INEEL - Forced Flow in Complex Internal Cavities

Goal

Provide fundamental flow physics knowledge necessary to develop reliable predictive techniques for application to drying and passivation problems in Environmental Management (in the forced flow limit)

Typical non-dimensional parameters of generic idealization (for $Re_{tube} \approx 2500$, $L/D \approx 80$)

- Impinging jet: $Re_{jet} \approx 2500$, $s/D \approx 2$, $H/D \approx 2$, $R/D \approx 6$
- Support plate: $Re_{hole} \approx 40\text{-}160$, Approx. angle $\approx 90°$, $p/D \approx 4$
- Elements: $Re_{Dh\ avg} \approx 70$, $L/D_h \approx 6$, $p/D \approx 2$, $Turb_{in} \approx$??
- $L^+ \approx 0.4$, Angle of flow $\approx$?, "Equiv." $K_V \approx 0.02$, $K_P \approx 0.11$

Aim for application

Reliable prediction of mass transfer between the fluid and elements

Fundamental flow physics questions evolving

- Effects of turbulence on mass (heat) transfer in an array of elements? Streamwise pressure gradient? Crossflow?
- Decay of turbulence in flow through an array of elements?
- Characteristics of turbulence entering the array?
- Effects of flow through multiple holes on turbulence fields?
- What are the turbulence fields approaching the holes?
- Turbulence in semi-confined low-Re turbulent impinging jet?
- Effects of inflow turbulence on behavior of impinging jet?
- Turbulence distribution from low-Re turbulent tube flow?

Initial concentration

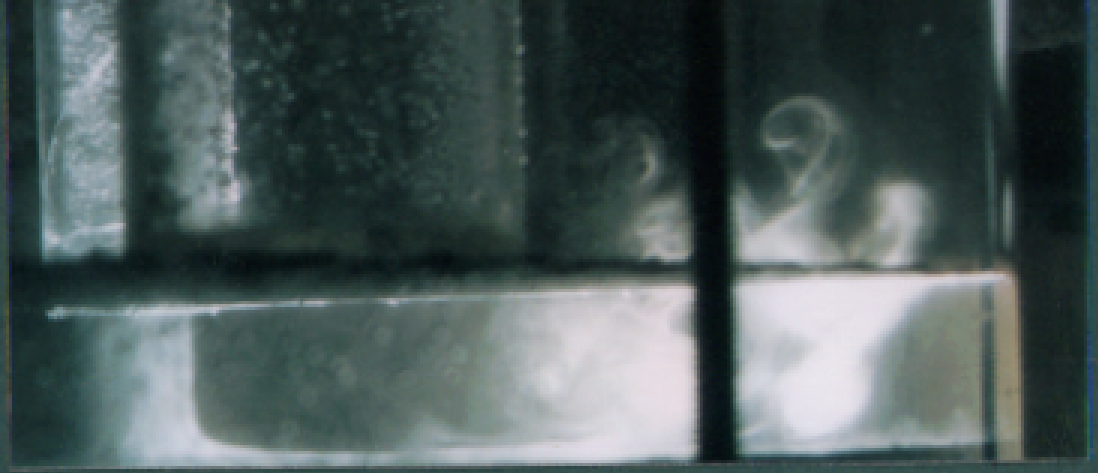
Turbulence structure in the low-Reynolds number flow of a semi-confined impinging jet

Previous work, low-Re tube flow (jet inlet)

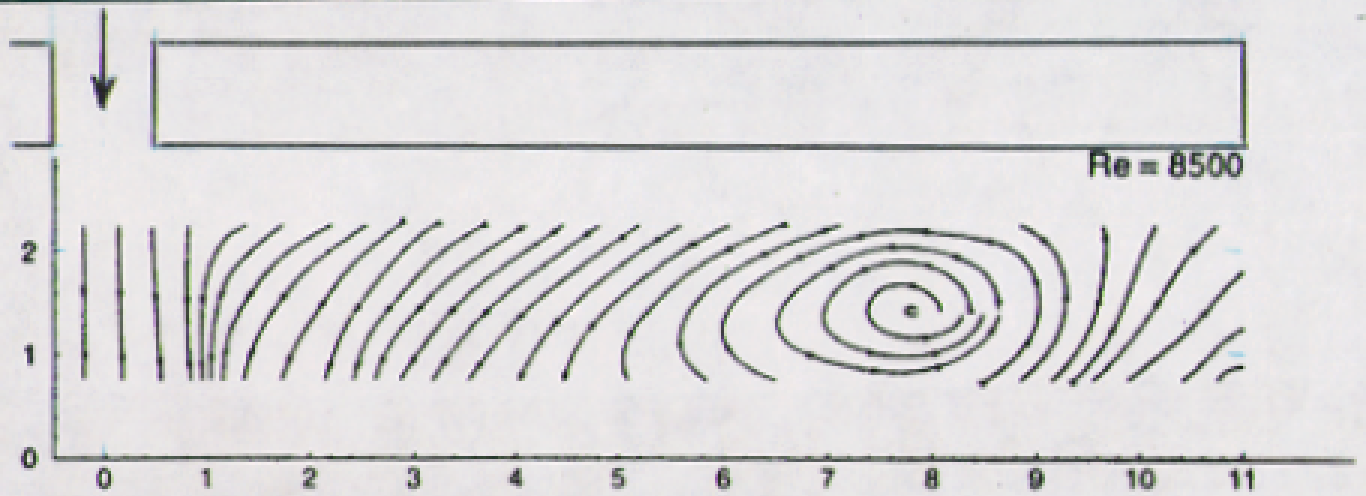
- Mean velocity profile data available
- Poor predictions by popular general purpose codes
- Turbulence data, Re > 4000 [Durst et al.]
- DNS-LDV/PIV turbulence data, Re ≈ 5500

Previous work - impinging jets

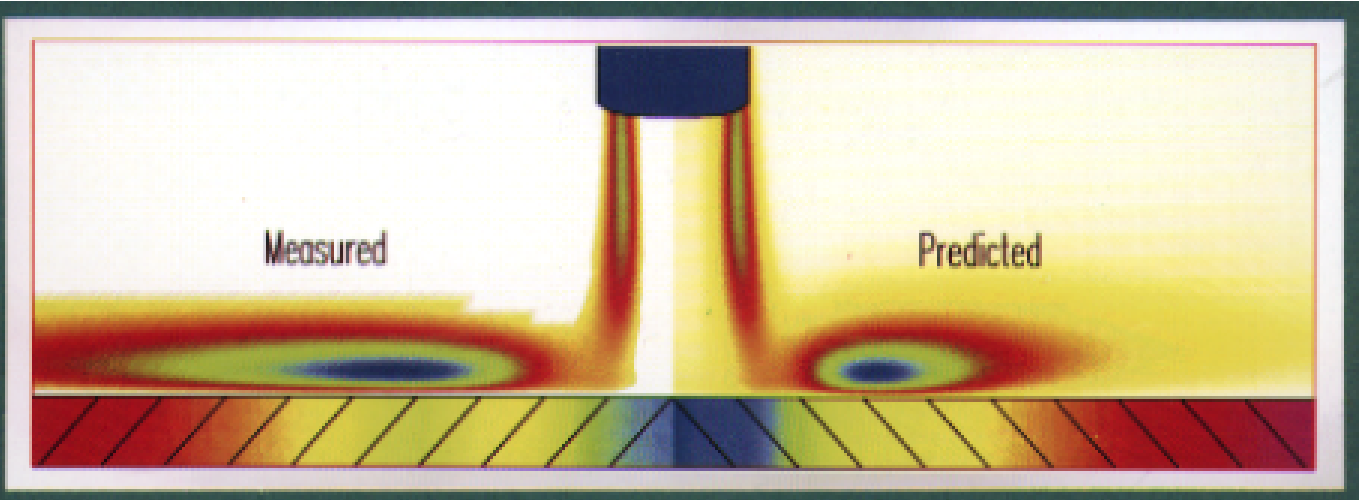
- Poor agreement of predictions and data (see figure at right)
- Most data are for unconfined jets and heat transfer
- Paucity of flow measurements
- Useful turbulence data scarce
- Velocity and turbulence data for unconfined impinging jets, Re ≈ 6000 [Adrian], Re ≈ 23,000 [Launder]
- Limited flow data for confined jets [Garimella and colleagues]
- Laminarization criterion available for confined flow [Kreith]
- Apparently no turbulence or velocity field data available for semi-confined impinging jets (as in idealized geometry)



