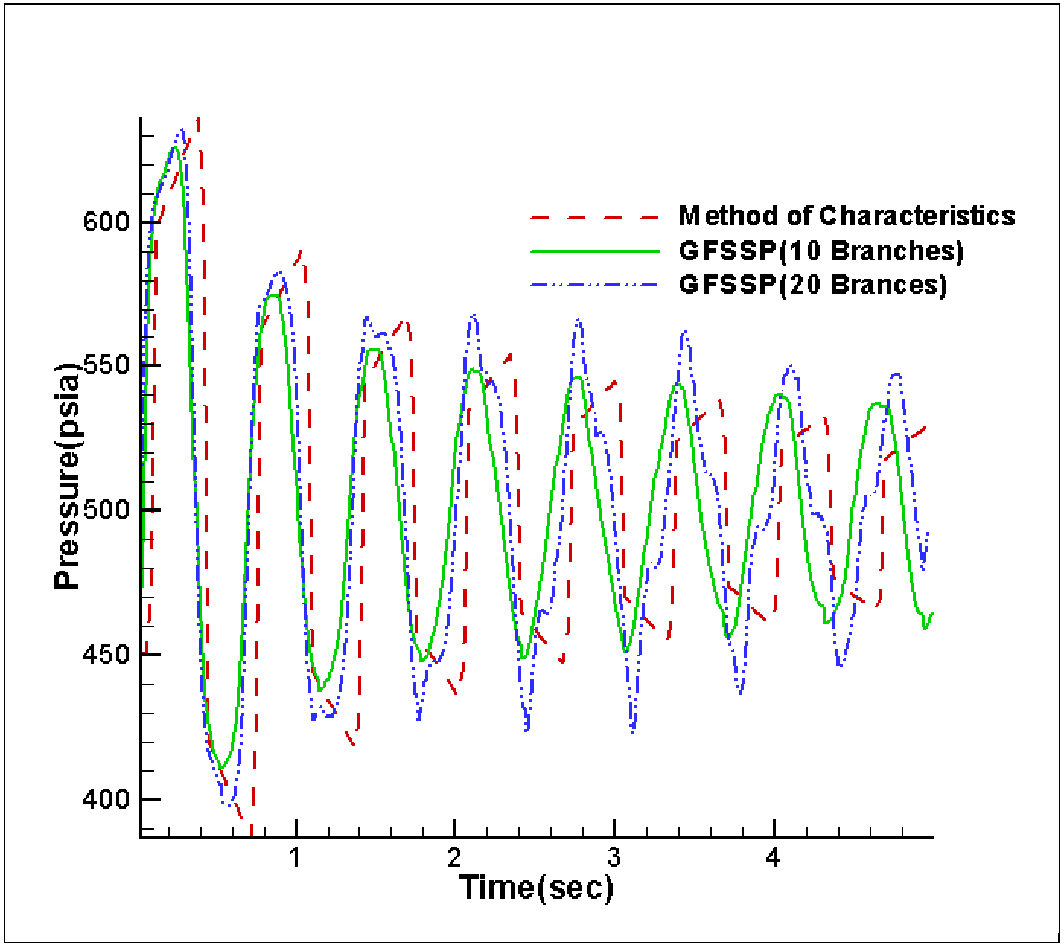
** Estimated from period of oscillation [a=4L/λ]

- **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

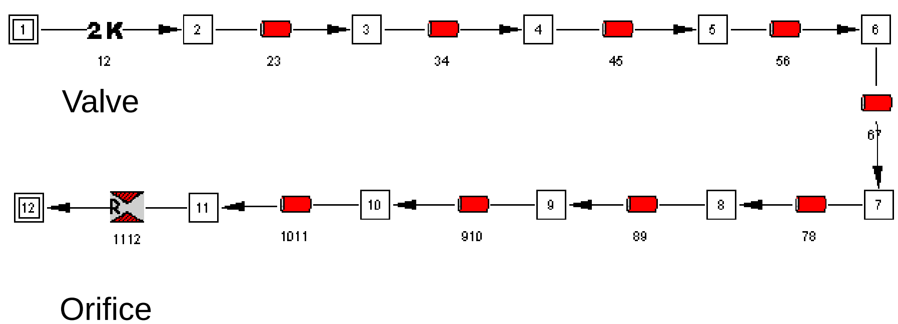
Objectives of Analysis:

