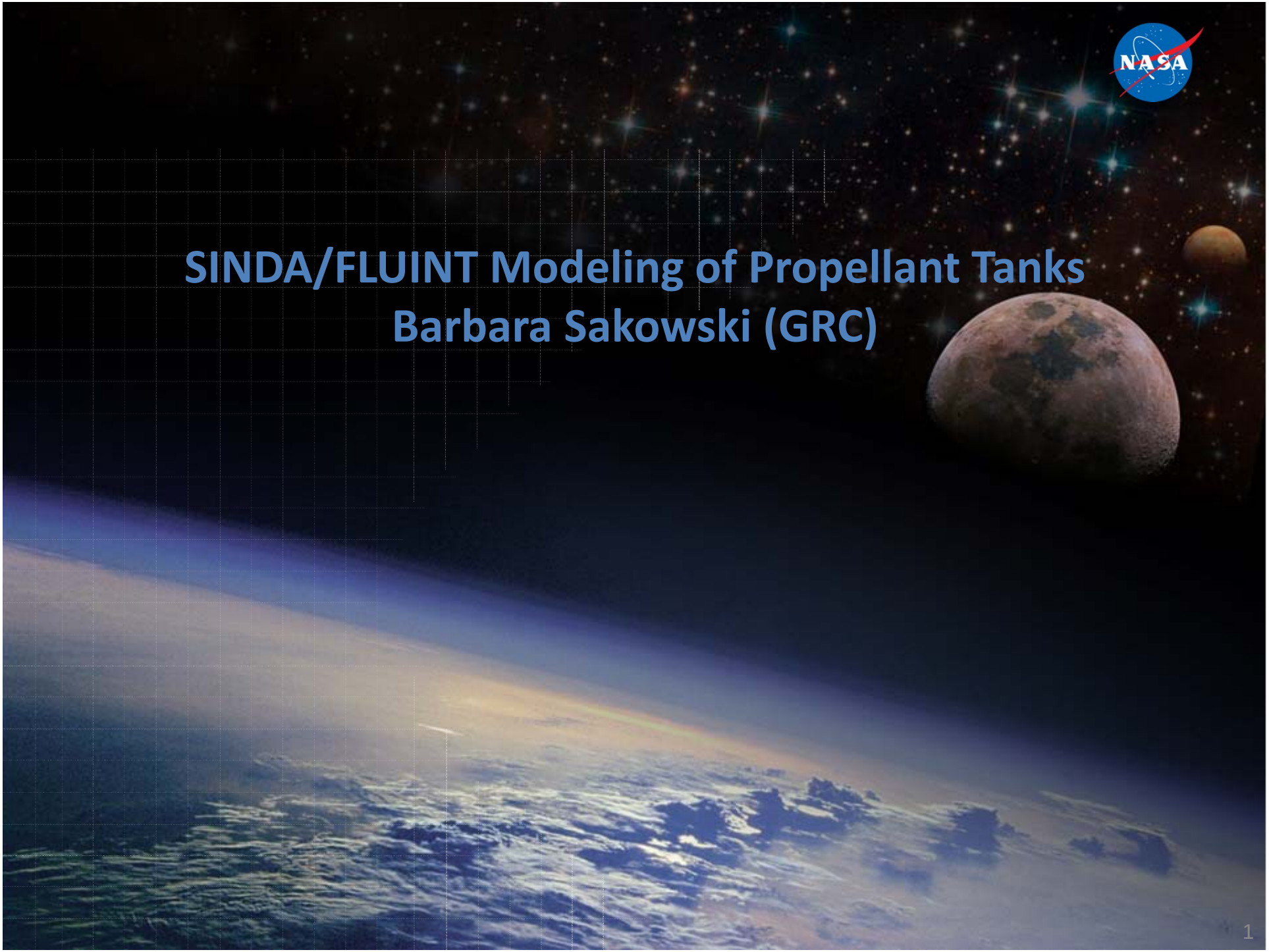


SINDA/FLUINT Modeling of Propellant Tanks

Barbara Sakowski (GRC)

Customization for Cryogenic Tank Analysis

- A general purpose SINDA/FLUINT (S/F) stratified tank model was created to simulate self-pressurization and axial jet TVS
- Stratified layers in the vapor and liquid are modeled using S/F **lumps**.
- The stratified tank model was constructed to permit incorporating the following additional features:
  - Multiple or singular lumps in the liquid and vapor regions of the tank
  - Real gases (also mixtures) and compressible liquids
  - Venting, pressurizing, and draining
  - Condensation and evaporation/boiling
  - Wall heat transfer
  - Elliptical, cylindrical, and spherical tank geometries

Customization for Cryogenic Tank Analysis

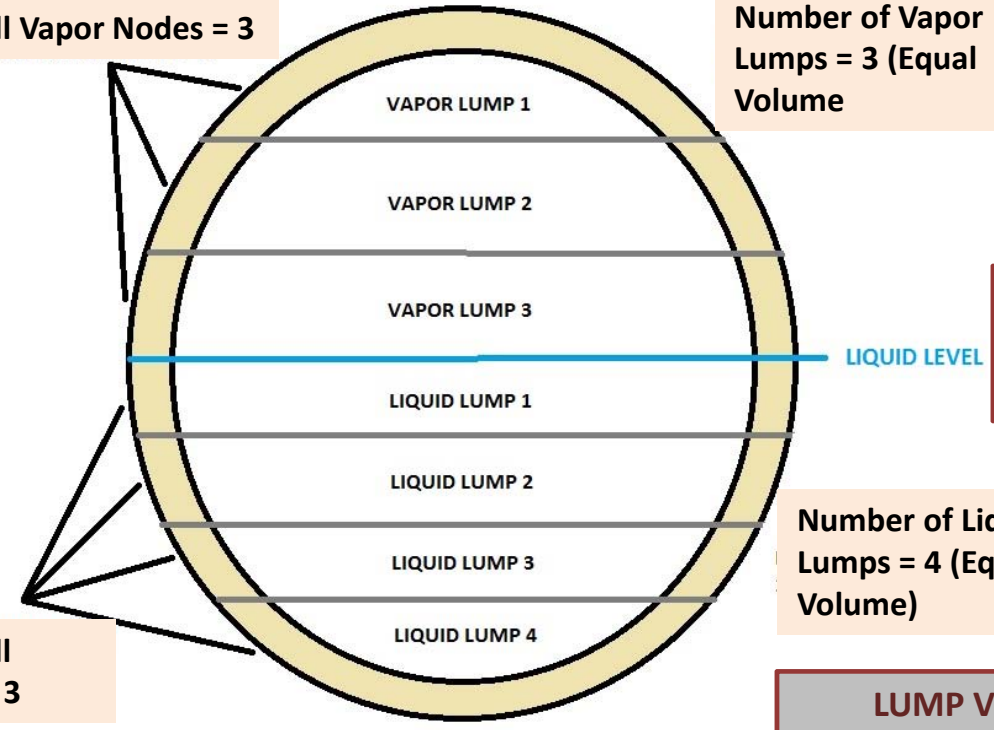
- Extensive user logic is used to allow detailed tailoring – Don't have to rebuilt everything from scratch!!
- Most code input for a specific case is done through the **Registers Data Block**:
  - Lump volumes are determined through user input:
    - Geometric tank dimensions (height, width, etc)
    - Liquid level could be input as either a volume percentage of fill level or actual liquid level height

SINDA/FLUINT Stratified Tank Setup

1 The number of lumps in the vapor region need not be the same as the number of lumps in the liquid region.

2 The number of wall nodes in the vapor region need not be the same as the number of wall nodes in the liquid region.

Number of Wall Vapor Nodes = 3



Number of Vapor Lumps = 3 (Equal Volume

3 S/F IFACES between ALL lumps

4 Liquid level input as volume percentage of fill level or actual liquid level height.

Number of Liquid Lumps = 4 (Equal Volume)

Number of Wall Liquid Nodes = 3

5 LUMP VOLUMES:
- Initial values (guesses) required
- Extensive logic determines equal volume distribution

Fig 1: Stratified Tank Setup

SINDA/FLUINT Stratified Tank Setup

- **Initialization of wall node volumes:**
  - Determined by the number of nodes input for the vapor wall and liquid wall regions
  - Wall node volumes are not uniform values in the vapor region or liquid region
  - Wall node volumes correspond to “equal” fluid volumes in the vapor or liquid region

SINDA/FLUINT Stratified Tank Setup

- Volume Flow Rate Connectors (**VFRSETs**) are placed between the layered lumps in each region to equalize volumes:
  - Used during venting, draining
  - Used during mass transfer of evaporation, condensation, boiling
  - User logic determines the volume flow rate through these connectors so that the volumes of the lumps in each respective region remains constant within a small percentage
  - Avoids lumps from becoming too small or too large relative to one another, and consequently avoids the problem of having very small lumps to somehow “disappear”
  - Converted “balloon-like-behaving” lumps with **IFACES** to something more like a “fixed volume” approach (still at constant pressure)

