Hydrogen Safety, Codes & Standards SNL Technical Program -- Update

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DOE H_2 Safety, Codes & Standards Program Definition

H_2 Codes & Standards

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H_2 Safety

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SNL H_2 Safety, Codes and Standards Risk Assessment

- Sandia has a long history of safety engineering
  - Non-nuclear safety for all weapons systems, accident scenarios
  - Hydrogen combustion assessments for NRC
- Probability risk assessment
  - Use engineering analysis and experimental correlations
  - Validate high-risk cases using detailed analysis and testing
- Use well-characterized, physically relevant benchmarks to validate methods for detailed analysis

SNL H_2 Safety, Codes & Standards Program Definition

- Sandia and our team are providing the technical basis for assessing the safety of hydrogen based systems with the accumulation of knowledge feeding into the development/modification of codes and standards

- Primary element of the program is the development of experimentally validated analysis tools backed by a sound scientific fundamental base Scenario Analyses
  - Risk assessments for safety
  - Hydrogen-compatible materials
  - Sensors
  - Testing

SNL H_2 Safety, Codes & Standards Program Definition (Cont'd)

- Hydrogen Safety Scenario Analysis will provide a scientific basis for defining credible safety scenarios, leading to defensible codes and standards:
  - Defensible first principles analysis and prediction with models and experiment
  - Fluid dynamics and dispersion of gases
  - Heat and mass transfer, ignition and combustion processes
  - Structural analysis and failure mechanisms
  - Storage: reactive materials (metal hydrides), cryogenics, high pressures
  - Risk assessments (with approaches based on our experiences with weapons systems safety)
  - Scenario analysis tools (reusable, continually evolving with knowledge base; e.g. engineering tools to predict dispersal, accumulation, diffusion times, flammability)
  - Validation benchmarks for uniform calibration of CFD/FEA analysis

SNL H_2 Safety, Codes & Standards Program Elements

- **Diagnostic / sensor development for hazards assessment**
  - **Remote leak detection (*e.g. spectroscopy*)**
  - **Non-destructive testing, structure integrity**
  - **Tracers for remote leak detection**

- **Fire suppression**
  - **Chemical development for H_2 compatible fire suppression**

SNL H_2 Safety, Codes and Standards Program Elements (Cont'd)

- **Materials work for analysis and characterization**
  - **Material selection guidelines**
    - **Develop materials selection handbook**
  - **Aging and cycling of existing materials (*e.g., tube tanks, …*)**
  - **New materials, degradation and hazards *(e.g., fatigue in composites, permeation, …)***

- **Codes and Standards support activity**
  - **Enhance and maintain best practices handbook**
  - **Interface to international standards committee**
  - **Critical evaluation of standards**
  - **Contribute to the definition of standards and rules**

SNL H_2 Safety, Codes and Standards Safety Themes

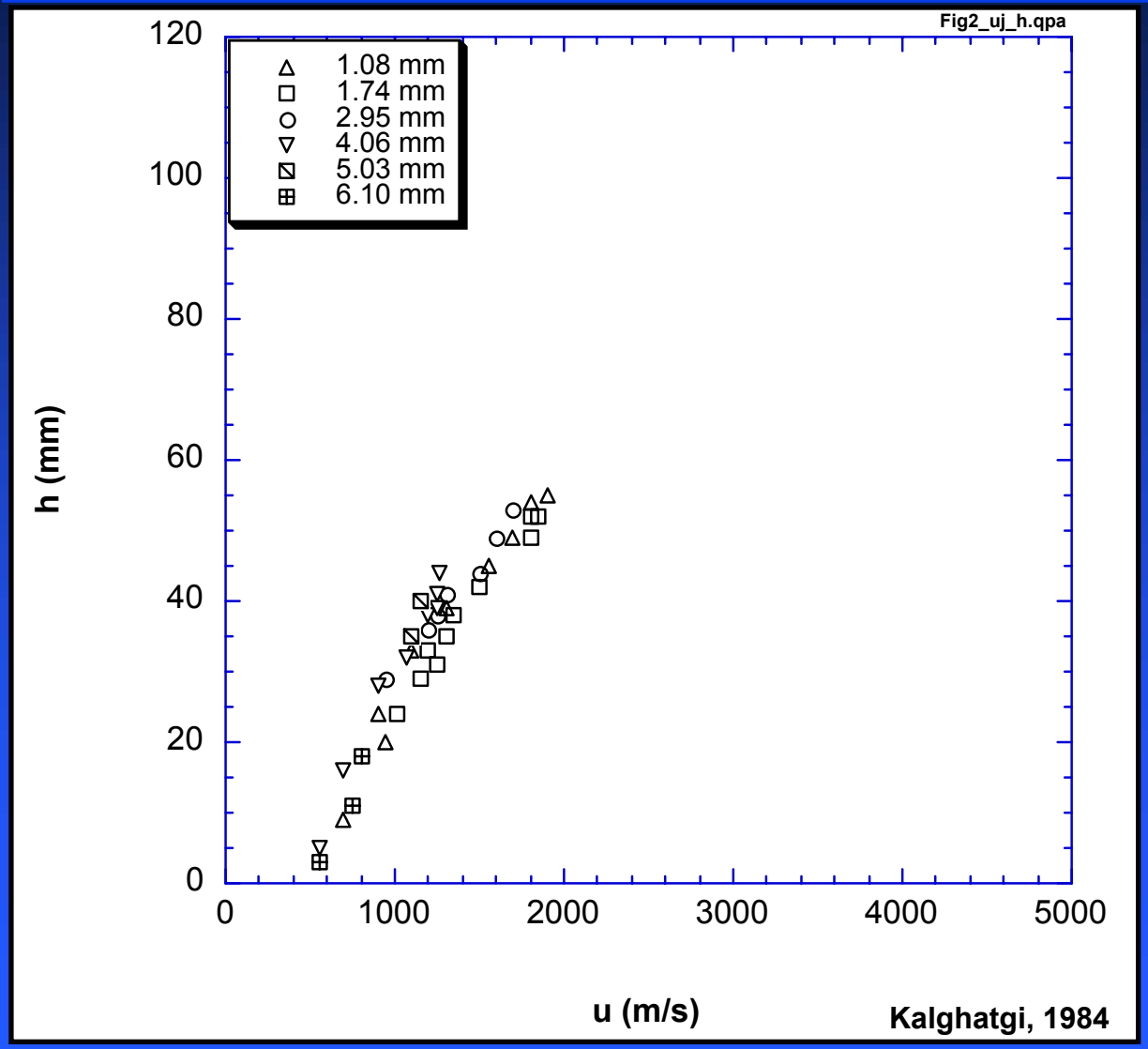
- Defensible codes and standards are backed by the understanding of credible use-scenarios