50% semi-confined [McCreery, INEEL, 1998]



Confined [Garimella, U. Wisc-Mil, 1997]



Unconfined [Craft, UMIST, 1998]

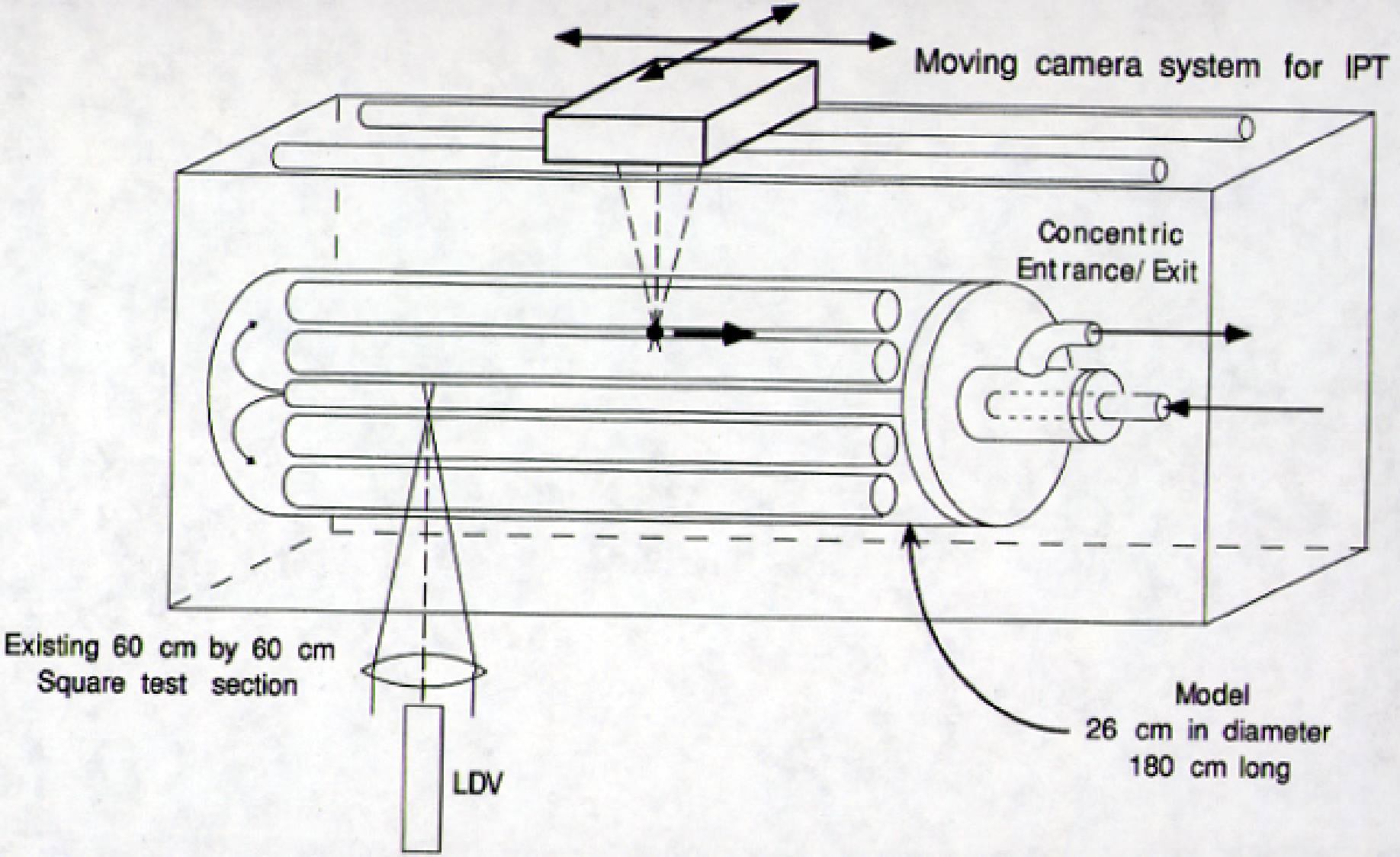
4% semi-confined [McCreery, INEEL, 1998]

Flows of impinging jets

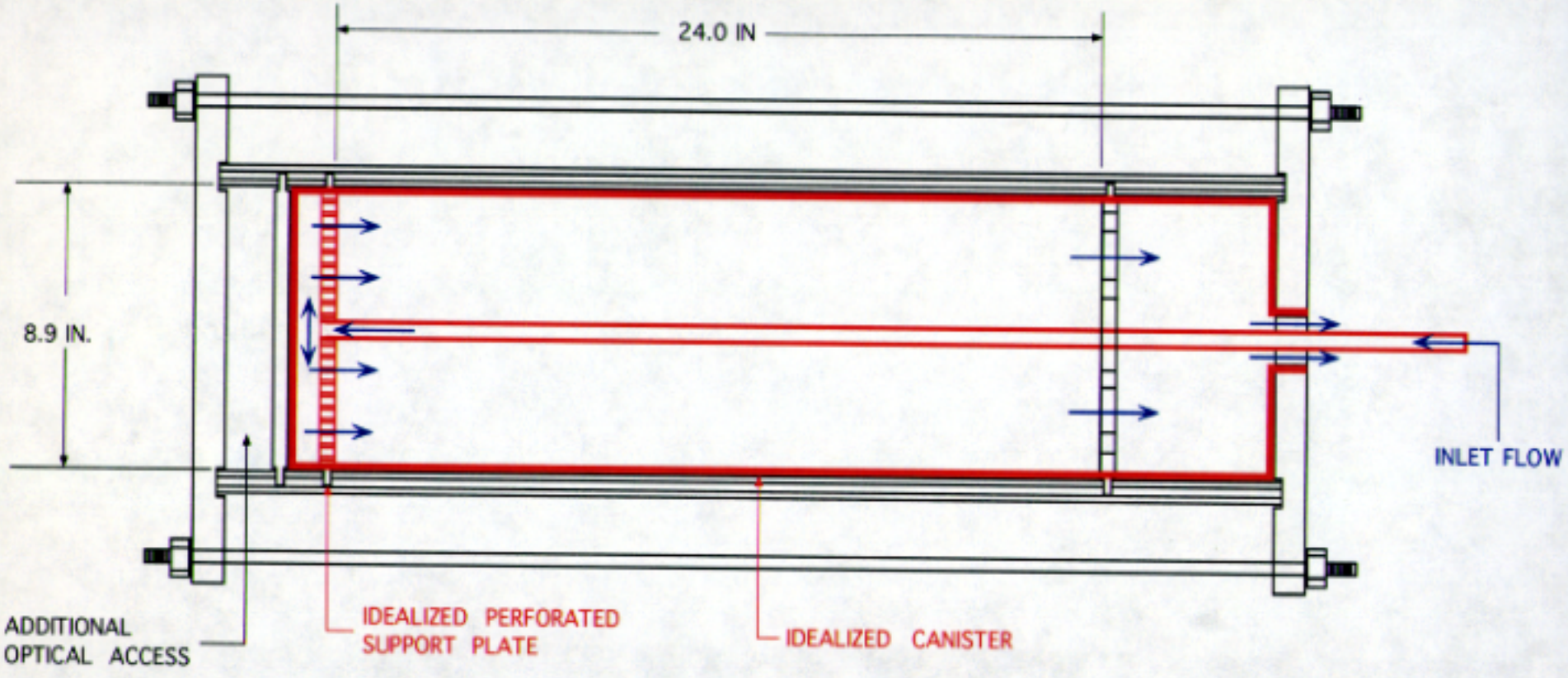
INEEL Matched-Index-of-Refraction system