SINDA/FLUINT Stratified Tank Setup

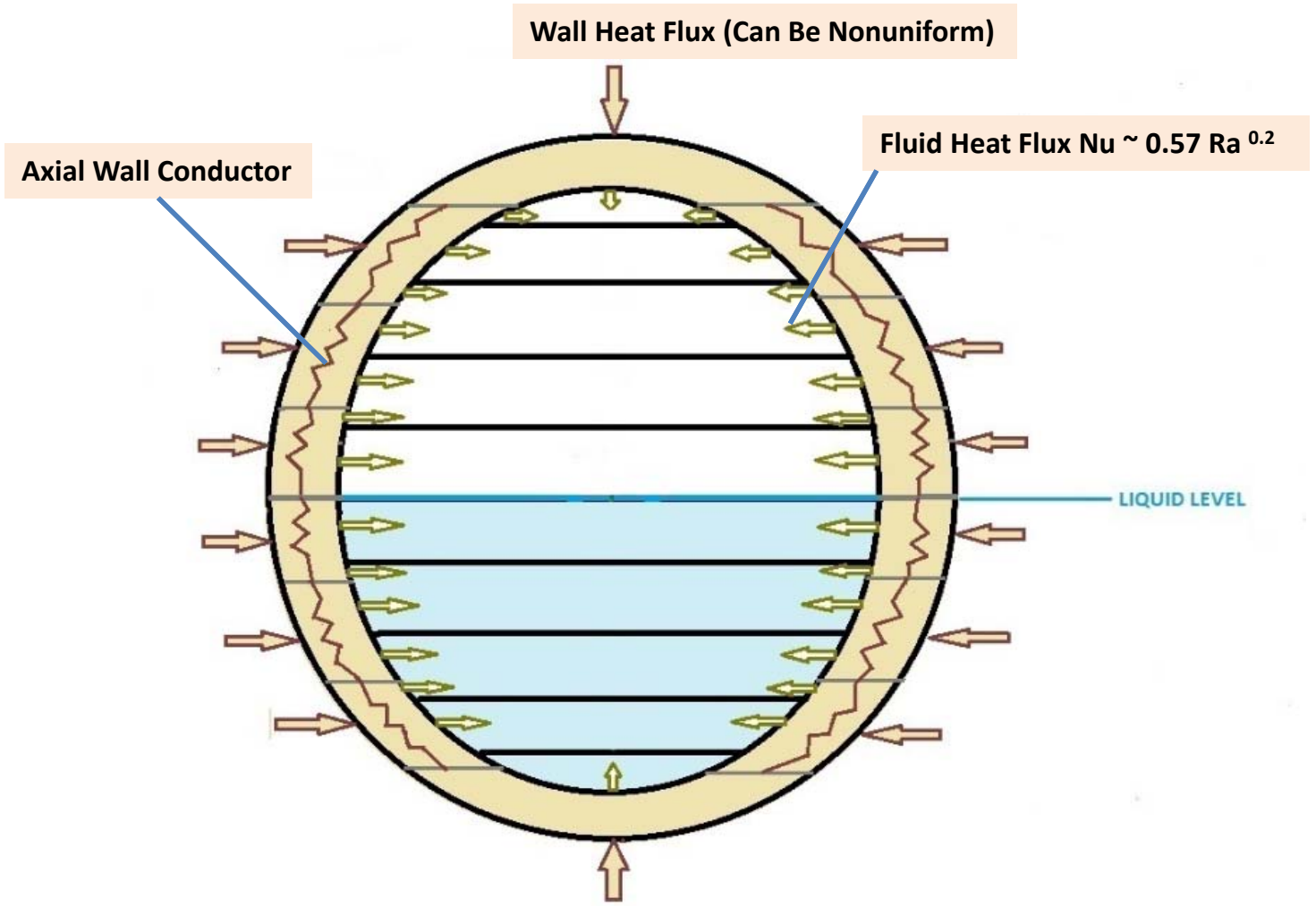
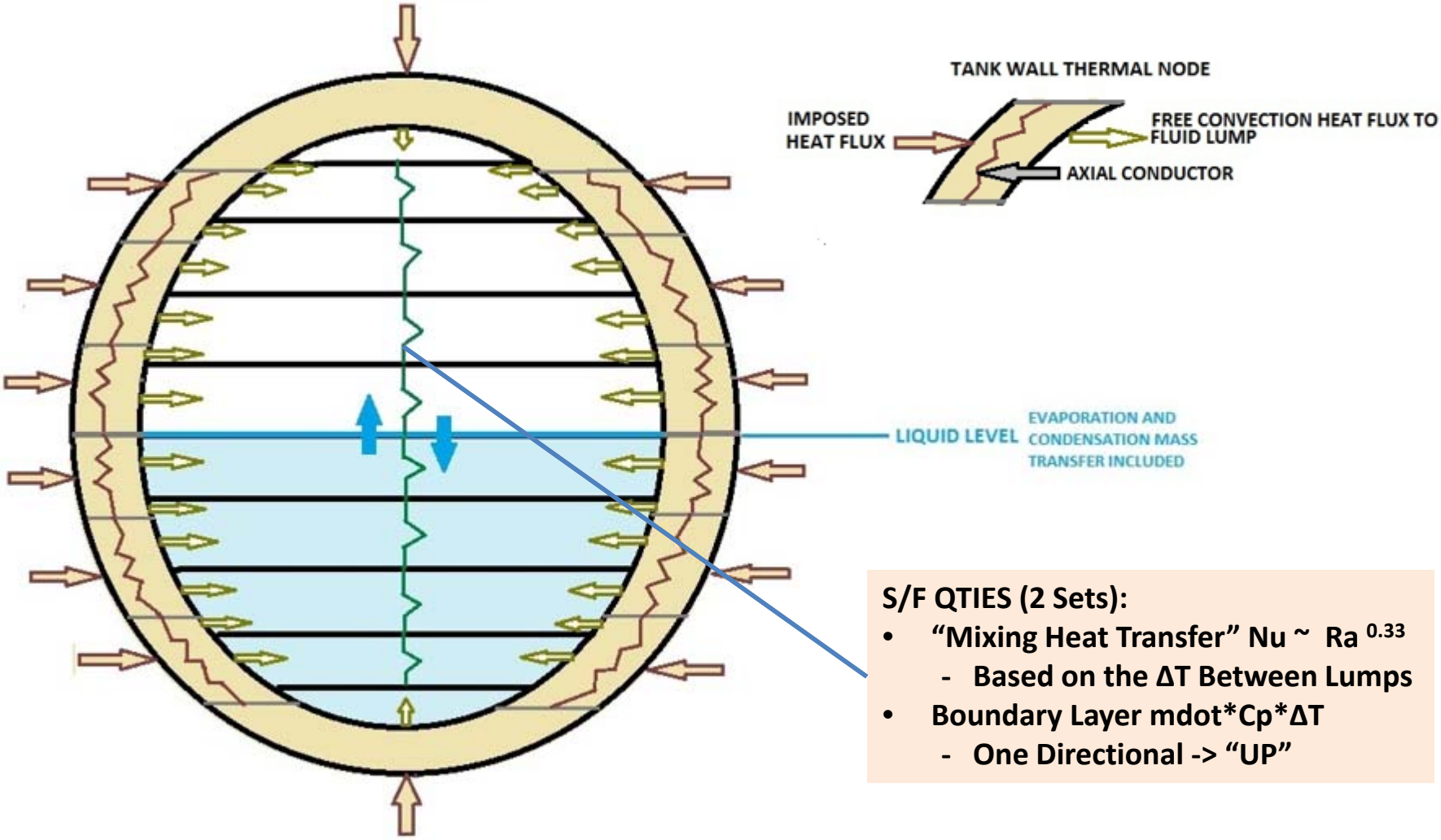


Fig 2: Stratified Tank Heat Transfer

SINDA/FLUINT Stratified Tank Setup



S/F QTIES (2 Sets):

- **"Mixing Heat Transfer" Nu ~ Ra $^{0.33}$**
  - **Based on the ΔT Between Lumps**
- **Boundary Layer mdot*Cp*ΔT**
  - **One Directional -> "UP"**

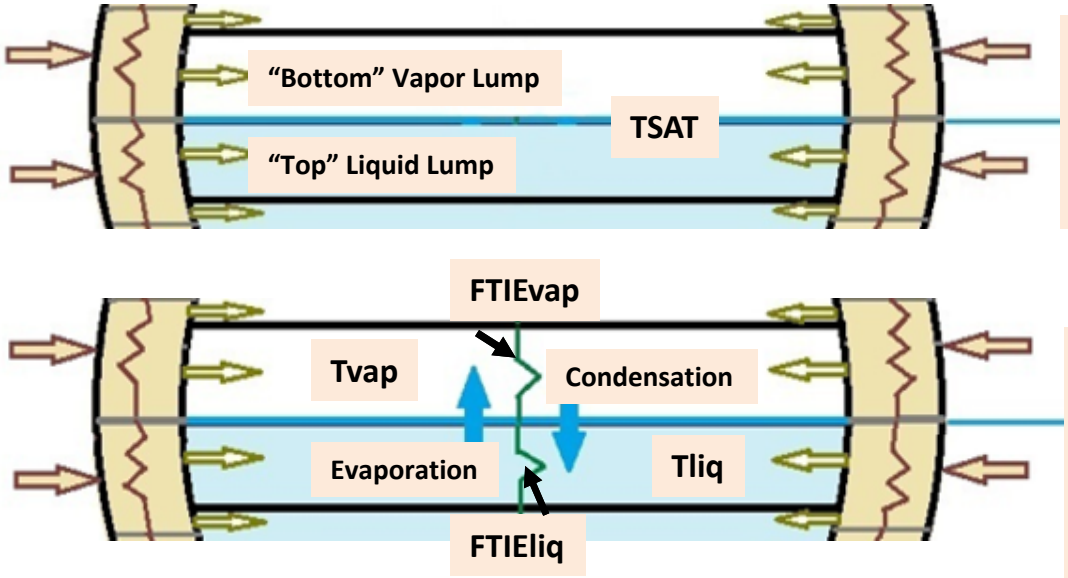
Fig 3: Stratified Tank Heat and Mass Transfer