- Scenario analysis has three themes
  - Normal environments (*impacts the supplier/consumer*)
    - Safe operating conditions
      - (*structural loads/pressures, temperatures/heating*)
    - Production, delivery, storage, conversion
  - Abnormal environments (*impacts the supplier/consumer*)
    - Transportation accidents, crashes, …
    - Fires, earthquakes, lightning strike, …
  - Hostile Environments (*impacts the general public*)
    - Direct assault on components
    - Attack on infrastructure

Flame Characterization

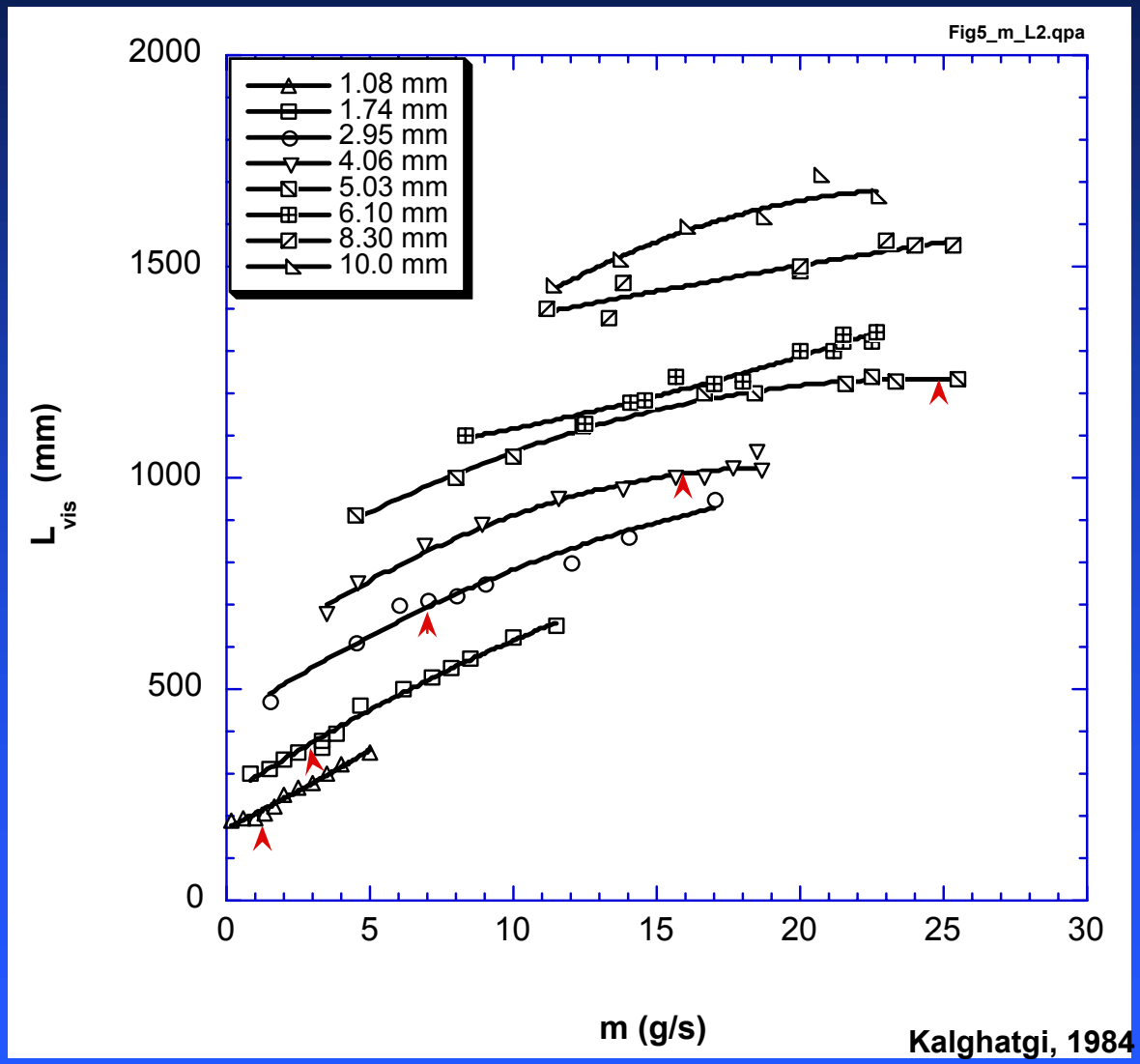
- Can we characterize large-scale flame in terms of observations of laboratory-scale flames?
  - Flame Lift off
  - Flame length
  - Radiant Heat Flux (action at a distance)
  - Convective Heat Flux (flame impingement)

Flame Lift-Off



- Lift-off occurs at critical exit velocity
- Independent of jet diameter for range shown
- Lift-off distance depends on:
  - Fuel
  - Exit velocity
  - Still air or co-flow
- H_2 jet stabilizes closer to jet exit than CH_4 due to higher flame speed