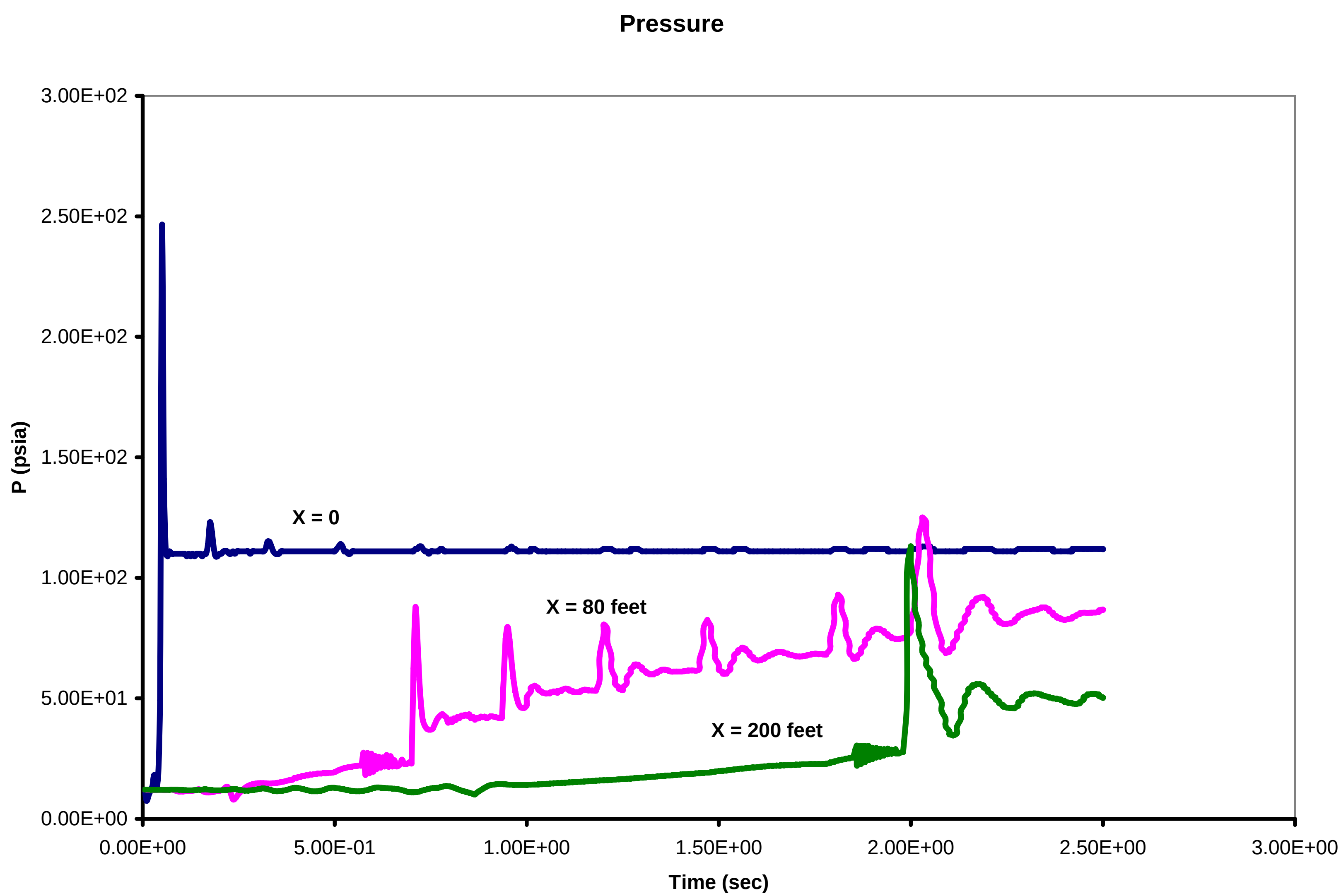
- **Maximum Pressure**
- **Time to reach steady-state**