SINDA/FLUINT Boundary Layer Analysis

- **Thermal boundary layer** that forms along the tank wall, due to wall heat leak, is **modeled empirically** using correlations for free convection.
- Although the **two dimensional flow dynamics** of the boundary layer could not directly be incorporated into the one dimensional stratified tank model, it is **incorporated in a one dimensional sense**. Within each fluid lump the following boundary layer characteristics are determined:
  - Characteristic velocity
  - Boundary layer thickness
  - Buoyancy driven volume flow rate

SINDA/FLUINT Vapor Liquid Interface Modeling

- SINDA/FLUINT contains pre-built utility functions to model heat and mass transfer between a liquid and vapor interface (**TWIN TANKS**)
- For more modelling flexibility, user logic could incorporate the necessary physics to model a wide variety of scenarios:



LIQUID LEVEL -> VAPOR/LIQUID INTERFACE:
- **Modelled as a PLENUM (Boundary State)**
- **TSAT = Saturation Temperature of "Top" Liquid Lump (Updated Every Iteration)**

A S/F FTIE is placed between the "bottom" vapor lump (Tvap) and this boundary PLENUM
A S/F FTIE is placed between the "top" liquid lump and the boundary PLENUM

Fig 4: Vapor Liquid Interface Model

SINDA/FLUINT Vapor Liquid Interface Modeling

- The heat rates for these FTIEs are defined as follows:

  $QFTIEvap = h * A_{INTERFACE} * (T_{VAP} - T_{INTERFACE})$

  $QFTIEliq = h * A_{INTERFACE} * (T_{INTERFACE} - T_{LIQ})$

- where,

  $h = Nu / D_{INTERFACE} * k$

  $Nu = const * Ra^{(1/3)}$

  $const \sim 0.04 * Function(Height/Diameter)$

- The **net evaporation rate at the interface** is calculated to be:

  $mdot_{EVAP} = (QFTIEvap - QFTIEliq) / (heat\ of\ vaporization)$

SINDA/FLUINT Vapor Liquid Interface Modeling

- **Evaporation** is modeled via the process:
  - Liquid leaves the "**top**" liquid lump and enters a DUMMY **PLENUM**
  - Vapor enters the "**bottom**" vapor lump from a DUMMY vapor **PLENUM**
- **Condensation** is modeled via the process:
  - Vapor leaves the "**bottom**" vapor lump and enters a DUMMY **PLENUM**
  - Liquid enters the "**top**" liquid lump from a DUMMY liquid **PLENUM**
- The DUMMY **PLENUMS** are set at the saturation temperature of the "**top**" liquid lump (updated every iteration)

NOTE!

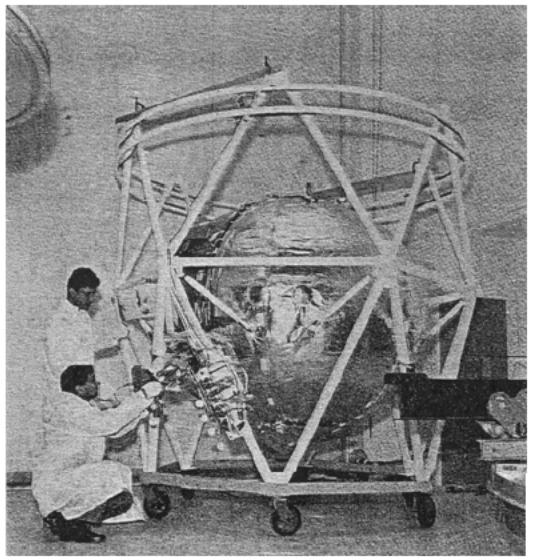
- The mass flow rate, whether condensing or evaporating, should be at saturated conditions. However the "**bottom**" vapor and "**top**" liquid lumps may not be saturated. Thus when mass is removed from either of these lumps the amount of energy leaving these lumps needs to be adjusted to account for this discrepancy.

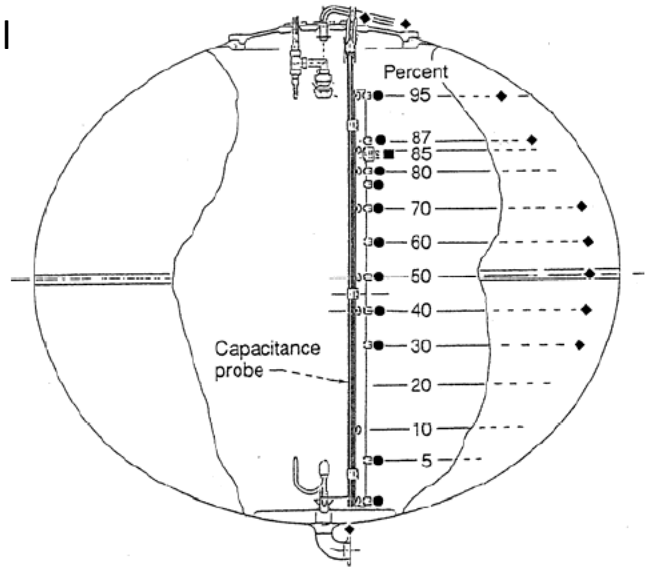
Validation Cases

- **K-Site LH2 Self-pressurization (1g)**

K-Site LH2 Self-Pressurization (1g)

1. Flightweight insulated aluminum ellipsoidal tank
   - Internal volume: 175 ft^3
   - Tests conducted in vacuum chamber.
   - Tank is supported by 12 fiberglass composite struts.
   - Test article is enclosed by a cryoshroud whose temperatures are maintained with electrical heaters.
   - Tank insulated with 2 blankets of MLI.
2. Test fluid is liquid hydrogen
3. Steady boil-off test and measurement performed at 95% fill and 117 kPa.
4. Tank fill level was reduced to desired fill level.
5. Several hours of additional venting at 103 kPa to achieve stationary state.
6. Self-pressurization tests were initiated from stationary stratified state.

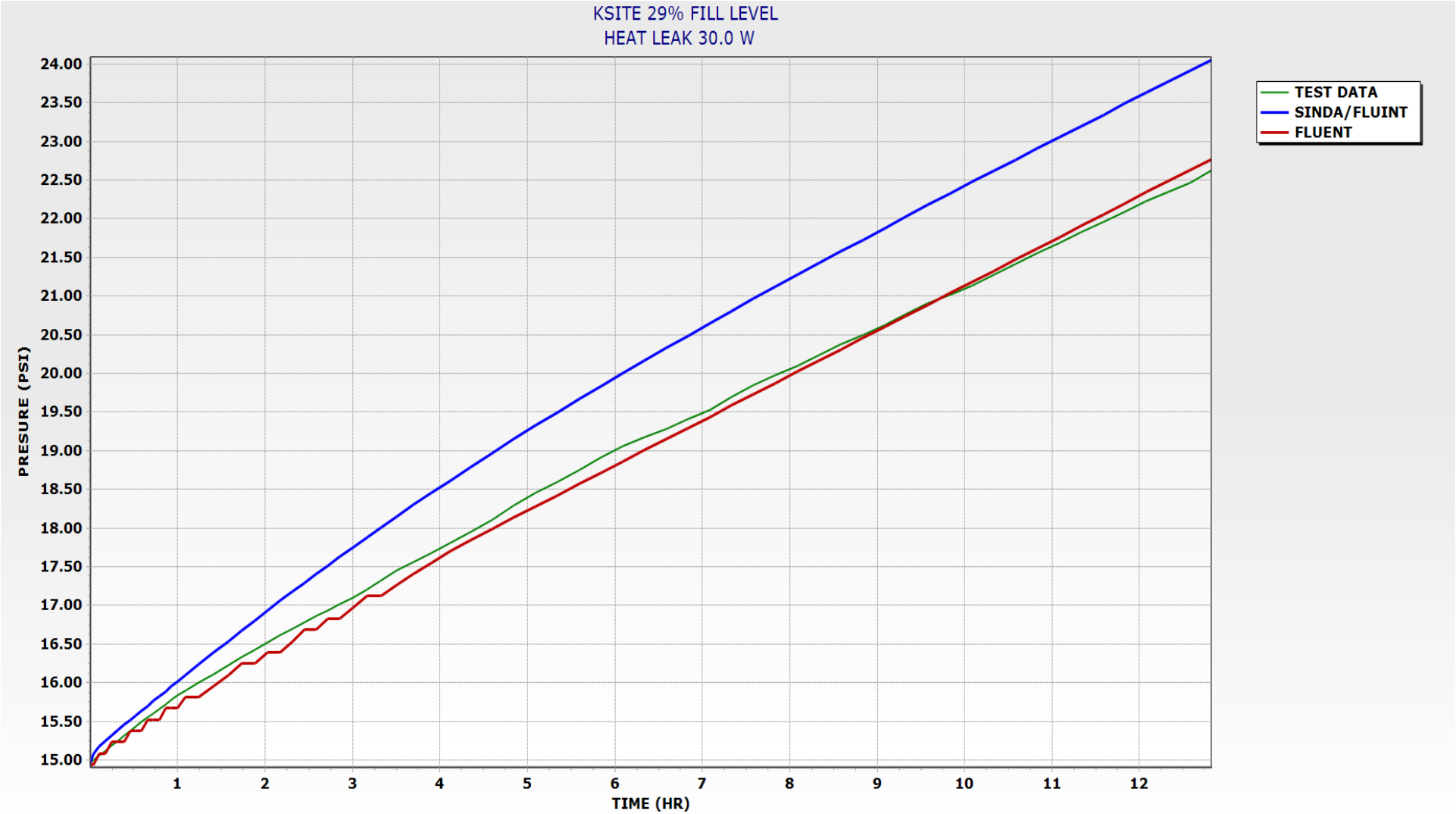




NASA TM-103804, 1991 and NASA TM-105411, 1992

K-site LH2 1g Self-pressurization: Experimental and SINDA/FLUINT RESULTS

SINDA/FLUINT: 75 LIQUID LUMPS, 40 VAPOR LUMPS, 50 LIQUID WALL NODES, 40 VAPOR WALL NODES Fluent = lumped ullage model