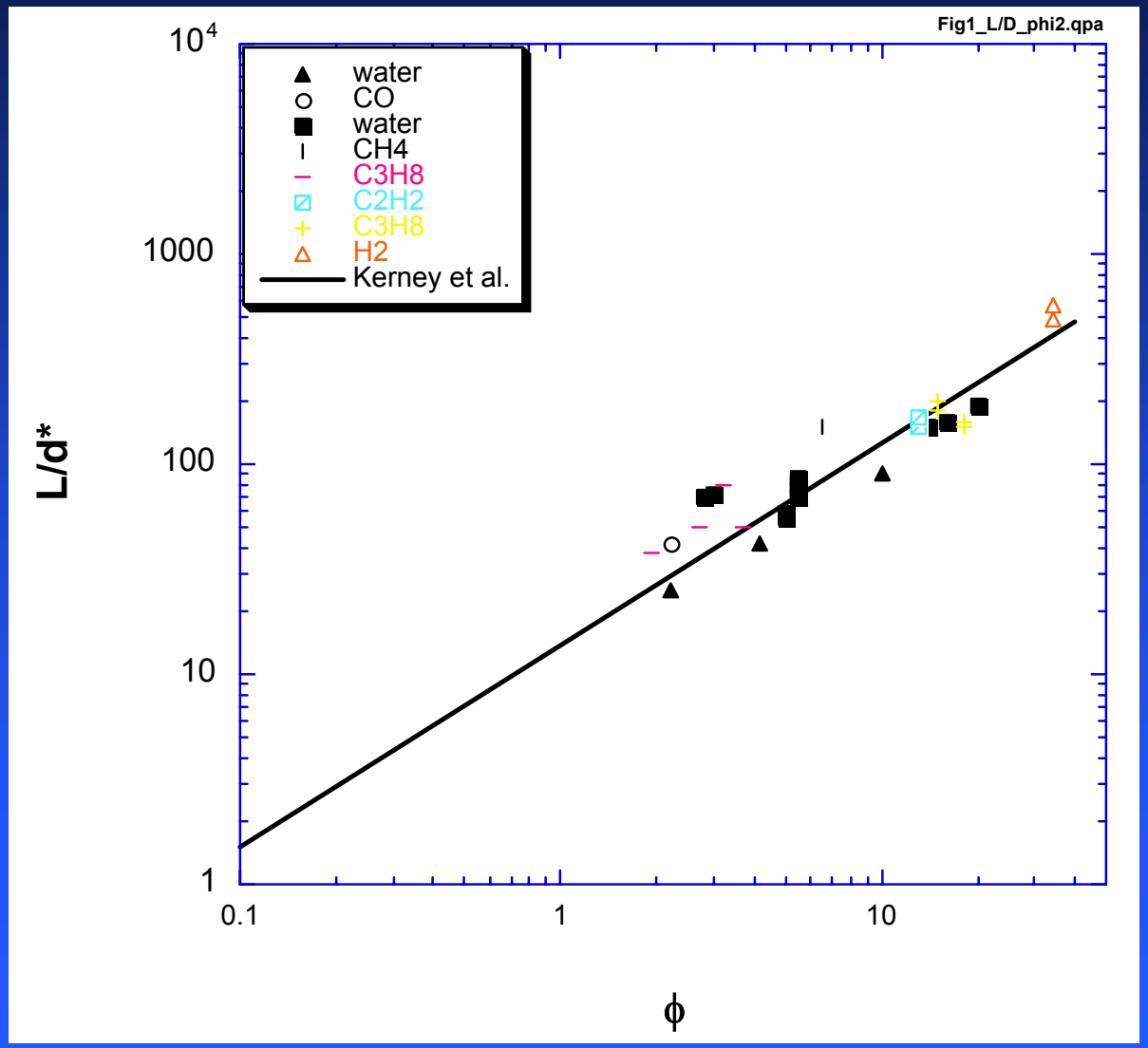
Visible Flame Length



Kalghatgi, 1984

- Becker and Liang (1978) used visual observations of the "furthest point at which the flaming gas was seen to dwell with appreciable frequency" to define the flame tip.
- Flame length increases with mass flow rate
- Flame length increases with jet diameter
- Flame lengths for H_2 shown in the plot. Results for methane, propane, and ethylene are similar.