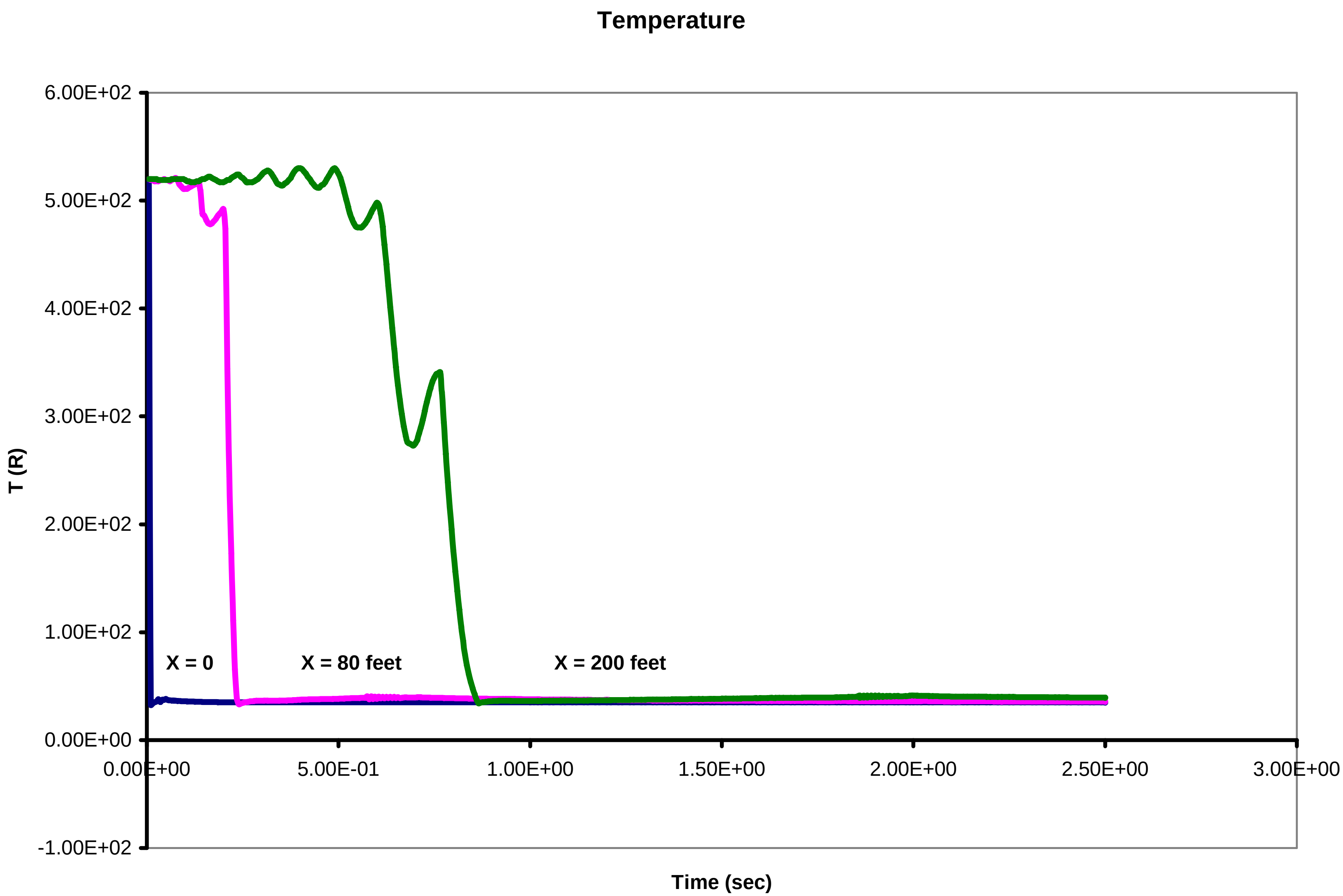
GFSSP Model

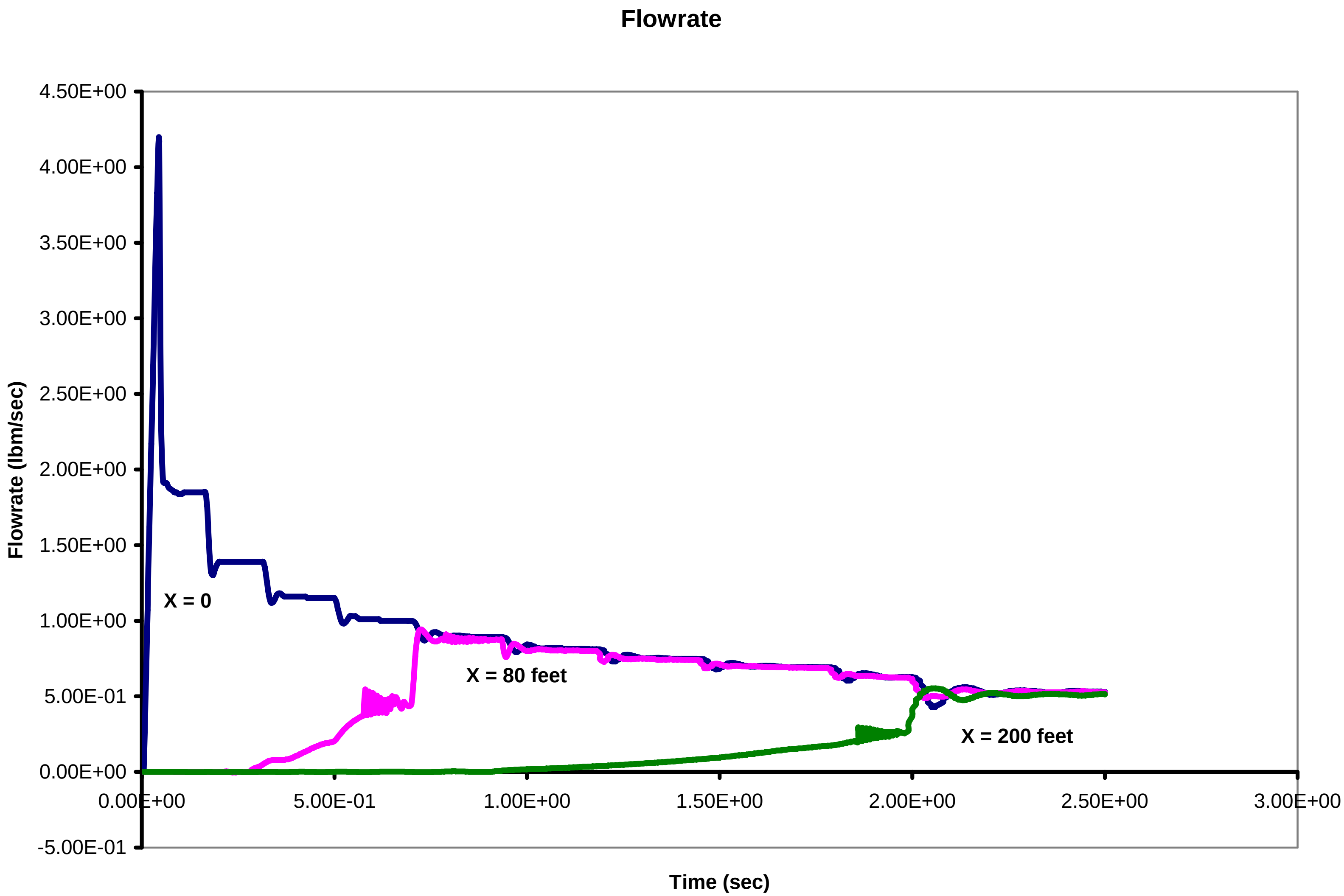
LH_2 Propellant Tank

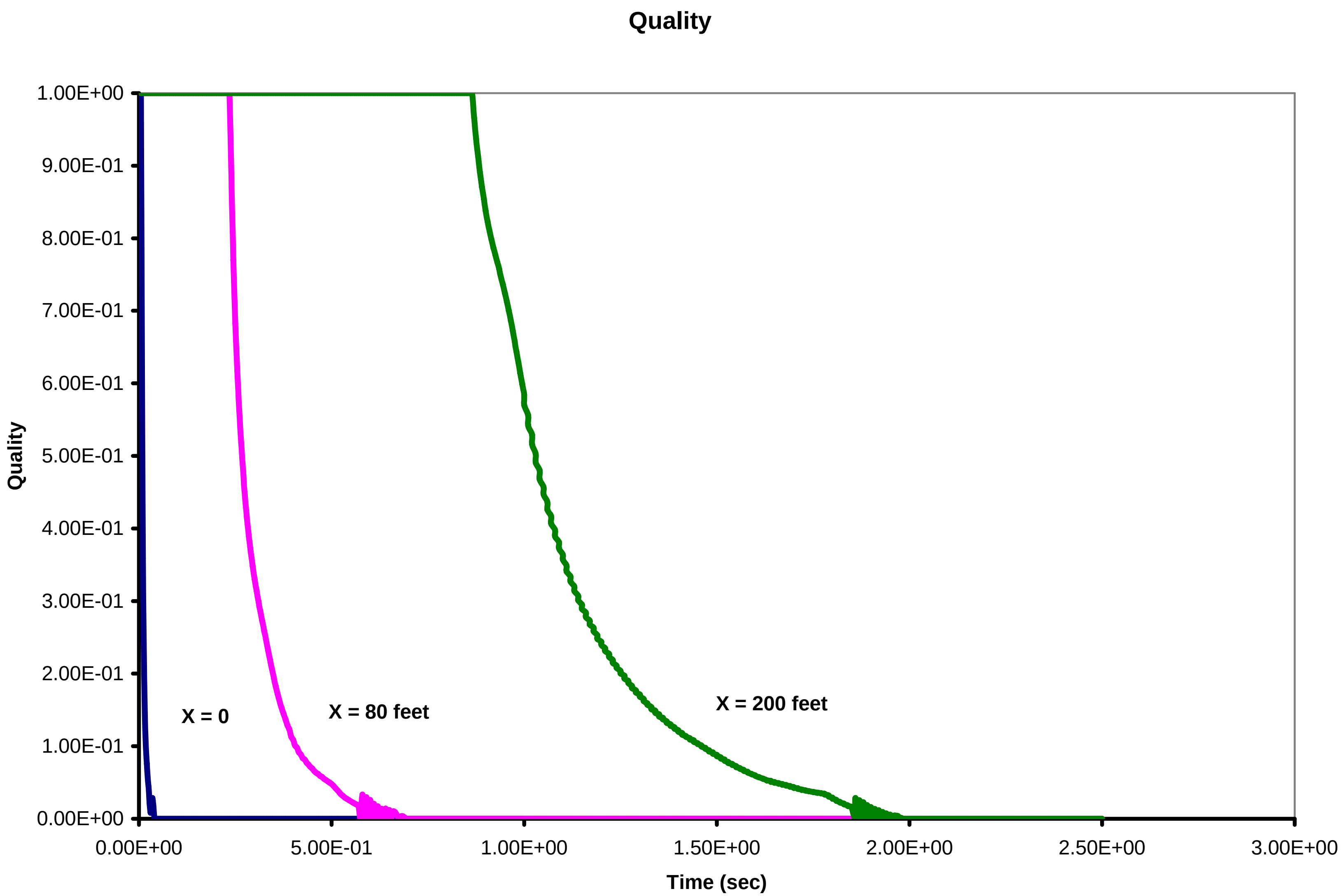
112 psia, -425 ° F




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
6.00E+02
5.00E+02
4.00E+02
3.00E+02
2.00E+02
1.00E+02
0.00E+00
-1.00E+02
T (R)
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)