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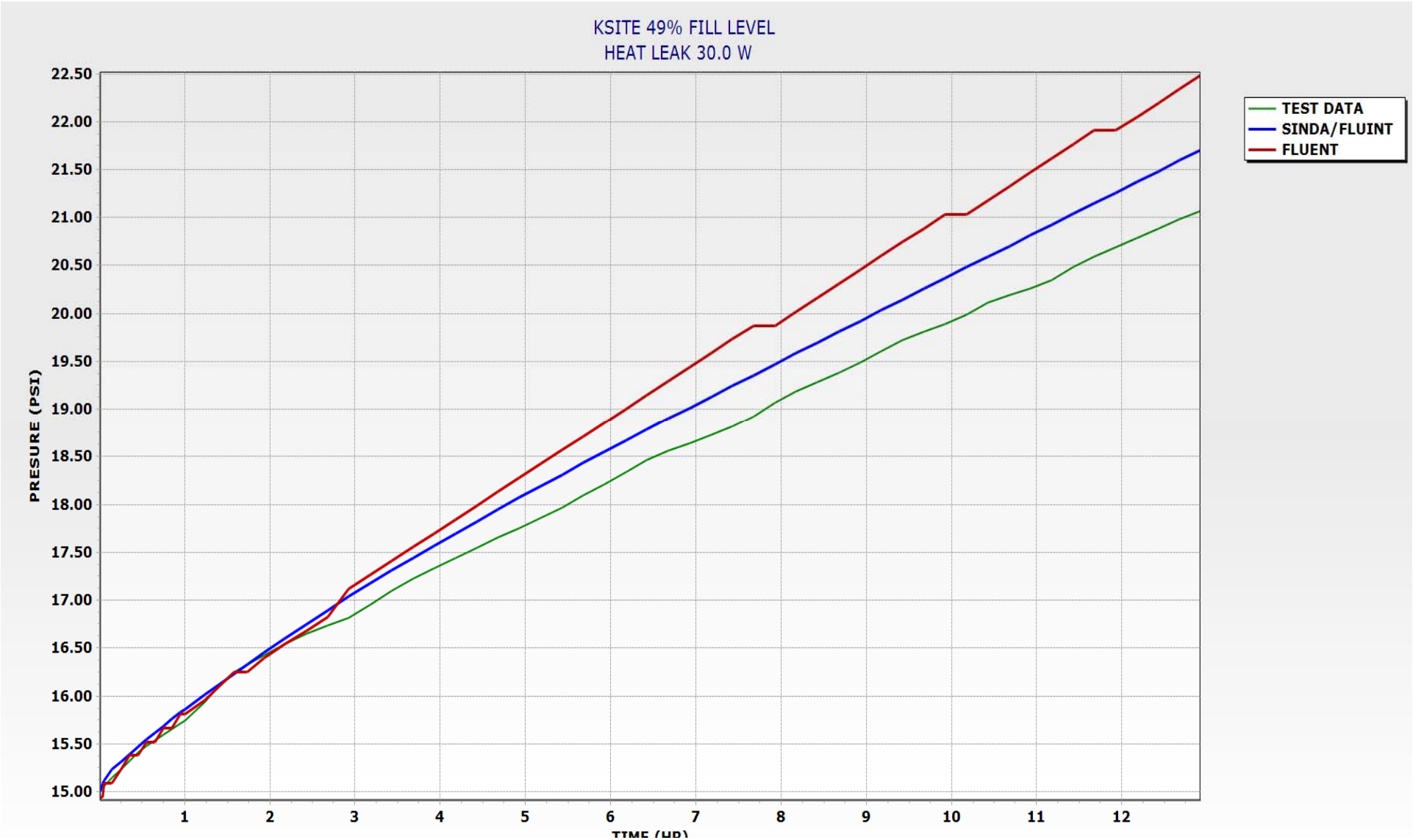

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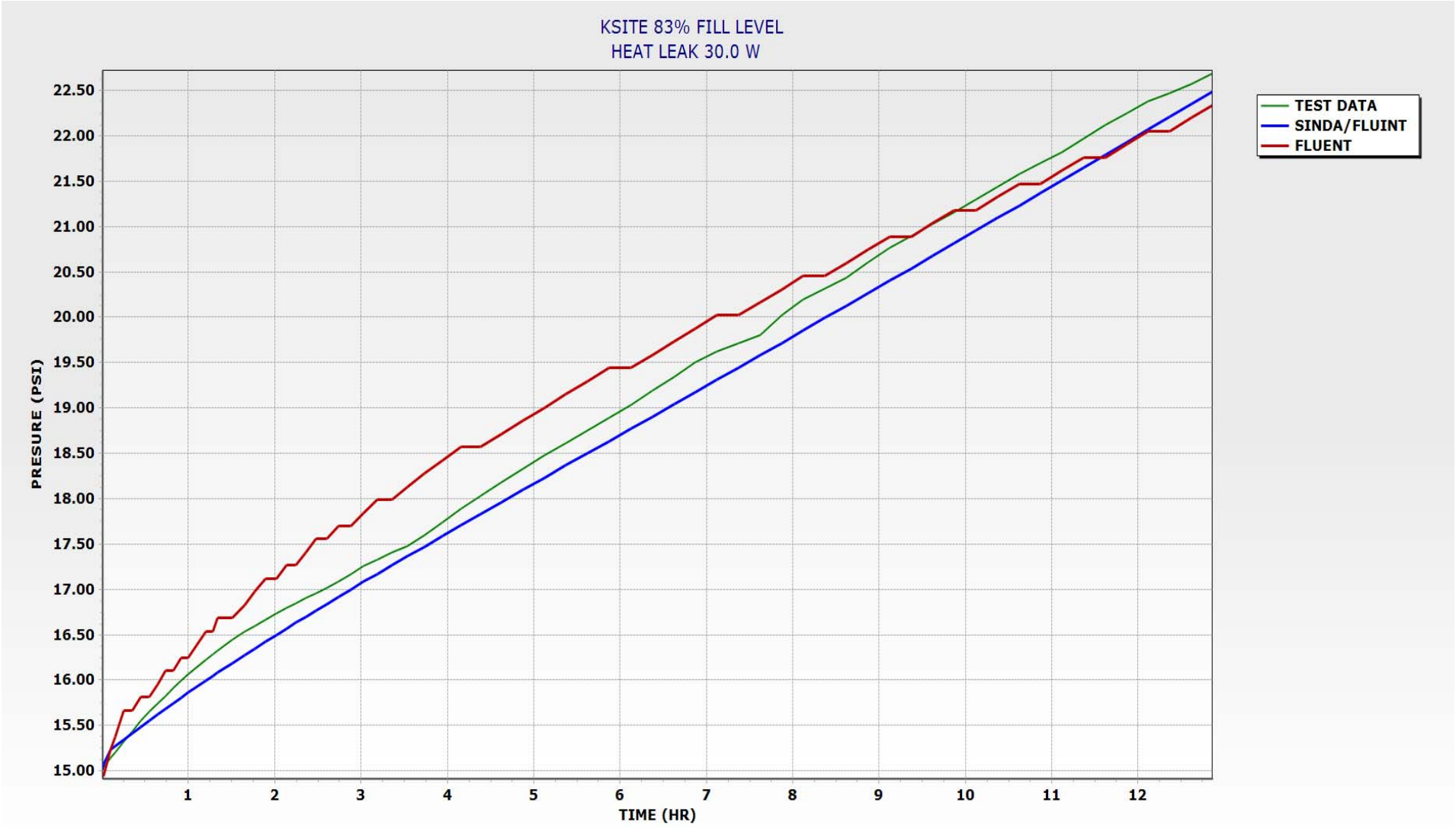