- Versatile system with good temporal and spatial resolution for complex flows
- Internationally unique facility, largest system in the world
- Resolution, $H/d_{meas} = 2 \times 10^4$, ~ 5-10 x typical
  Reynolds number, ~ 5 x typical
- Permits optical measurements otherwise impossible
- Temperature control to match refractive index
- Experiments that will benefit: *Complex geometries*
  - Steady and unsteady low-Reynolds-number viscous flows
  - Steady and unsteady flows over blunt bodies
  - Curved surfaces (turbine blade passages), flow junctions
  - Unsteady flows induced inside buildings and vehicles
  - Flow in porous media, such core debris; particulate flows
  - Enhanced internal cooling passages
  - Near wall turbulence (viscous layer $y^+ < 50$)
  - Active control of turbulent flows, scaled MEMS models
  - Rod bundles for Spent Nuclear Fuel drying and storage

Dr. Stefan Becker, Lehrstuhl für Strömungsmechanik, Erlangen, using INEEL MIR system with LDV for measuring the structure of boundary layer transition behind a 2-D rib



Conceptual design of experiment to study fundamental flow physics of forced convection in idealized generic SNF canister configurations



Half-scale model to measure velocity and turbulence fields of semi-confined impinging jet

Accomplishments in first nine months

- Received NOVA Award, top corporate prize, from Lockheed Martin Corp. for development and operation of World's largest MIR flow system
- Upgraded laser Doppler velocimetry system
- Established idealization of drying/passivation geometry for highly- and moderately-enriched SNF elements
- Completed preliminary flow visualization experiments in 3/4-scale water apparatus to identify key flow features of generic idealization with support plate open areas of 4, 8 and 50 per cent
- Demonstrated steady, approximately circumferentially periodic flow in array
- Found significant differences between flow with prototypical support plates (4, 8% open) and with typical perforated plate (50%)
- Completed preliminary design of 1/2-scale model for LDV measurements in MIR flow system to determine turbulence and velocity fields in low-Reynolds-number semi-confined impinging jet (see sketch above)

Lessons learned to design drying/passivation systems

- Bypass flow routes should be avoided
- Flow distribution should be controlled
- Assumptions of uniform flow would be misleading
- Previous wind tunnel measurements for flow through perforated plates are not likely to be applicable to prototypical basket support plates
- Modifications of basket support plates and lower regions of canisters could be useful to distribute turbulent flow to the elements

Purpose

- Visualize and understand the flow field in a storage canister
- Ensure that passivation gas is transported to exposed areas of the fuel elements
- Investigate flow visualization methods where the tracking particles react with a surface of a body in the flow
- Use the Matched-Index-of-Refraction facility at the Idaho National Engineering and Environmental Laboratory to experimentally measure the velocity field in the canister
- Investigate Particle Image Velocimetry and Individual Particle Tracking methods applied to SNF storage canisters
- Develop computational models of the flow field
- Deliver to DOE a design methodology for future SNF storage canister development

3-D Particle Tracking Velocimetry Development at Ohio State

The current system under development is designed to operate at 60 fps and a nominal 512^2 spatial resolution, with the data being transferred to the computer memory in real time. An added feature (required to eliminate many of the previous software restrictions) is to redevelop the entire software under a Windows operating system.

The development of a Windows-based system is not trivial since the DIPIX frame grabber software is poorly supported. Thus, the first and ongoing task is to develop the ability to grab a sequence of images directly into PC memory at the 60 fps rate and at the full resolution allowed by the image board (bandwidth limitation). The present large memory available can allow a long time sequence of 1/4 Mb images (512^2) at a 60 fps rate to be stored. The elimination of the SVHS recording step has many advantages: less noise in recording and reading back, VCR stepper motor relocation errors, etc. The need for a 32 bit Windows-based operation stems from the necessity to address a very large image space (impossible under the old 16 bit DOS-based system).

To date, we have accomplished the following steps, all based on Win95:

For single images:

- We can grab the images directly to the PC memory
- Display the images
- Save the images to an image file
- Copy the images back to the PC memory for image processing

For multi-images:

- We can grab the images directly to the PC memory
- During the transfer operation we can perform simple image processing operations, such as gray level averaging.

Clarksean & Associates – Computer Modeling

Purpose of Modeling Efforts

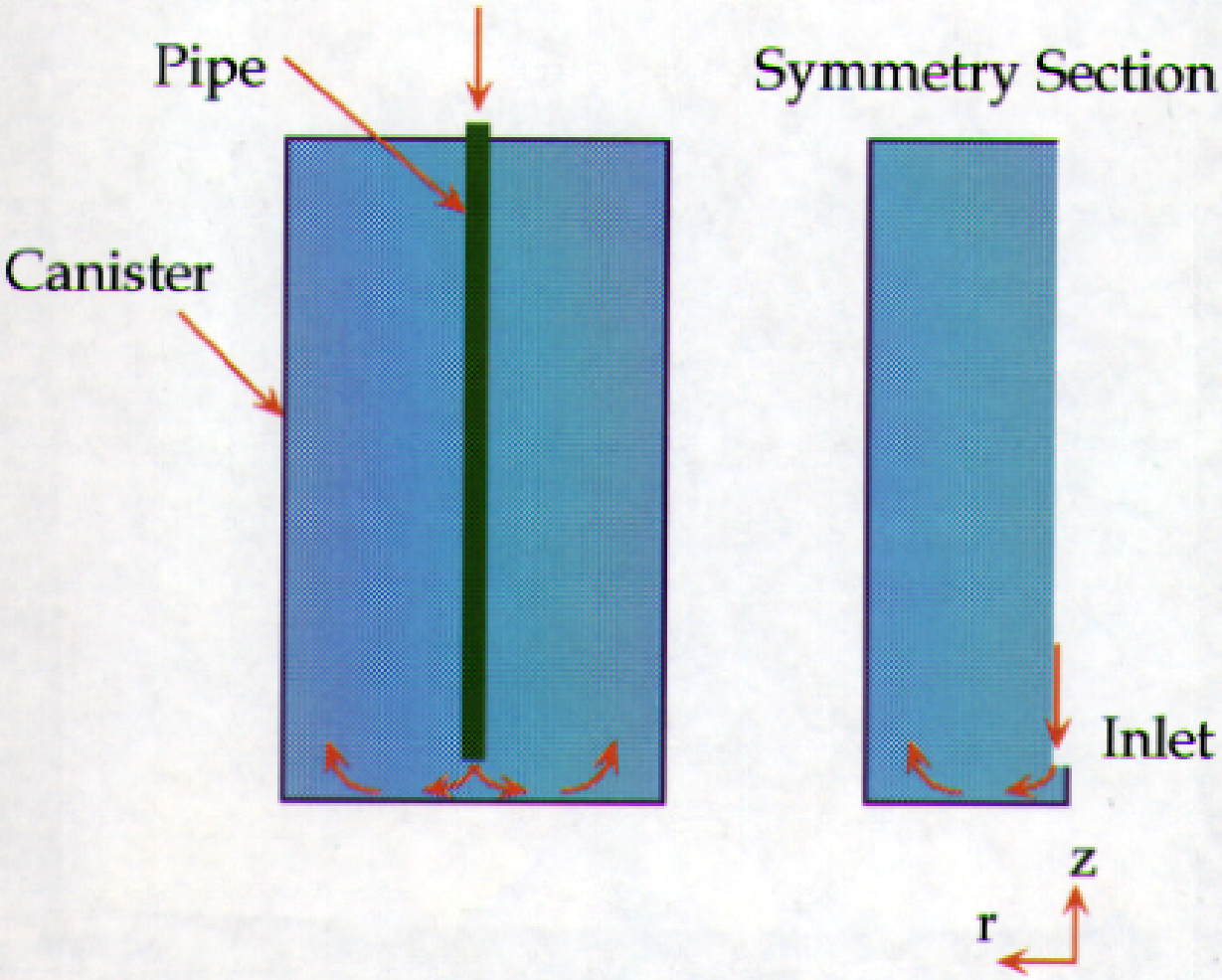
- Support experiments
- Develop and verify model for fuel storage
- Assist in understanding flow phenomenon