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

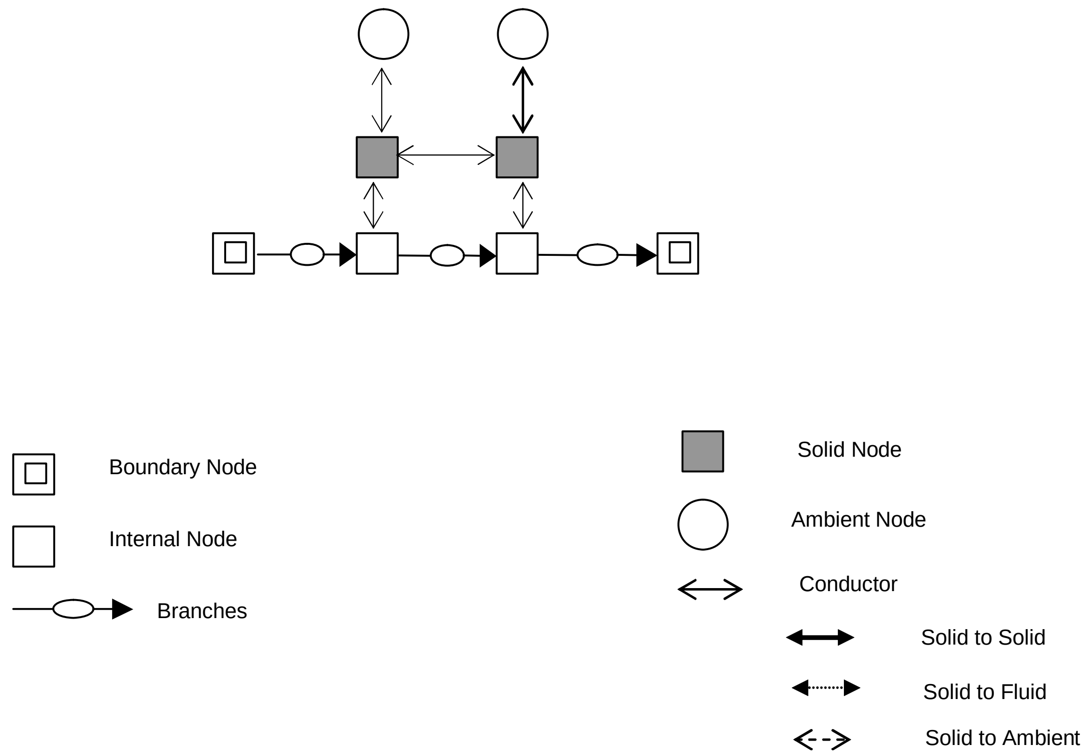

Quality
1.00E+00
9.00E-01
8.00E-01
7.00E-01
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Quality
X = 0
X = 80 feet
X = 200 feet
0.00E+00
5.00E-01
1.00E+00
1.50E+00
2.00E+00
2.50E+00
3.00E+00
Time (sec)

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

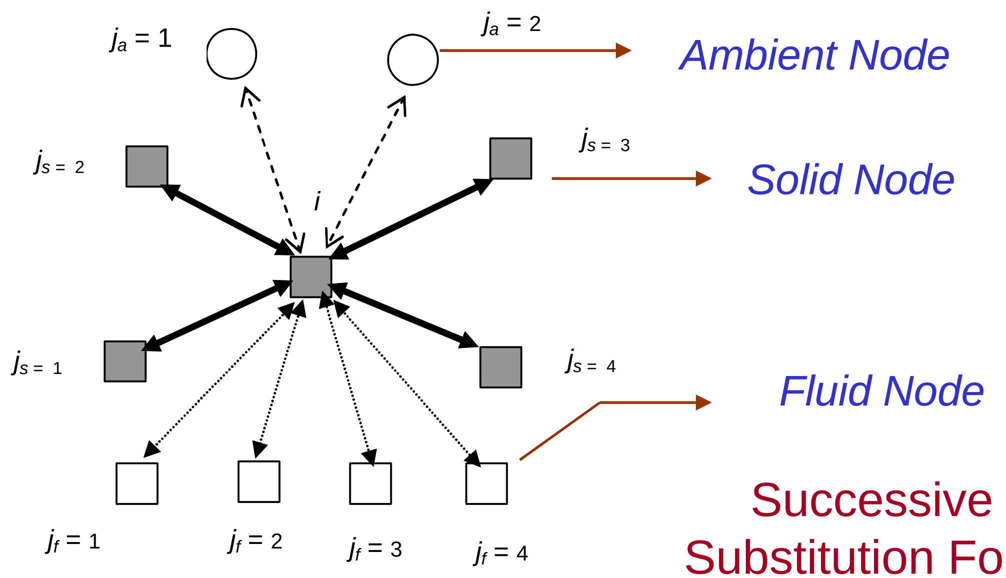
Conjugate Heat Transfer



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

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

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

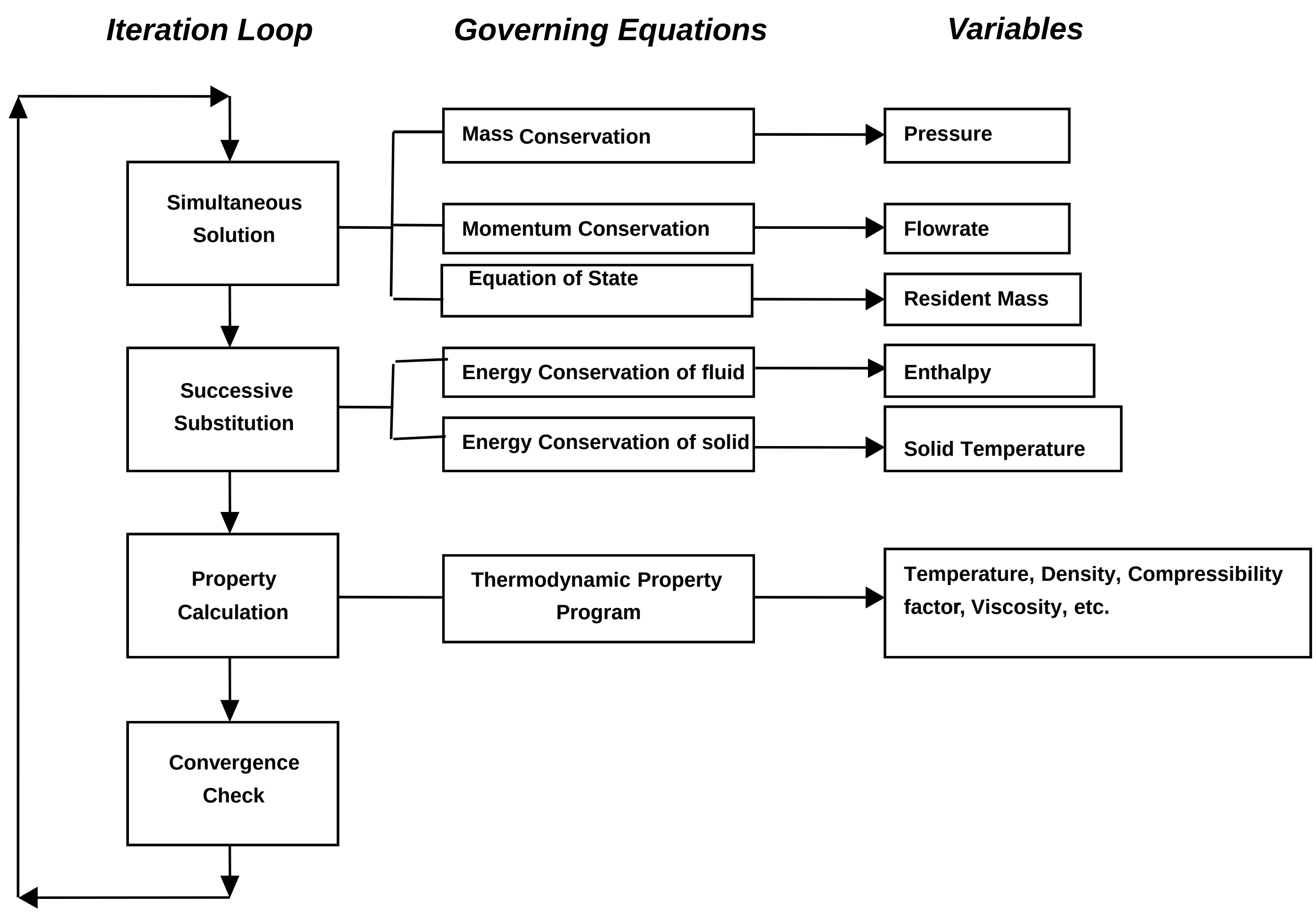
$$\dot{q}_{sf} = h_{ij_f} A_{ij_f} \left(T_f^{j_f} - T_s^i\right)$$