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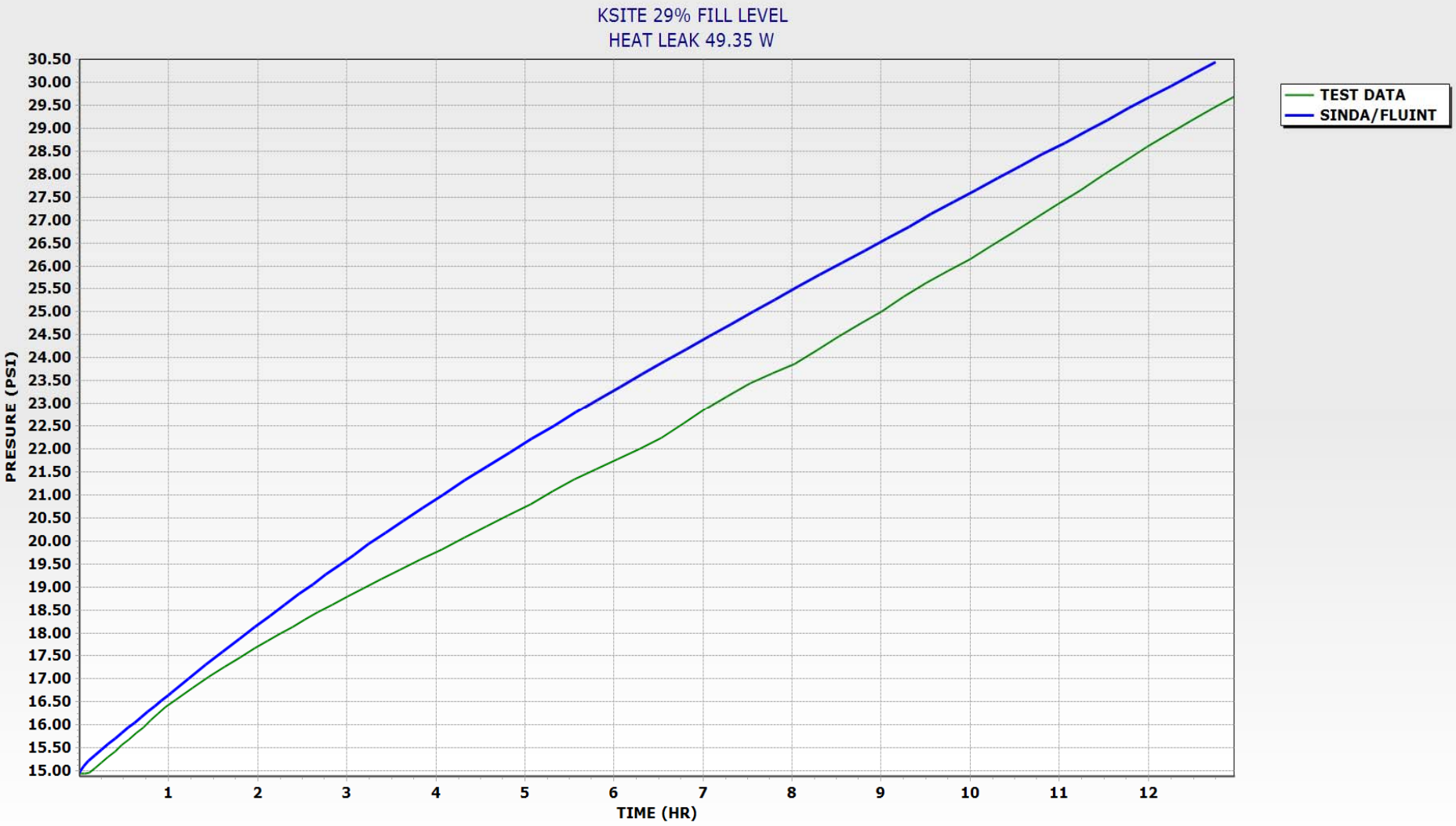

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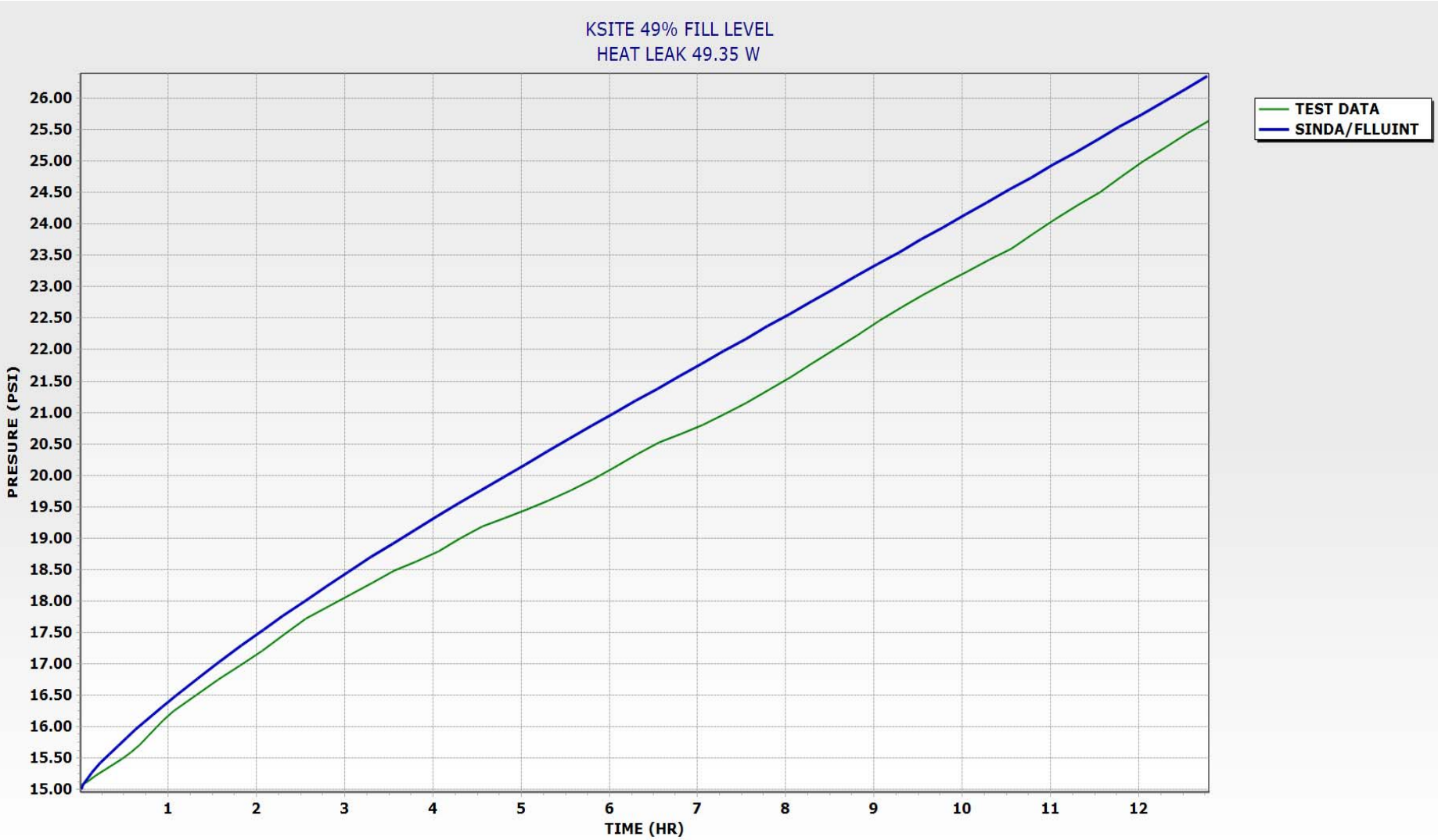