Stoichiometric Flame Length



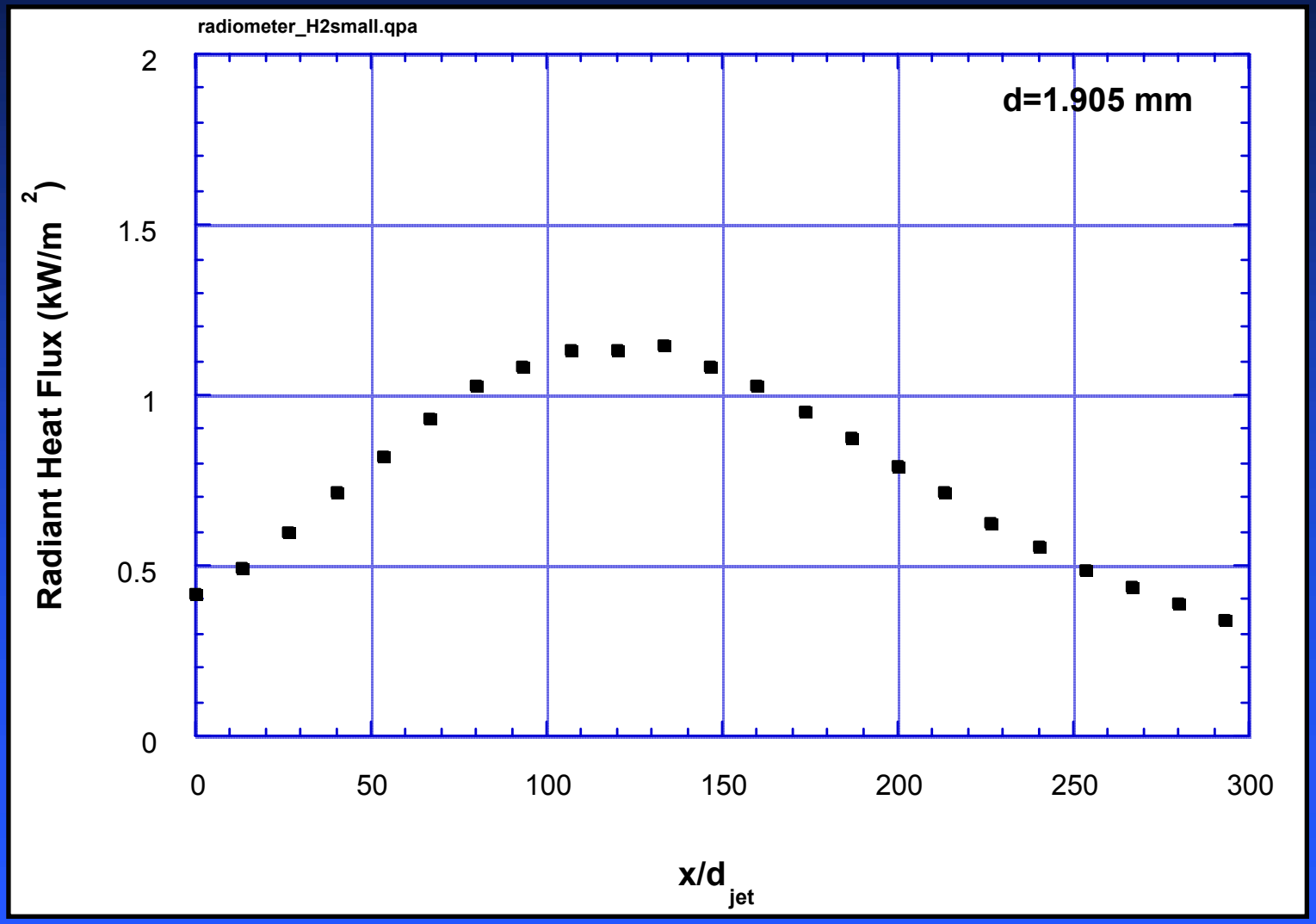
- Jet momentum diameter
  $d^* = (\rho_j/\rho_a)^{1/2} * d_j$
- Stoichiometric fuel ratio for H_2 is 34
- $L/d^* = 500$

Radiant Heat Flux is lower for H_2 than Hydrocarbons

Hydrocarbon Fuel Fire ~100 kW/m²

Hydrogen Flame ~ 1 kW/m²

Centerline Radiant Heat Flux Turbulent H_2 Flame



SNL H_2 Offset Distances Project Problem Definition - Example

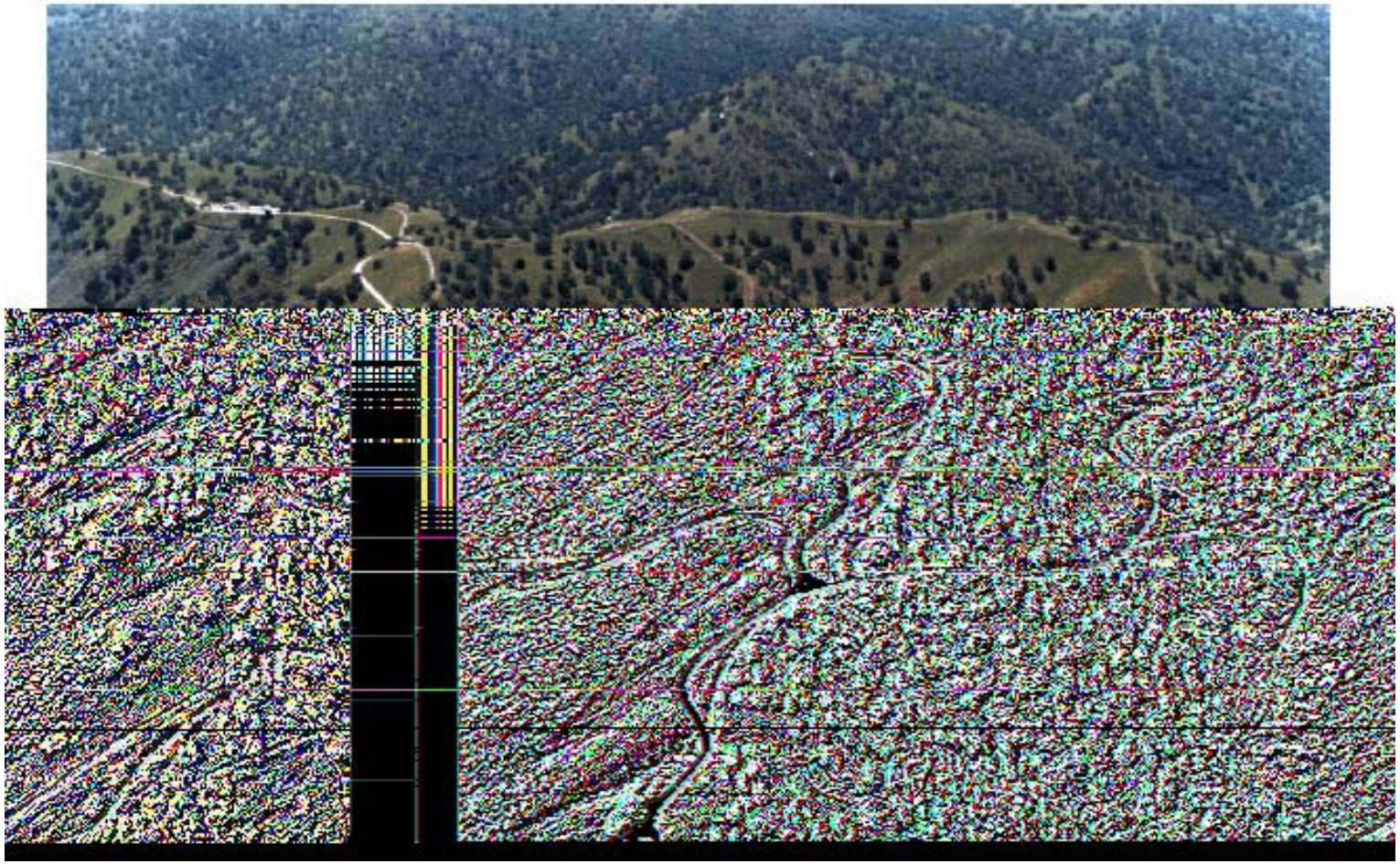
- Current separation distances for commercial sites based on natural gas experience
- This project aimed at supplying hydrogen properties information to codes developers to allow the generation of safe, effective site requirements for commercial applications
  - flame properties
    - size, shape, temperature profile, radiation, …
  - flame impact on wall
  - gas dispersion, accumulation and concentration
  - effects of orifice size, shape, flow rates.