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

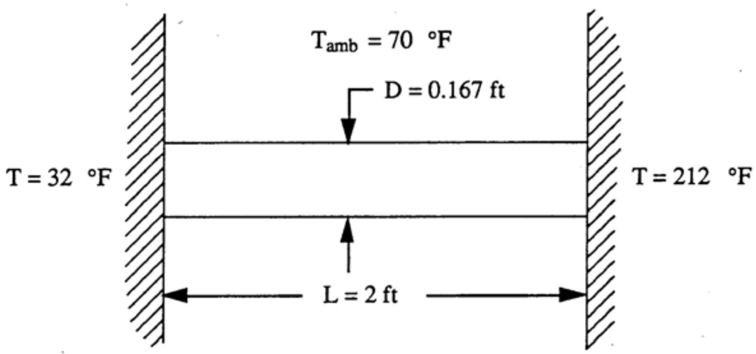
Successive Substitution Form

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

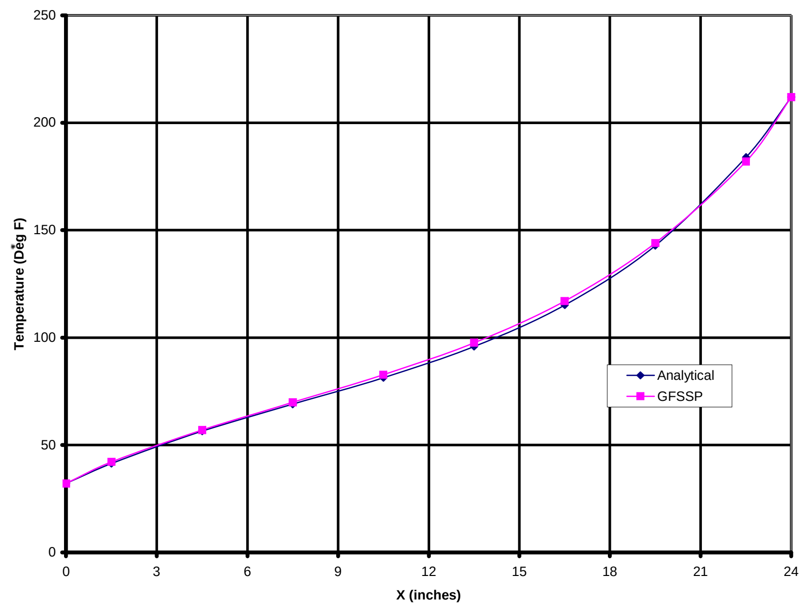
SASS Solution Scheme



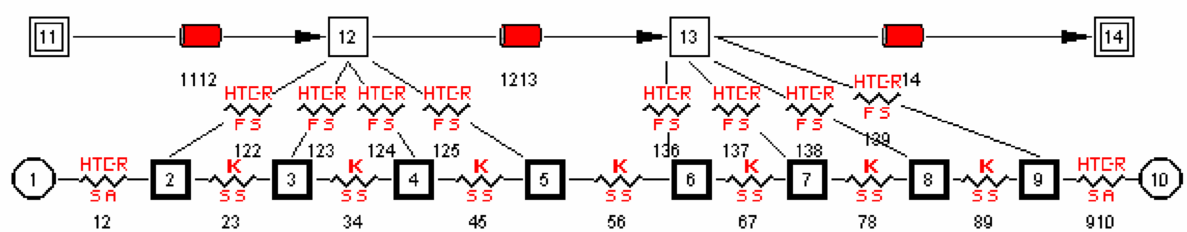
Verification of Conjugate Heat Transfer Results