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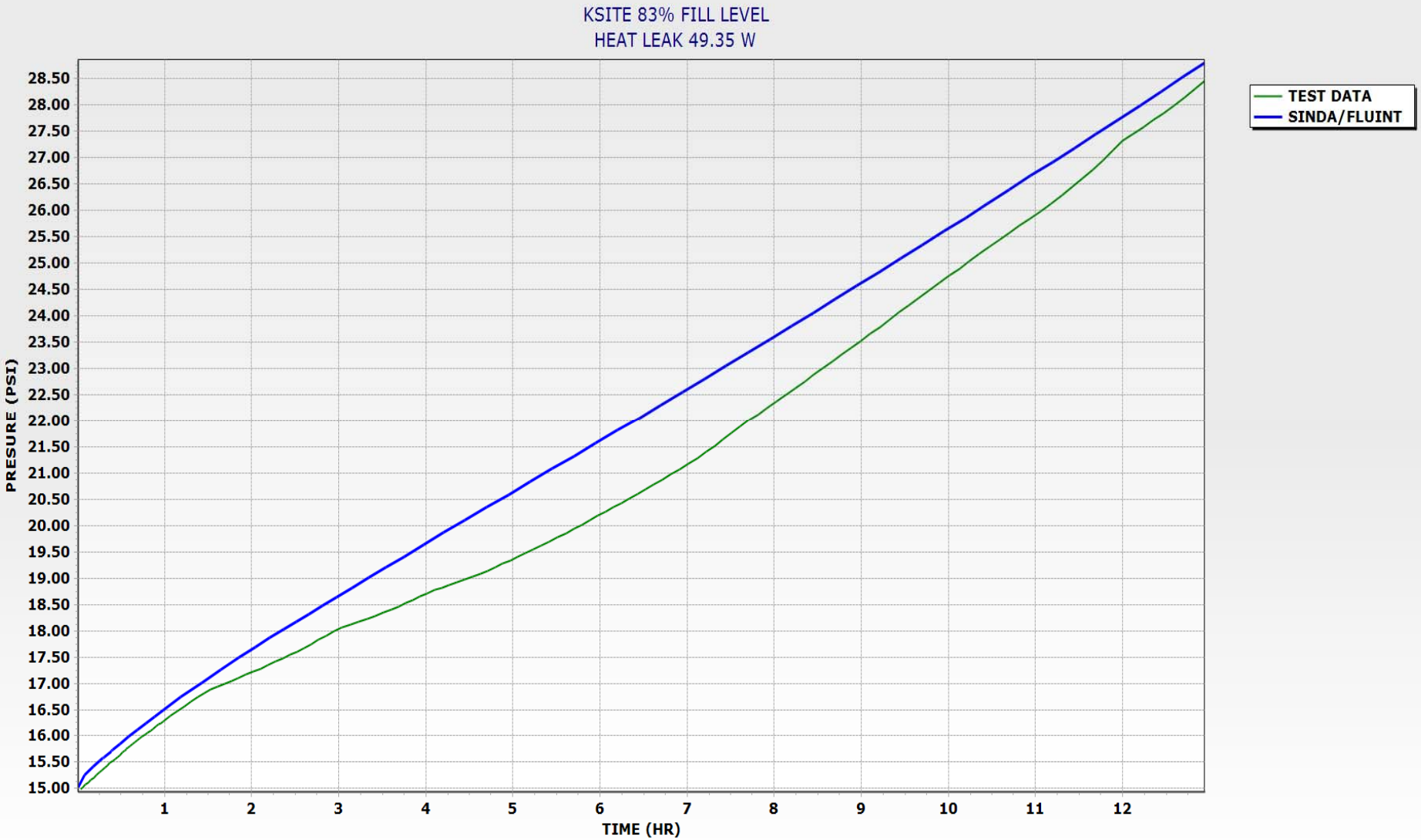
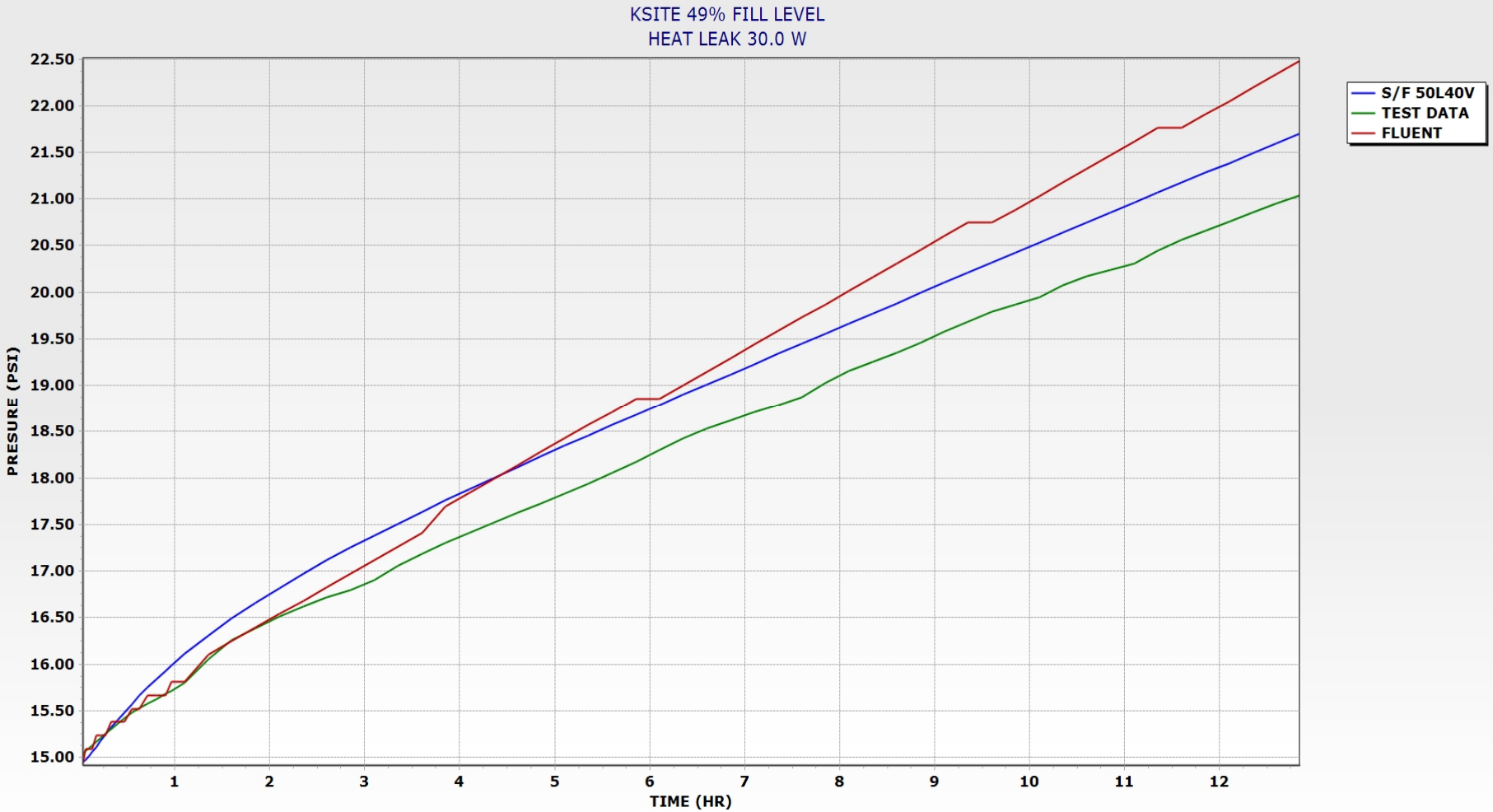


K-site LH2 1g Self-pressurization: Experimental and SINDA/FLUINT RESULTS

SINDA/FLUINT used 50 LIQUID LUMPS, 40 VAPOR LUMPS

49% Liquid Fill Level. Total Heat into Tank = 30 W

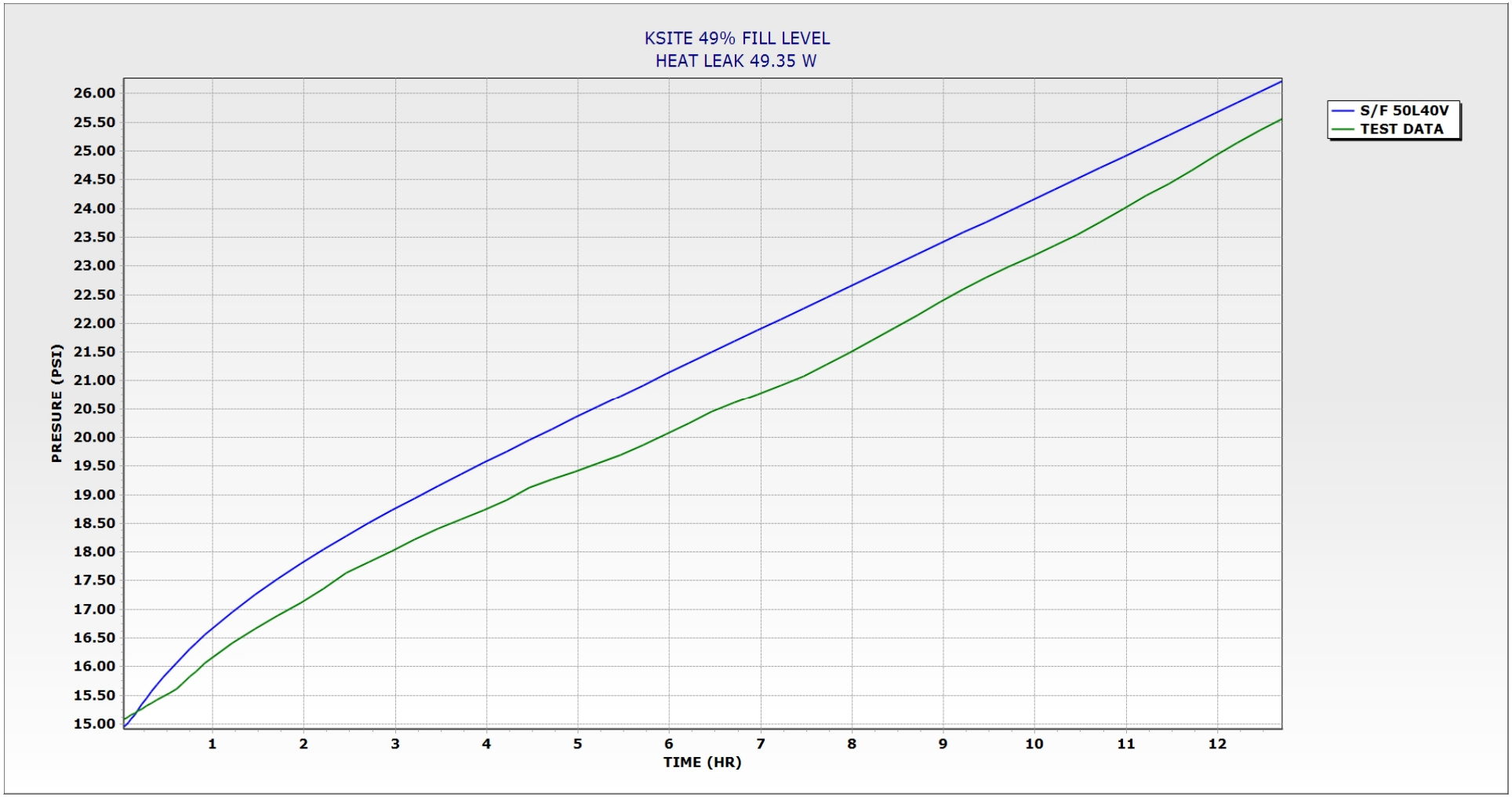
Fluent = lumped ullage model



K-site LH2 1g Self-pressurization: Experimental and SINDA/FLUINT RESULTS

SINDA/FLUINT used 50 LIQUID LUMPS, 40 VAPOR LUMPS

49% Liquid Fill Level. Total Heat into Tank = 49.35 W

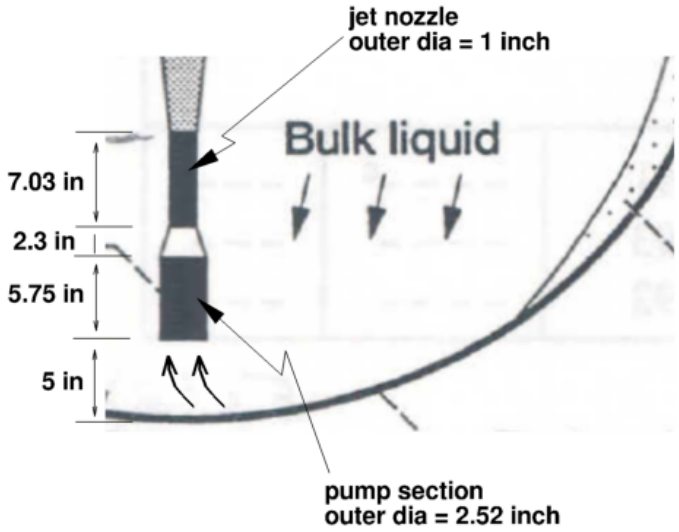


Validation Cases BACK UP SLIDES!!