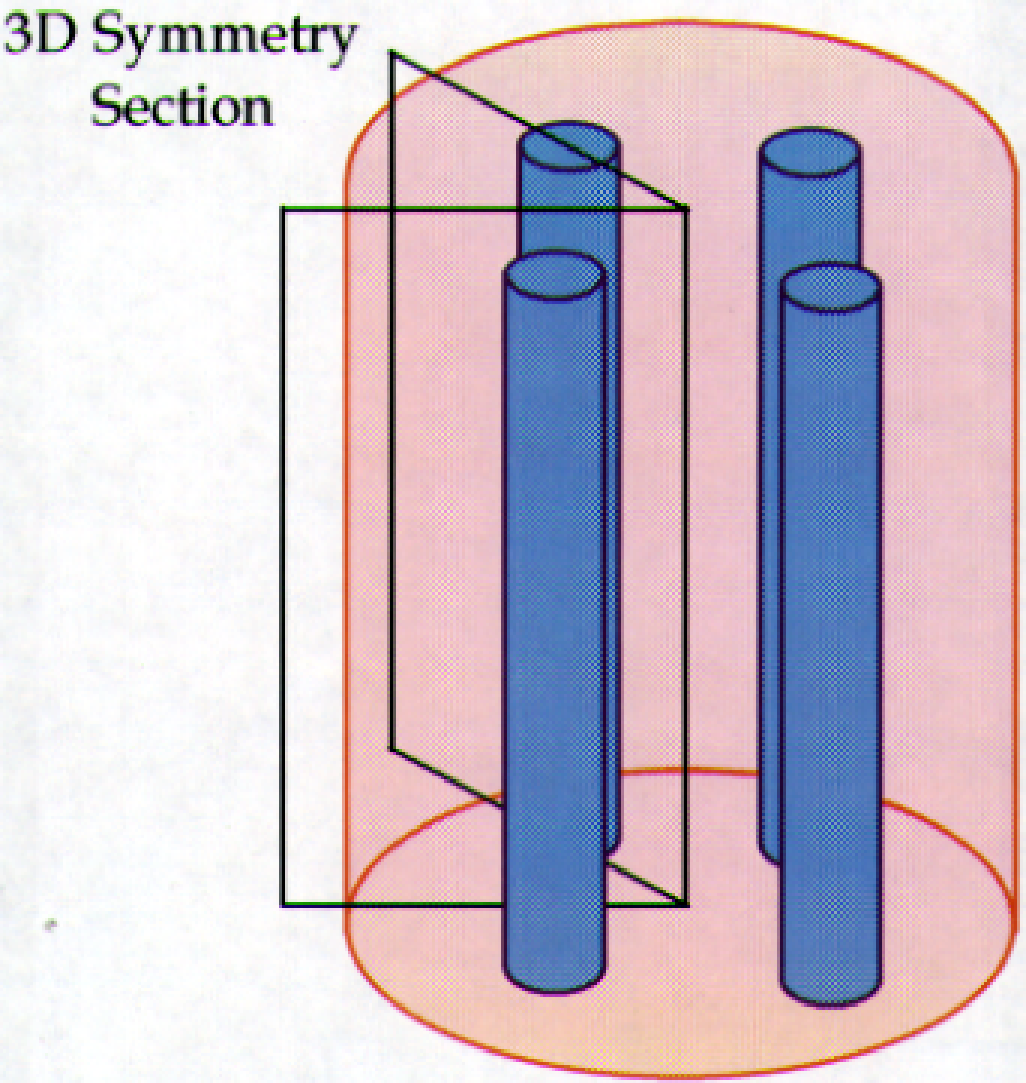
Present Efforts

- Preliminary 3D models of proposed test apparatus
- 2D models to examine general flow and pressure distributions
- Techniques to model perforated plate that supports the spent fuel elements