SNL H_2 Offset Distances Project Problem Definition

- Guide code development based on defensible scientific data
  - Specifically -- influence NFPA 50 development for hydrogen
- Combined experimental and modeling effort
  - Experiments conducted in collaboration with SRI and SNL
  - Modeling conducted in collaboration with Mike Swain at UofM and SNL
- In the first phase we have planned
  - 9 flame impingement tests
    - with and without a wall
    - vertical and horizontal orientations
  - 12 lean ignition tests

SNL H_2 Offset Distances Project
SRI Test Facility

SRI's Corral Hollow Test Site

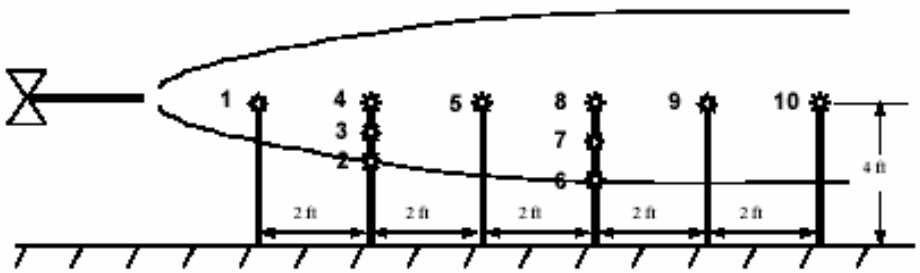


Tracy, CA

SNL H_2 Offset Distances Project
SRI Test Facility

10 type-B thermocouples

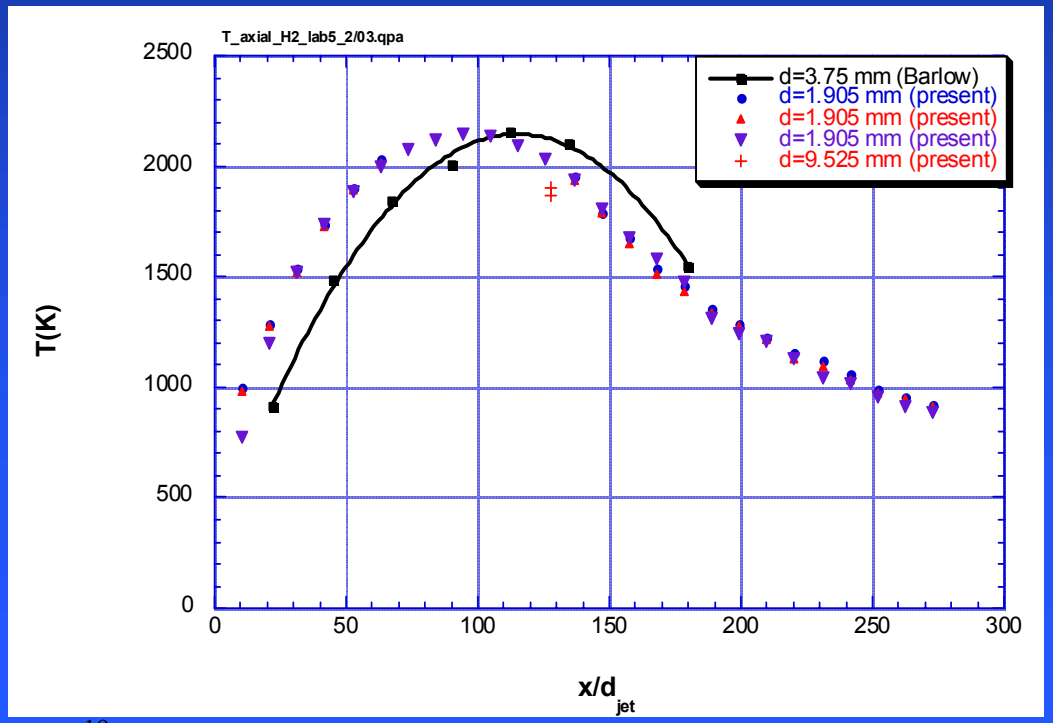
- 6 longitudinal measurements at 2-ft intervals from nozzle
- 4 radial measurements at 4 and 8 feet from nozzle
  - 4 and 8 inches at 4 feet from nozzle
  - 6 and 12 inches at 8 feet from nozzle