- **K-Site LH2 Axial Jet (1g)**

K-site LH2 Axial Jet Experiments (1g)

- Same Tank as K-site LH2 1g Self-pressurization experiments. Pump and jet nozzle (mixer unit) was hardware designed for Shuttle Centaur LH2 tank and installed in K-site LH2 tank.
- Jet nozzle and location not changed during axial jet runs, but the jet flow rate was varied.
- Only considering test runs where self-pressurization was used to pressurize tank before turning on jet (Test Series A and B). Tank typically pressurized to 186 kPa before initiating jet.
- Experimental data is available for:
  tank heat load,
  ullage pressure,
  fluid temperature rake,
  wall temperatures,
  jet flow rates.



NASA TM-106629, 1994

K-site LH2 Axial Jet: Test Runs Simulated

Table 1: Experimental conditions for mixing tests.

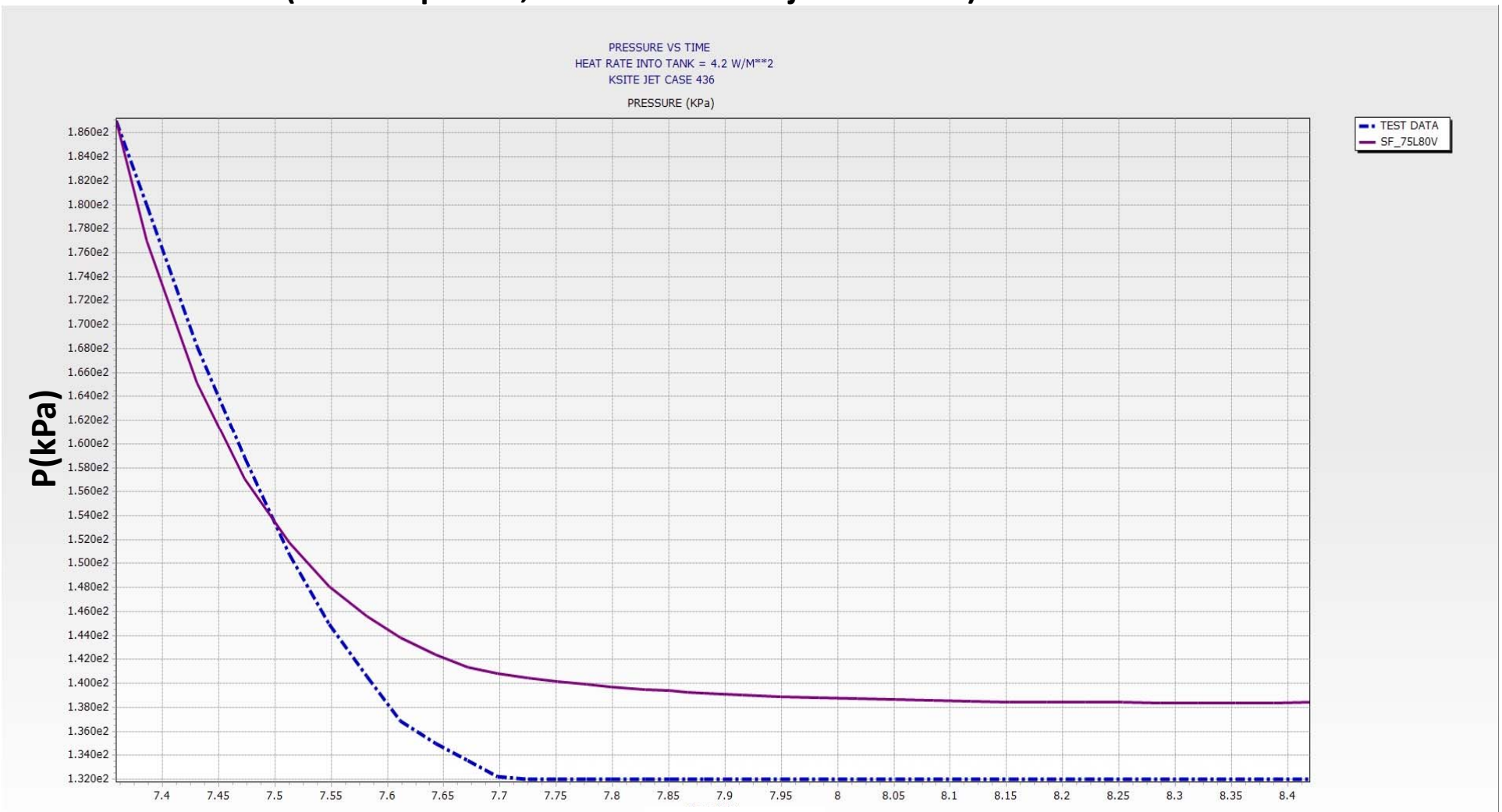
Test run #	Initial liquid fill, %	Jet volume flow rate, m^3/hr	Jet velocity, m/s	Re_{jet}	Initial pressure, kPa
436	85.3	1.82	1.32	160,000	187.0
434	86.3	3.47	2.51	304,000	186.1
457	49.1	1.82	1.33	161,000	186.5
449	49.1	3.41	2.47	299,000	186.1

1.82 m^3/hr = 8.0132 GPM LH2
3.41 m^3/hr = 15.0138 GPM LH2
3.47 m^3/hr = 15.278 GPM LH2

K-site LH2 1g Axial Jet: Experiment and SINDA/FLUINT

SINDA/FLUINT used 75 LIQUID LUMPS, 50 VAPOR LUMPS

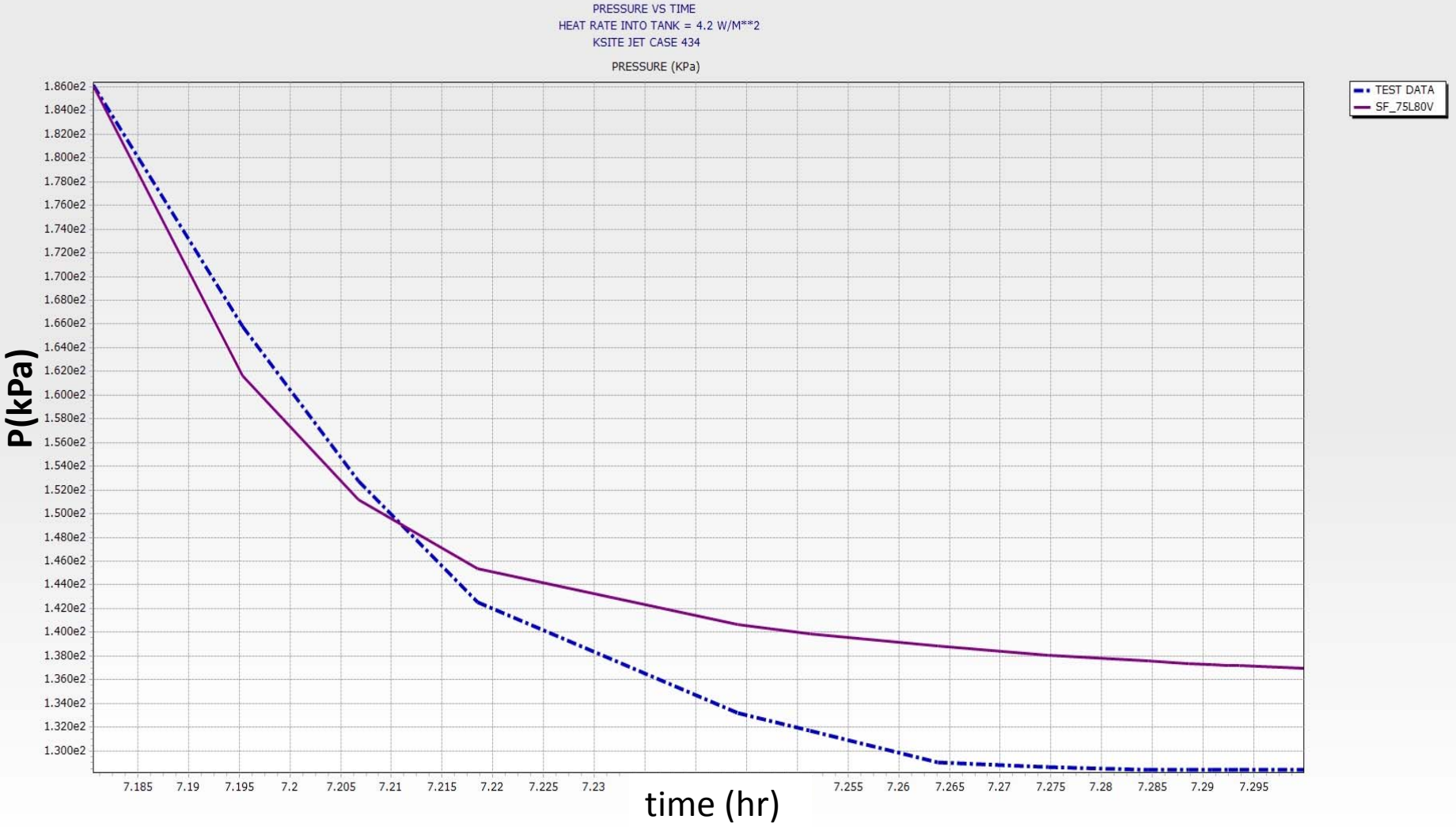
Test Run 436 (85.3% liquid fill, 8.0132 GPM LH2 jet flow rate)