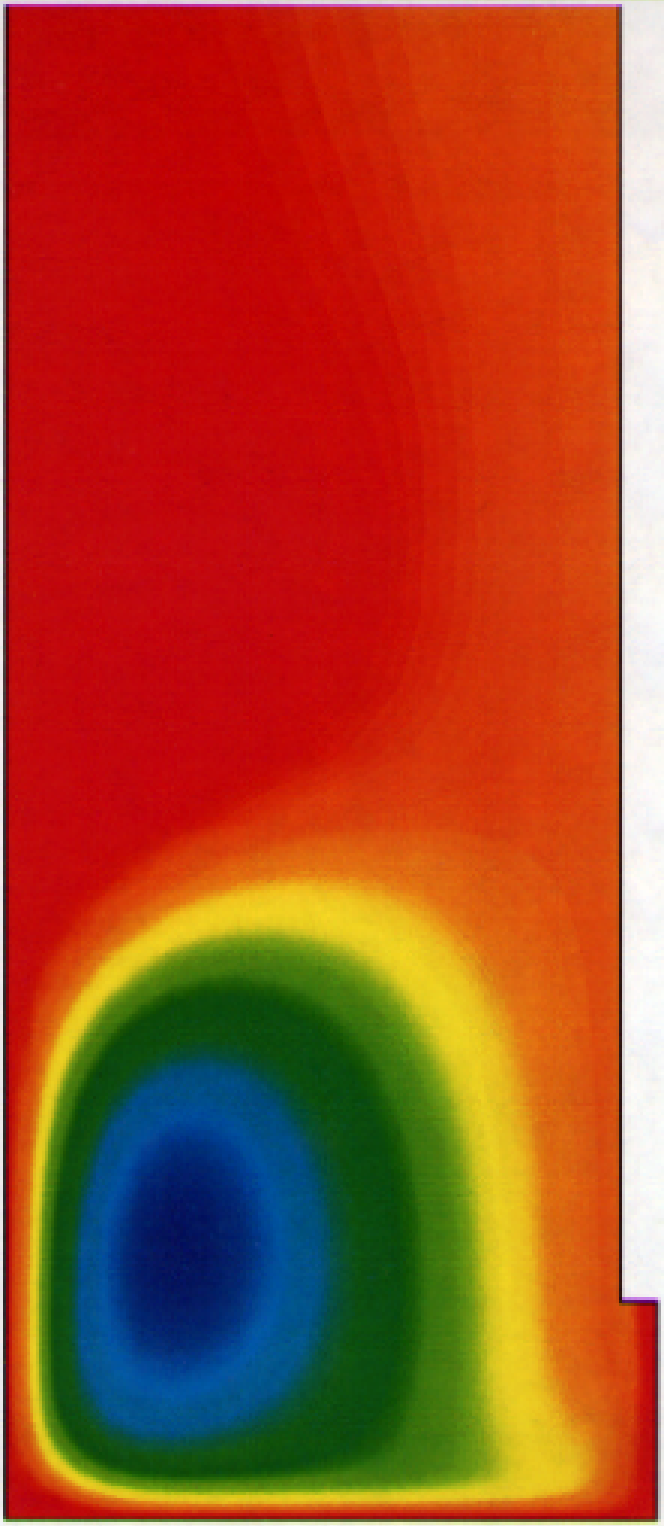
Model Geometry

- Axisymmetric model of center pipe in fuel storage apparatus
- Water flow – Re=2,000
- Laminar and Standard k-ε models used to analyze flow
- Re-laminarization and additional low Re turbulence terms NOT included in model