- **Baseline circular nozzle, 5/16”**
- **Peak flow rate ~2000 SCFM**

SNL H_2 Offset Distances Project Approach

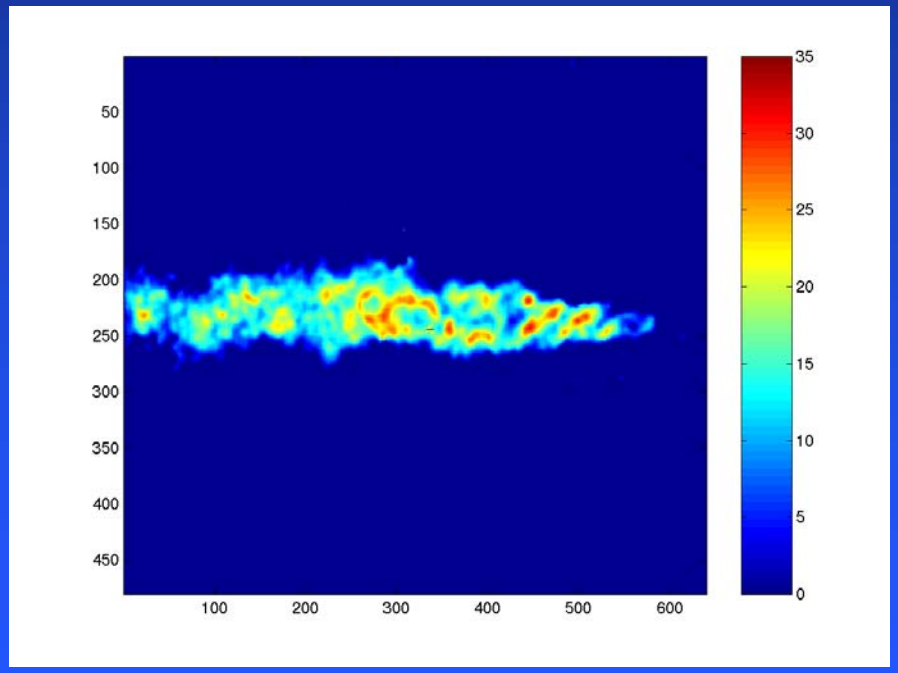
- Combined experimental – modeling approach
  - experimental tests help define scaling laws and validate models
  - large scale tests with lab tests span wide range of conditions



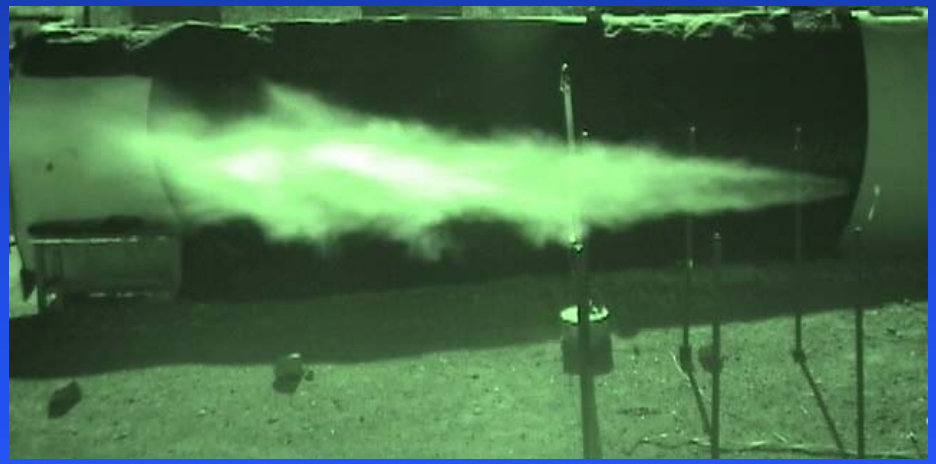
2200 scfm vertical plume
10-12 ft. length 2-3 ft width

SNL H_2 Offset Distances Project UV and IR Imaging of a H_2 Flame

The UV image is due to emission from excited-state OH* molecules (~304 to 350 nm) and indicate the location and structure of the primary reaction zone

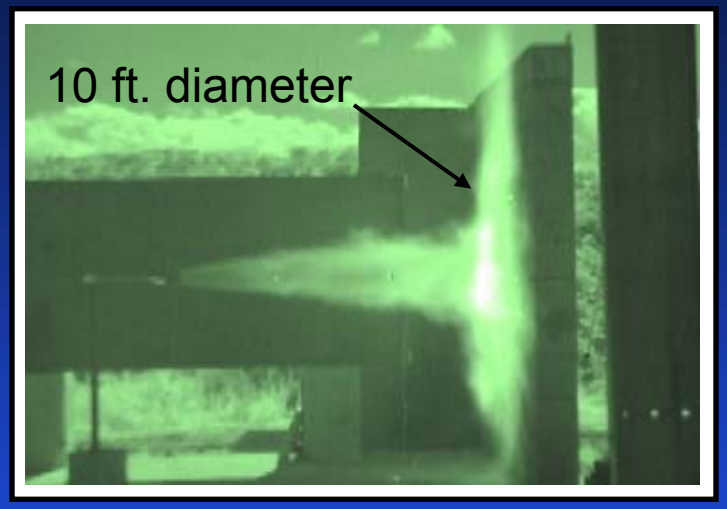


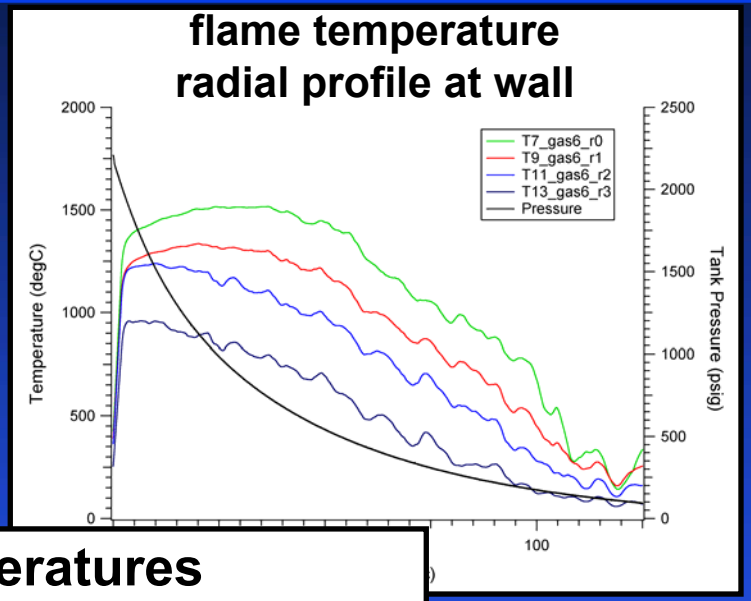
The IR image is due to emission from water (~0.5-23 mm) and any entrained substance like dust