Problem Considered

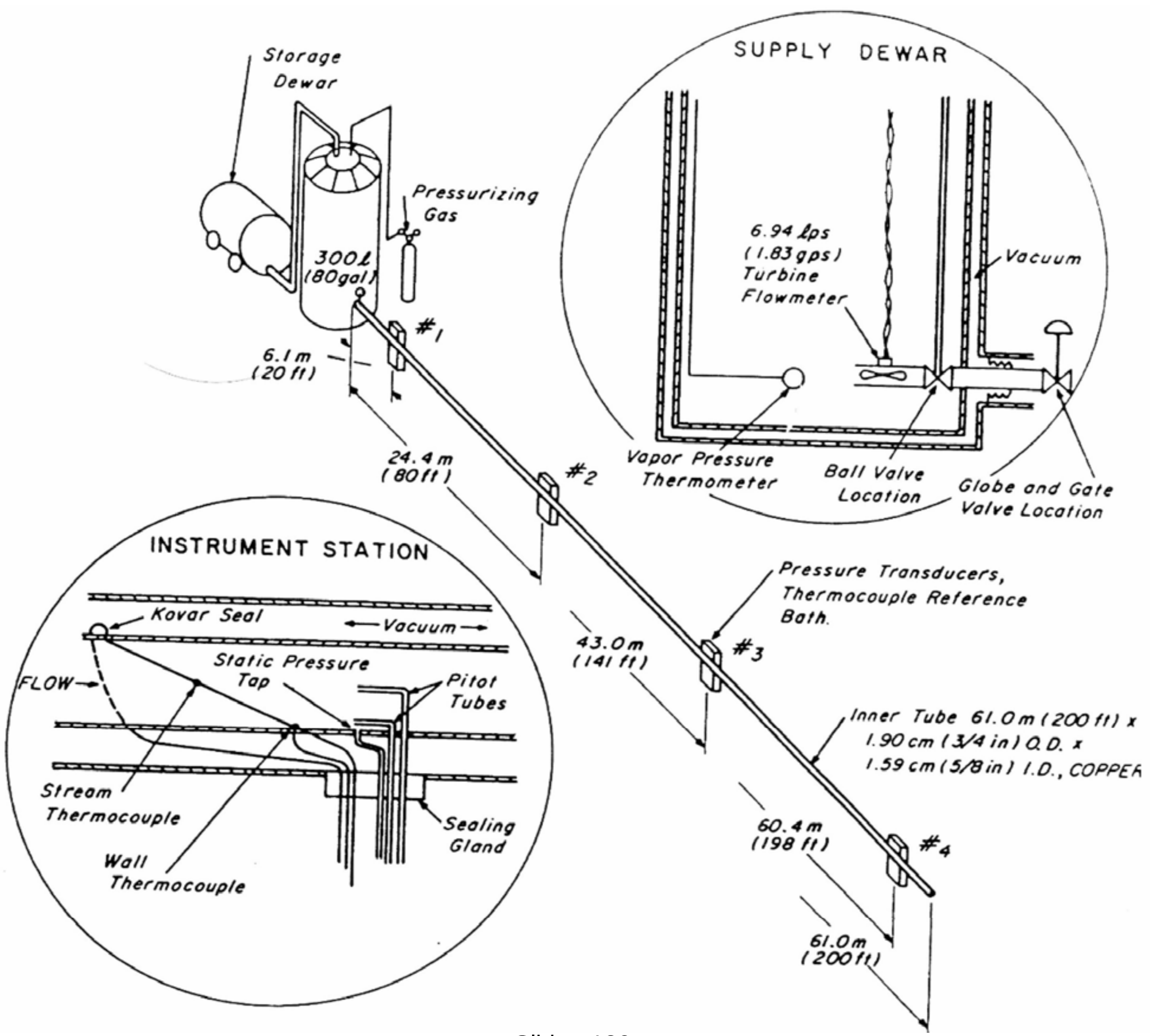


Comparison with Analytical Solution

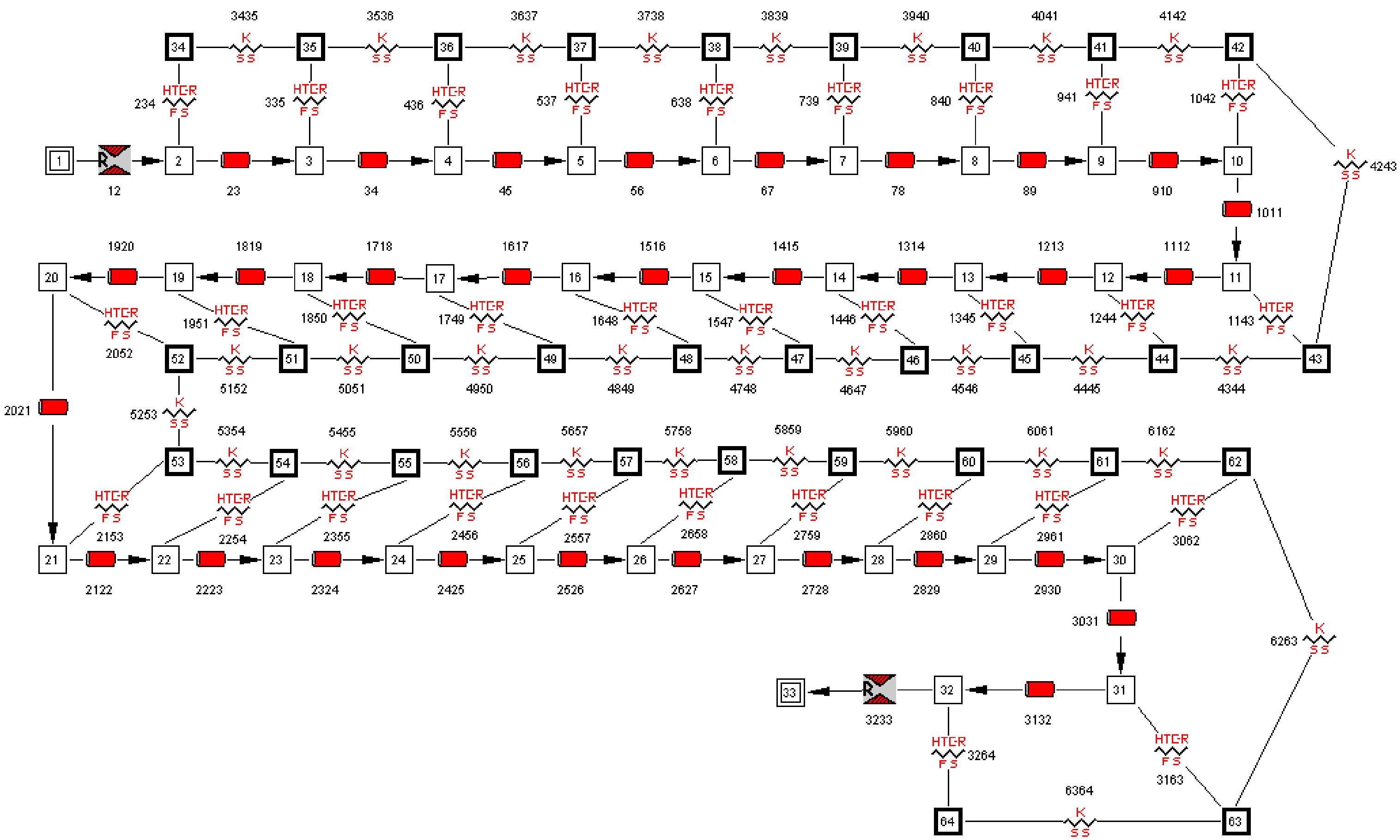