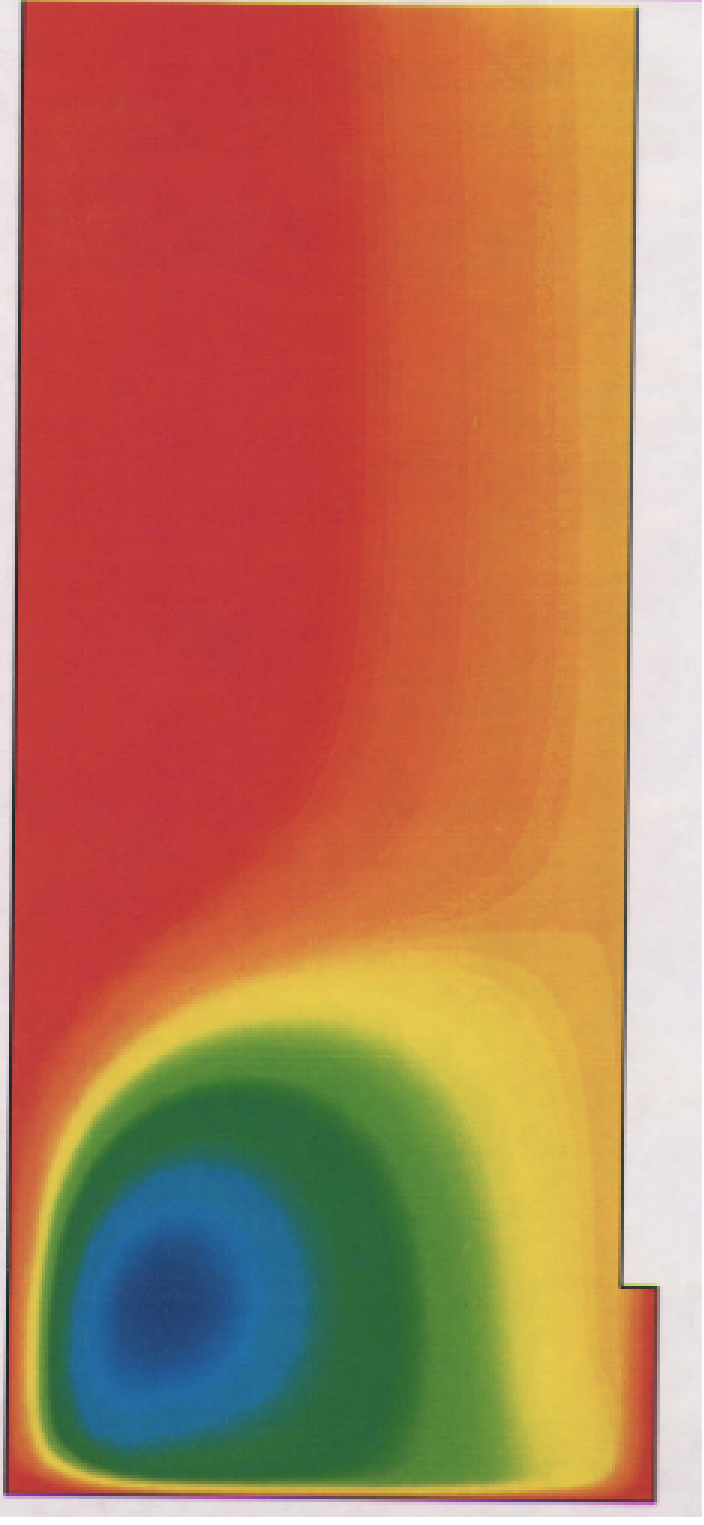


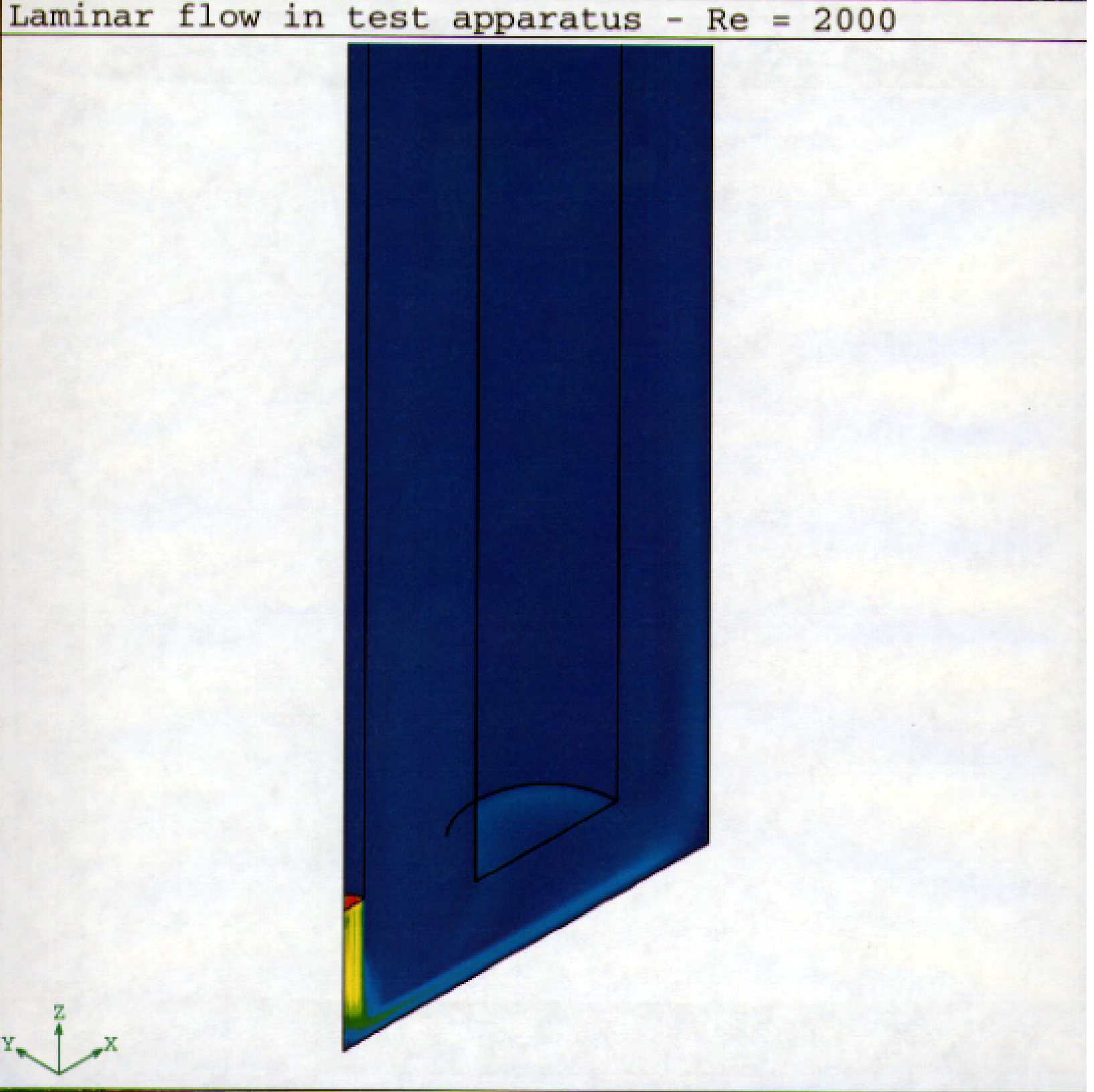


Cut-away View of
Fuel Rods in Canister

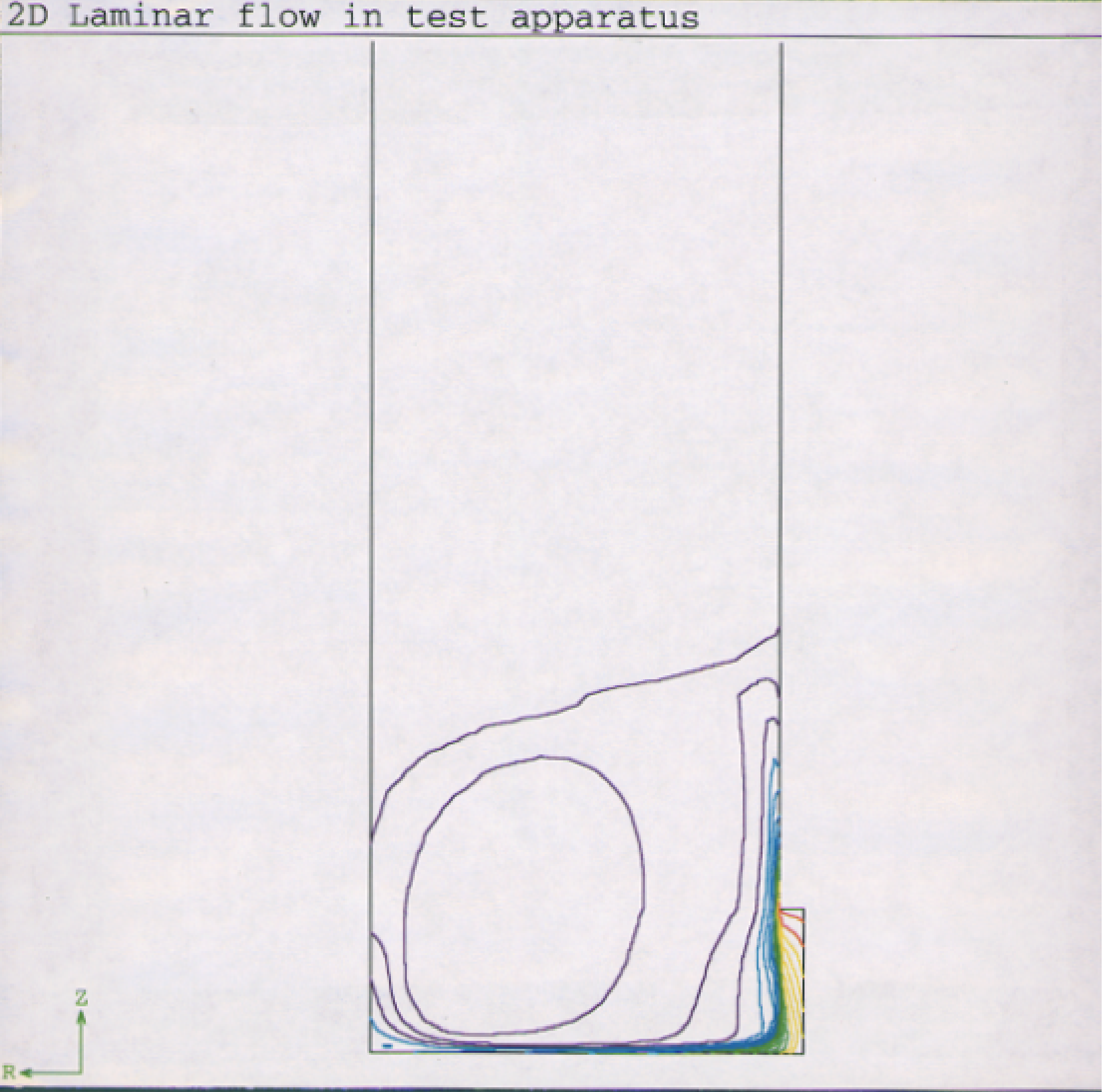


Streamline contour plots for laminar and turbulent simulations.





Speed contour plot for 3D simulation of laminar flow into canister.



Series of line contours for injection of species into canister (2D simulation).

Model Selection Important

- Flow field is markedly different when laminar or turbulence models are assumed
- Selection of Low Re model will be critical

Future Efforts

- Development of Direct Numerical Simulation (DNS) for simulation of orifice flow
- Selection and evaluation of low Reynolds number turbulence models
- Continued 3D flow simulations to support experiments and to validate proposed model