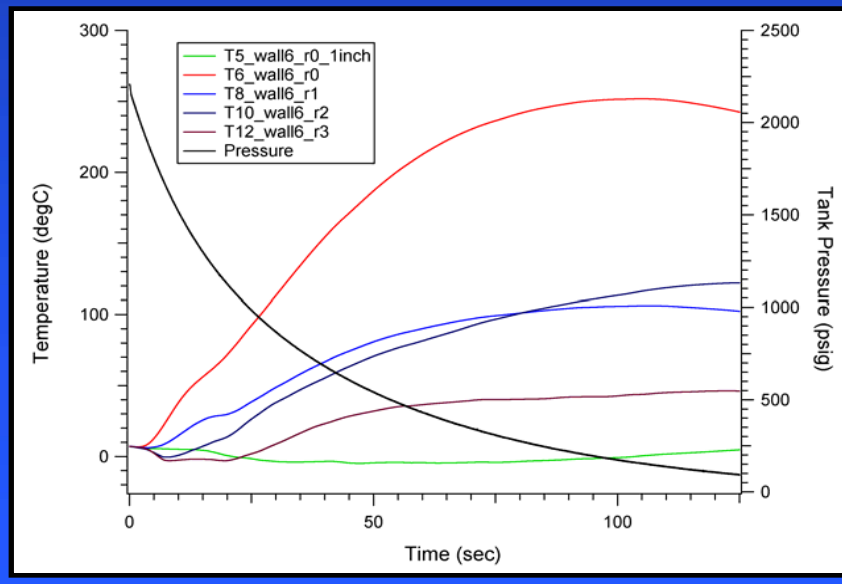


images of a turbulent, hydrogen-jet flame. d_{jet}=9.535 mm.