GFSSP Model

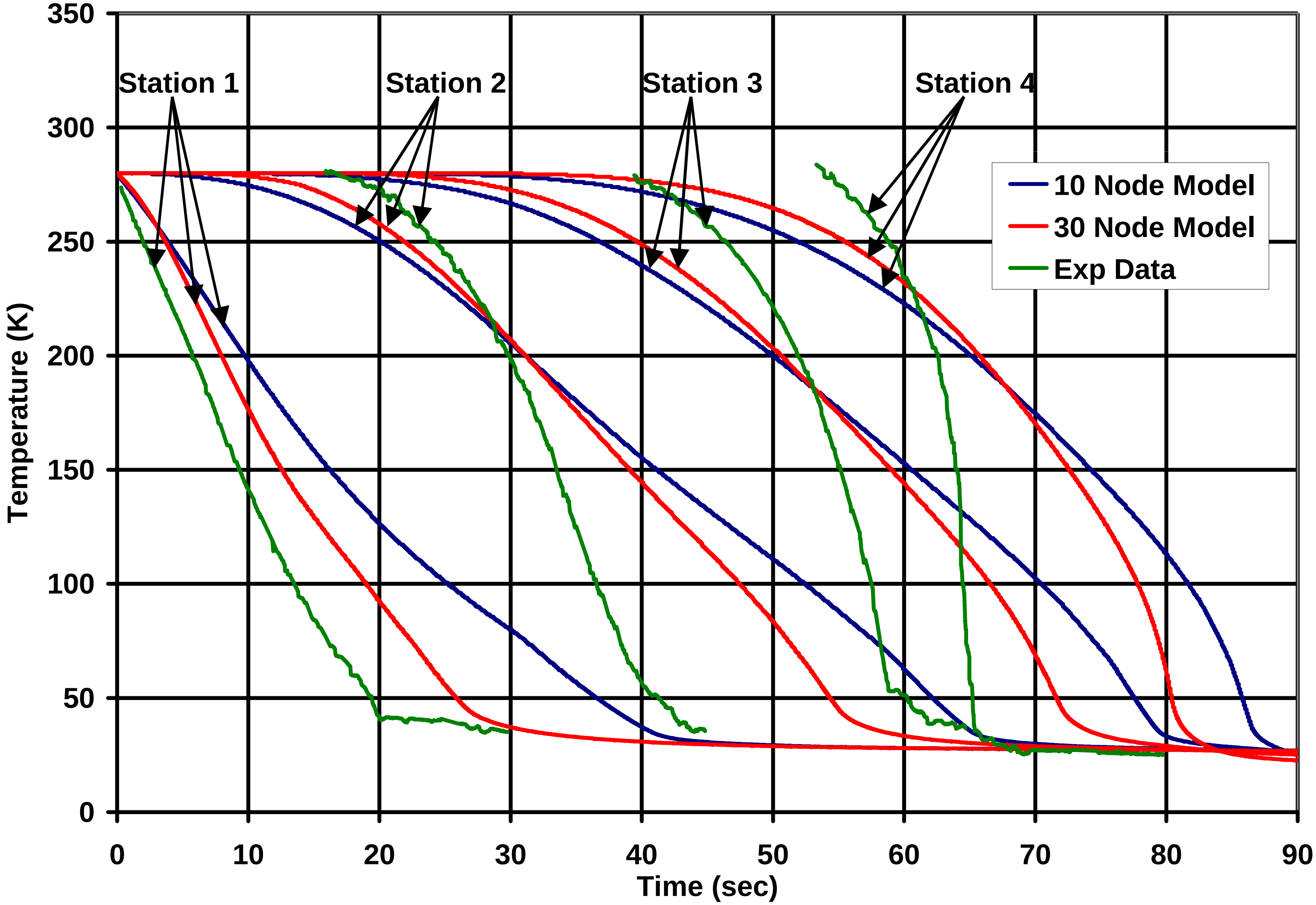
NBS Test Set-up of Cryogenic Transfer Line



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