Future Activities

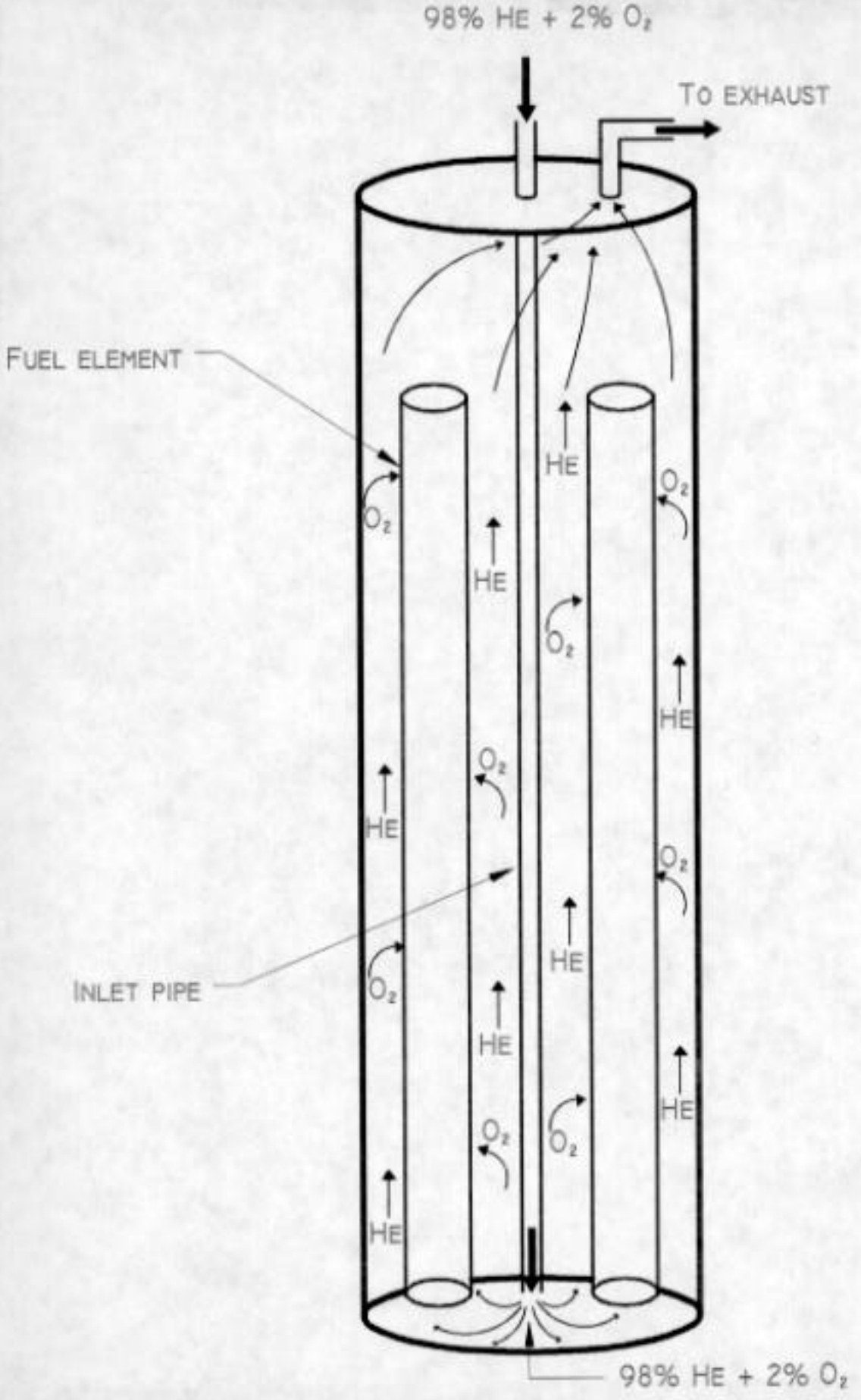
- Continue to develop methods to visualize flow in the presence of surface reactions
- Current techniques may include chemical tracers, reacting dyes, fluorescent particles, and electrochemical surfaces
- Compare visualization results with the data obtained from the MIR facility, IPT methods, and computer models

Introduction

- Thousands of tons of spent nuclear fuel (SNF) in the DOE complex are stored underwater
- SNF aluminum- and steel-clad elements have corroded, exposing fuel meat
- Uranium hydride has formed according to the reaction,

$$4\ U + 6\ H_2O \rightarrow 3\ O_2 + 4\ UH_3$$

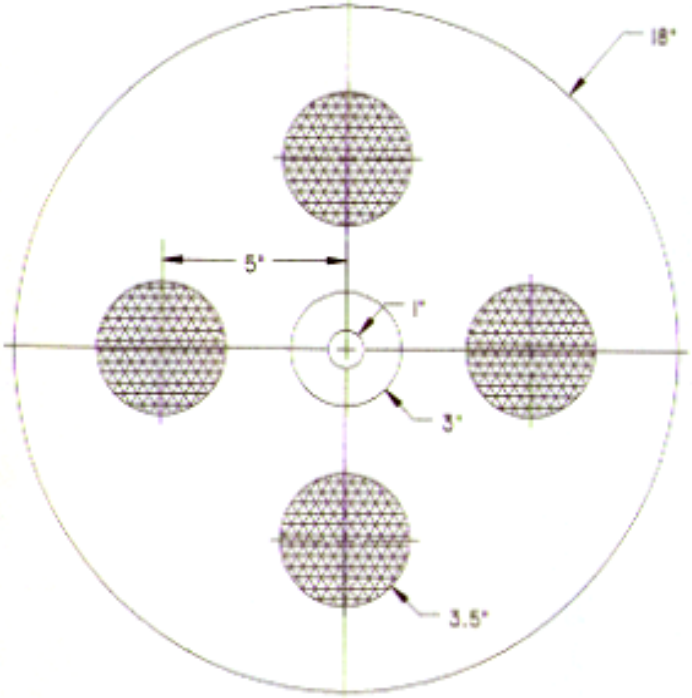
- An energetic, pyrophoric reaction occurs when uranium hydride is exposed to air
- A passivation process can be used to treat the corroded fuel elements and prevent a pyrophoric reaction
- See figure below for one proposed passivation method