SNL H_2 Offset Distances Project Flame Impingement on a Wall







wall temperatures

surface centerline

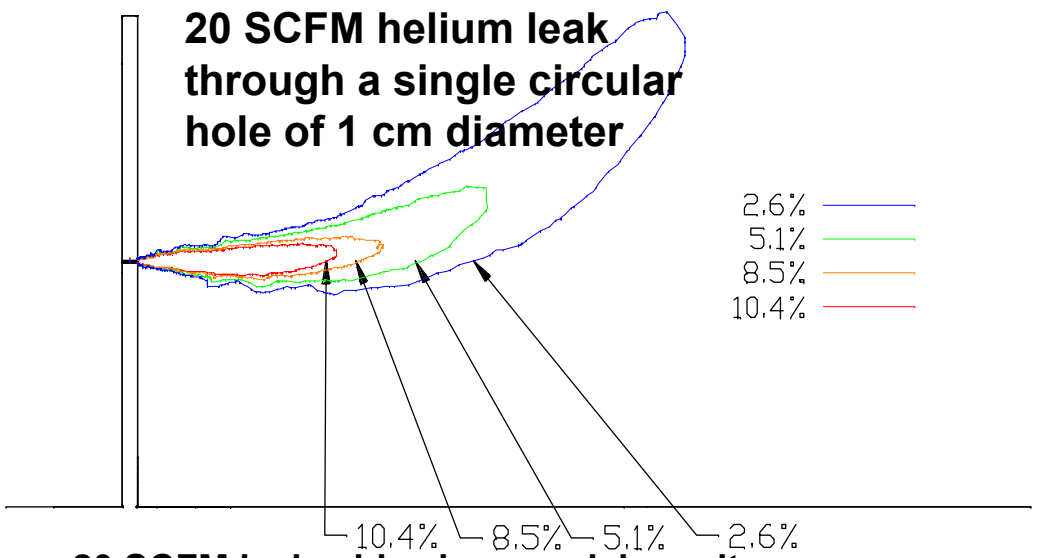
surface, 1 ft., 2 ft. from centerline

surface 3 ft. from centerline

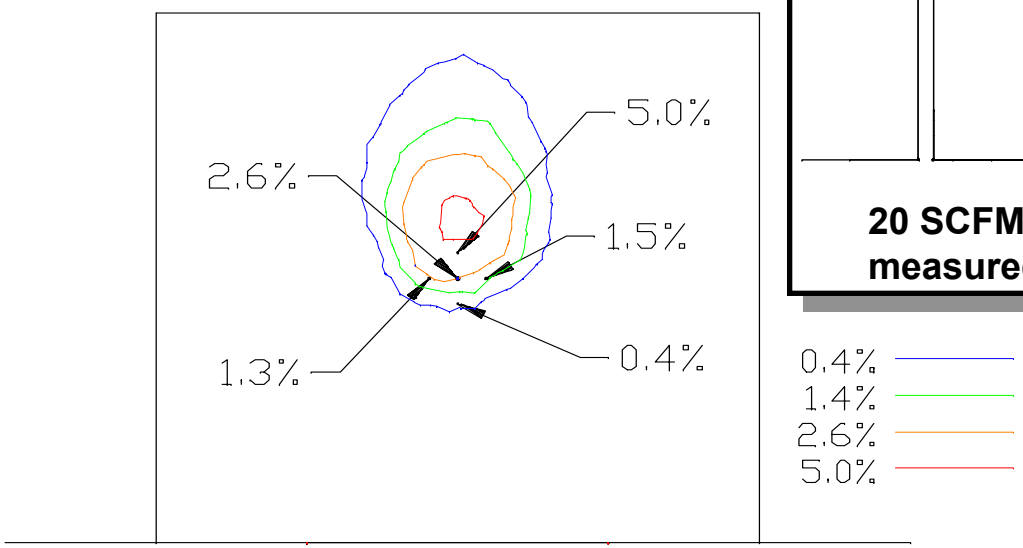
1 inch below surface centerline

2200 SCFM – 6 ft. from source

SNL H_2 Offset Distances Project Turbulent Jet Model Validation



20 SCFM leak, side view, model results vs. measured concentrations

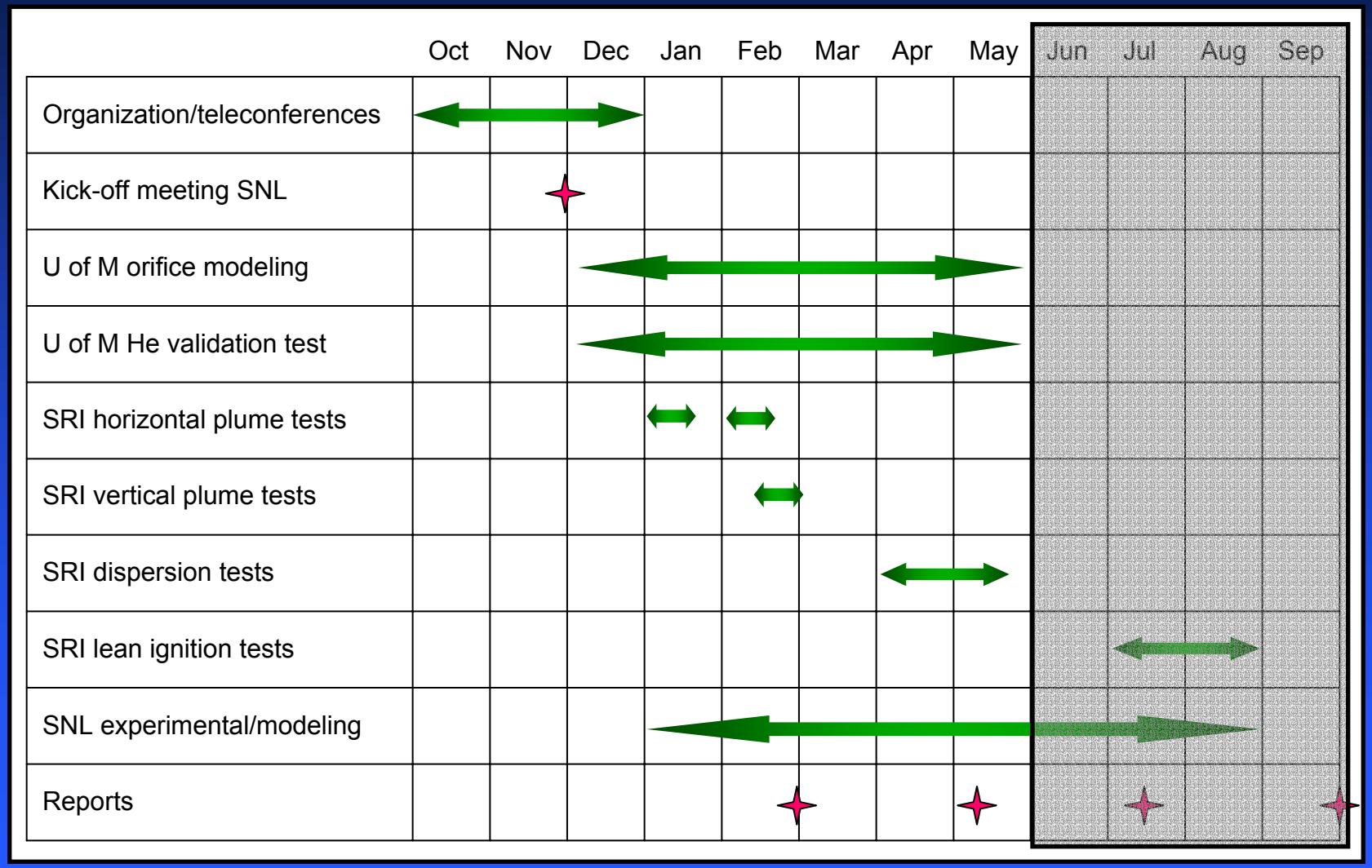


Front view, 68.75 inches from leak, model results vs. measured concentrations

SNL H_2 Offset Distances Project Summary and Status

- SRI/SNL experiments
  - Ignited vertical and horizontal 2200 scfm tests completed for 9.5 mm diameter circular orifice
    - longitudinal, radial temperature profiles
    - radiated energy
  - Wall impingement tests with 2200 scfm ignited horizontal plume for ~2 minutes duration
    - wall temperatures near surface showed a peak temperature of ~250 C at centerline
    - essentially no temperature rise 1 inch below surface
- Univ. of Miami modeling/ experiments
  - Modeling and experimental measurements of ignition near lower flammability limit with flow rates ~ 20 scfm.

SNL H_2 Offset Distances Project Schedule



SNL H_2 Safety, Codes and Standards Compatibility Handbook – SNL Expertise

- Active Sandia staff members have published over 70 papers on hydrogen effects in materials
  - Materials for Hydrogen Storage and Transmission (4)
  - Interactions Between Hydrides and Containment Materials (1)
  - Effect of Temperature on Hydrogen-Assisted Fracture in Metals (2)
  - Hydrogen-Assisted Fracture in Carbon and Stainless Steels (8)
  - Hydrogen-Assisted Fracture in Iron and Nickel - Based Super alloys (11)
  - Hydrogen-Assisted Fracture in Titanium Alloys (10)
  - Hydrogen Assisted Fracture of Films and Coatings (4)
  - Hydrogen-Assisted Fracture of Ceramics (1)
  - Hydrogen Effects on Plastic Deformation of Metals (3)
  - Physics of Hydrogen in Metals (9)
  - Modeling of Hydrogen-Assisted Fracture in Metals (17)

- Active Sandia staff members have organized 5 conferences and symposia on hydrogen effects in materials

SNL H_2 Safety, Codes and Standards Materials Compatibility Handbook

- First step, host workshop to define materials compatibility handbook

- Workshop topics might include:
  - Extending existing infrastructure to new environments and operating conditions
  - Materials for new infrastructure components
  - Performance of materials and components at cryogenic temperatures
  - Carbon fiber pressure tanks
  - Non-hydrogen materials compatibility
  - Design of components exposed to hydrogen environments
  - Non-destructive testing
  - Hydrogen sensors

SNL H_2 Safety, Codes and Standards Materials Compatibility Handbook

- **Timeline for formulating workshop**
  - **June 2003, organization meeting among key stakeholders**
  - **July 2003, call for contributions to workshop**
  - **October 2003, workshop to define handbook content**