K-site LH2 1g Axial Jet: Experiment and SINDA/FLUINT

SINDA/FLUINT used 75 LIQUID LUMPS, 50 VAPOR LUMPS

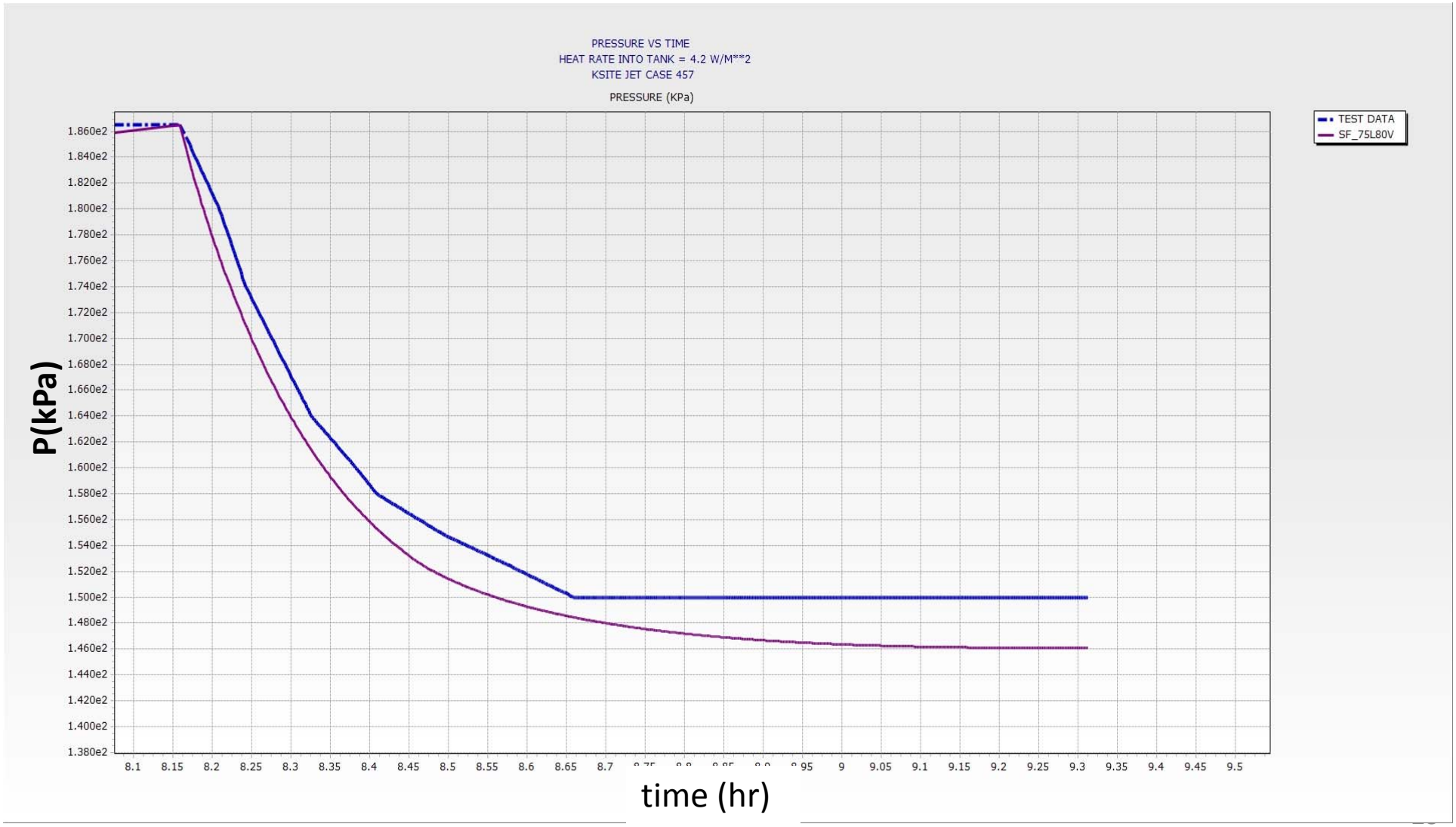
Test Run 434 (86.3% liquid fill, 15.278 GPM LH2 jet flow rate)



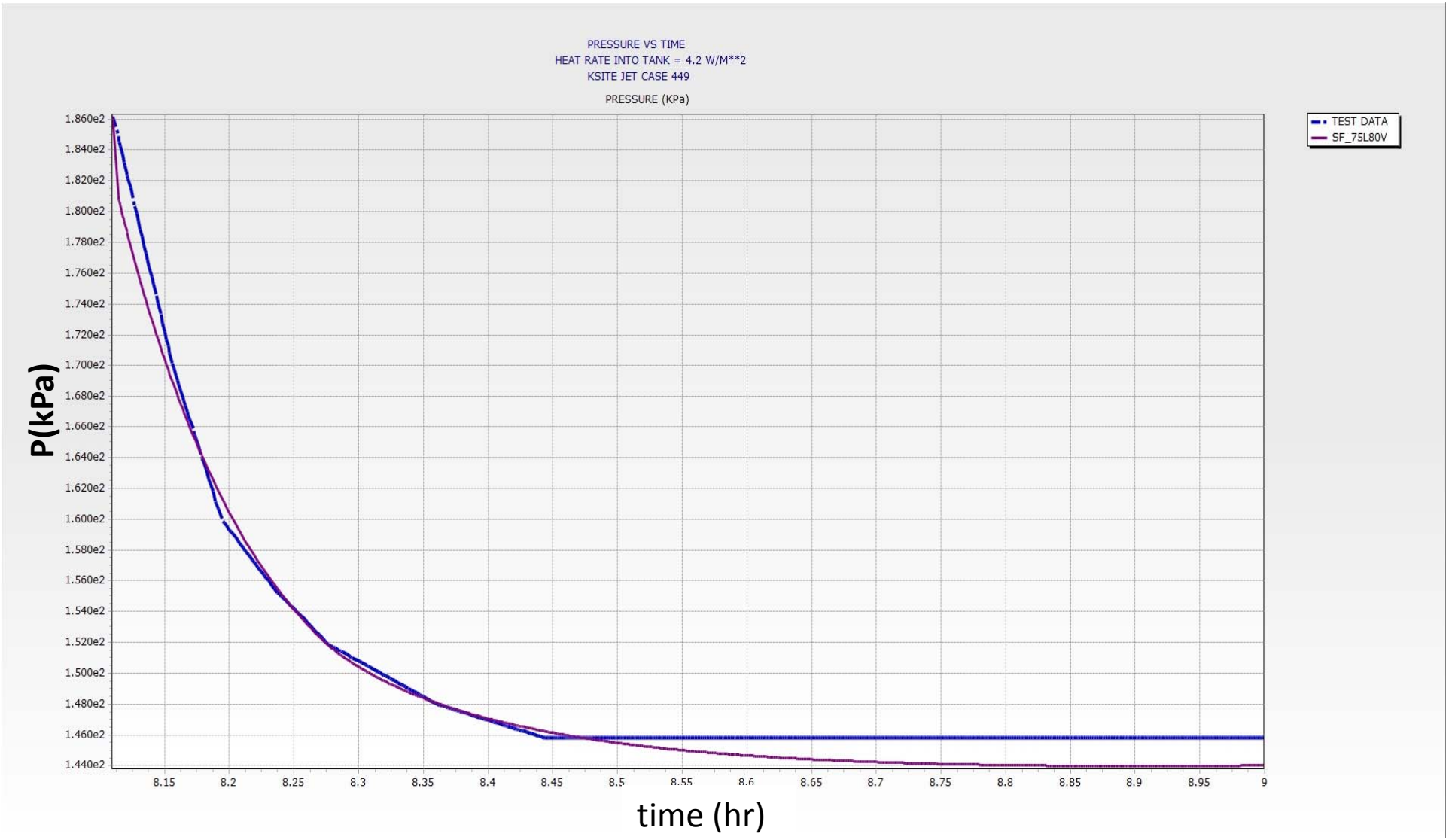
K-site LH2 1g Axial Jet: Experiment and SINDA/FLUINT

SINDA/FLUINT used 75 LIQUID LUMPS, 50 VAPOR LUMPS

Test Run 457 (49.1% liquid fill, 8.0132 GPM LH2 jet flow rate)



K-site LH2 1g Axial Jet: Experiment and SINDA/FLUINT

SINDA/FLUINT used 75 LIQUID LUMPS, 50 VAPOR LUMPS

Test Run 449 (49.1% liquid fill, 15.0138 GPM LH2 jet flow rate)