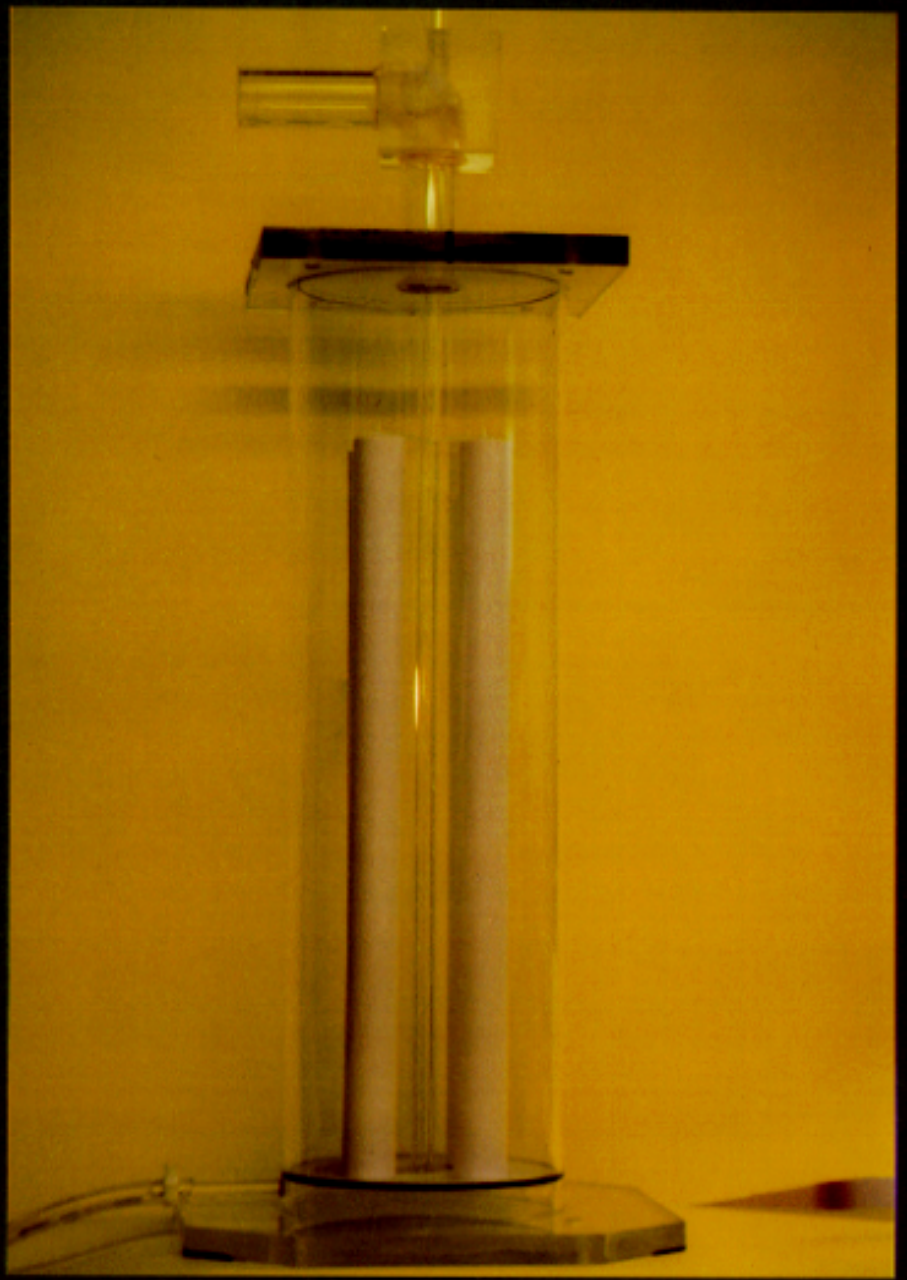

98% HE + 2% O_2
TO EXHAUST
FUEL ELEMENT
INLET PIPE
HE
O_2
98% HE + 2% O_2

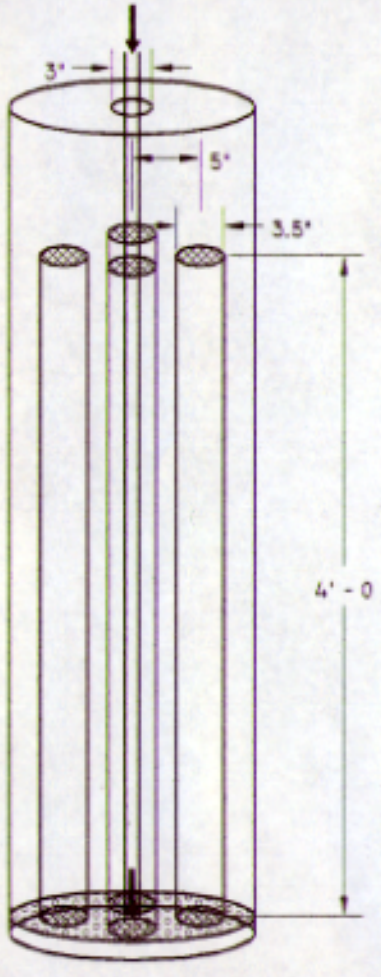
IDEALIZED SPENT NUCLEAR FUEL CANISTER WITH RODS DRAWING

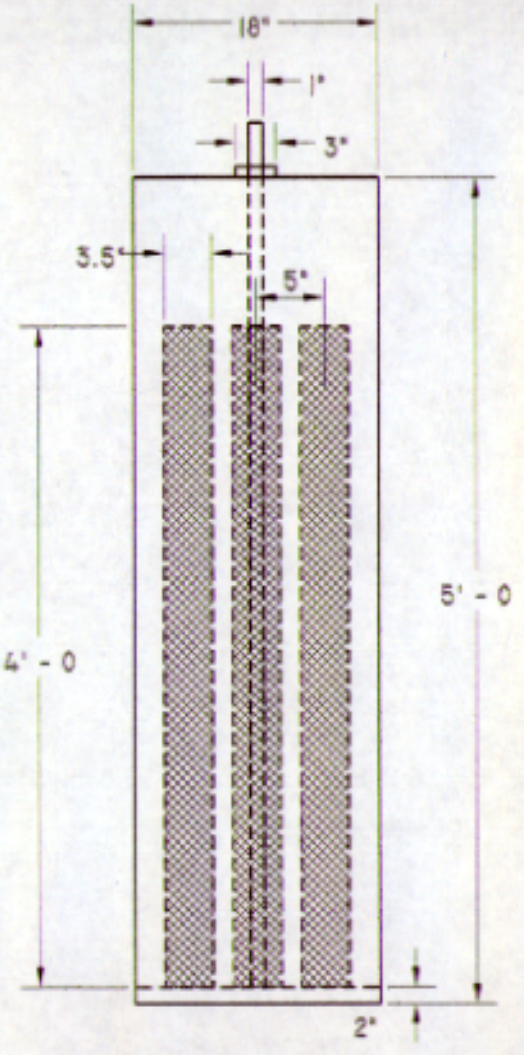
TOP VIEW

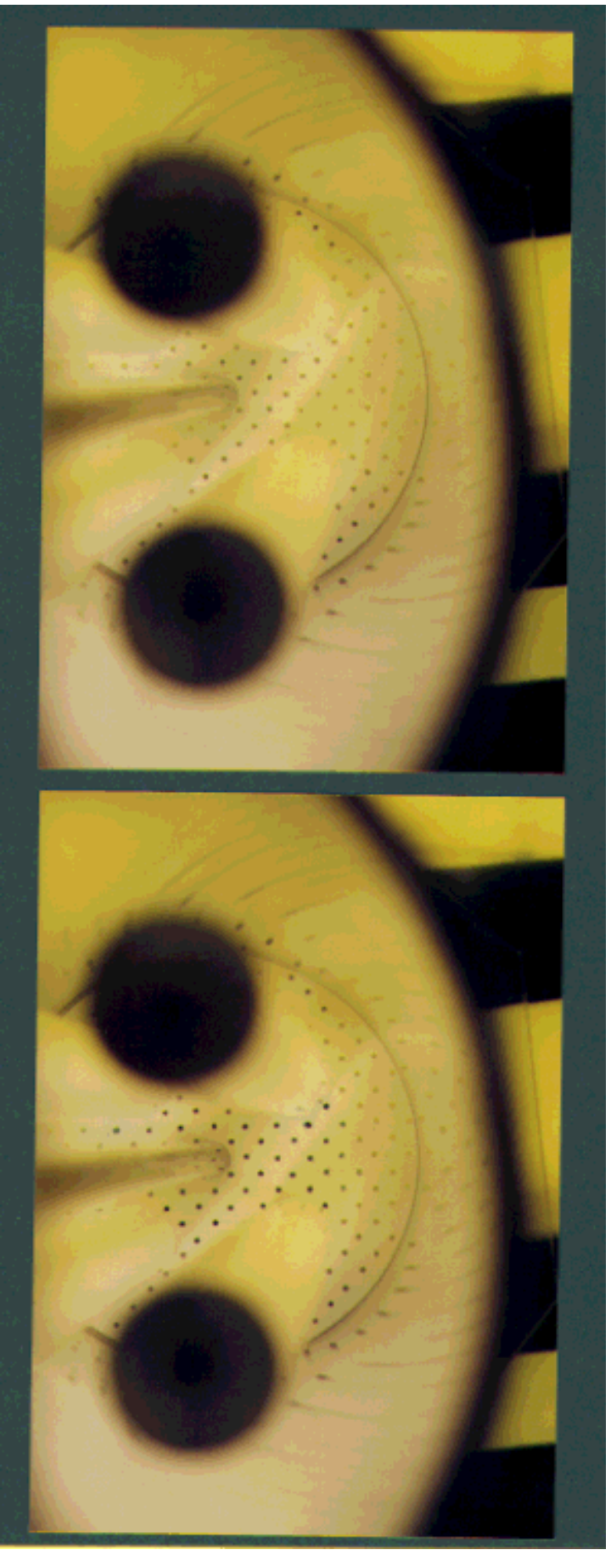
SCALE - 1:3

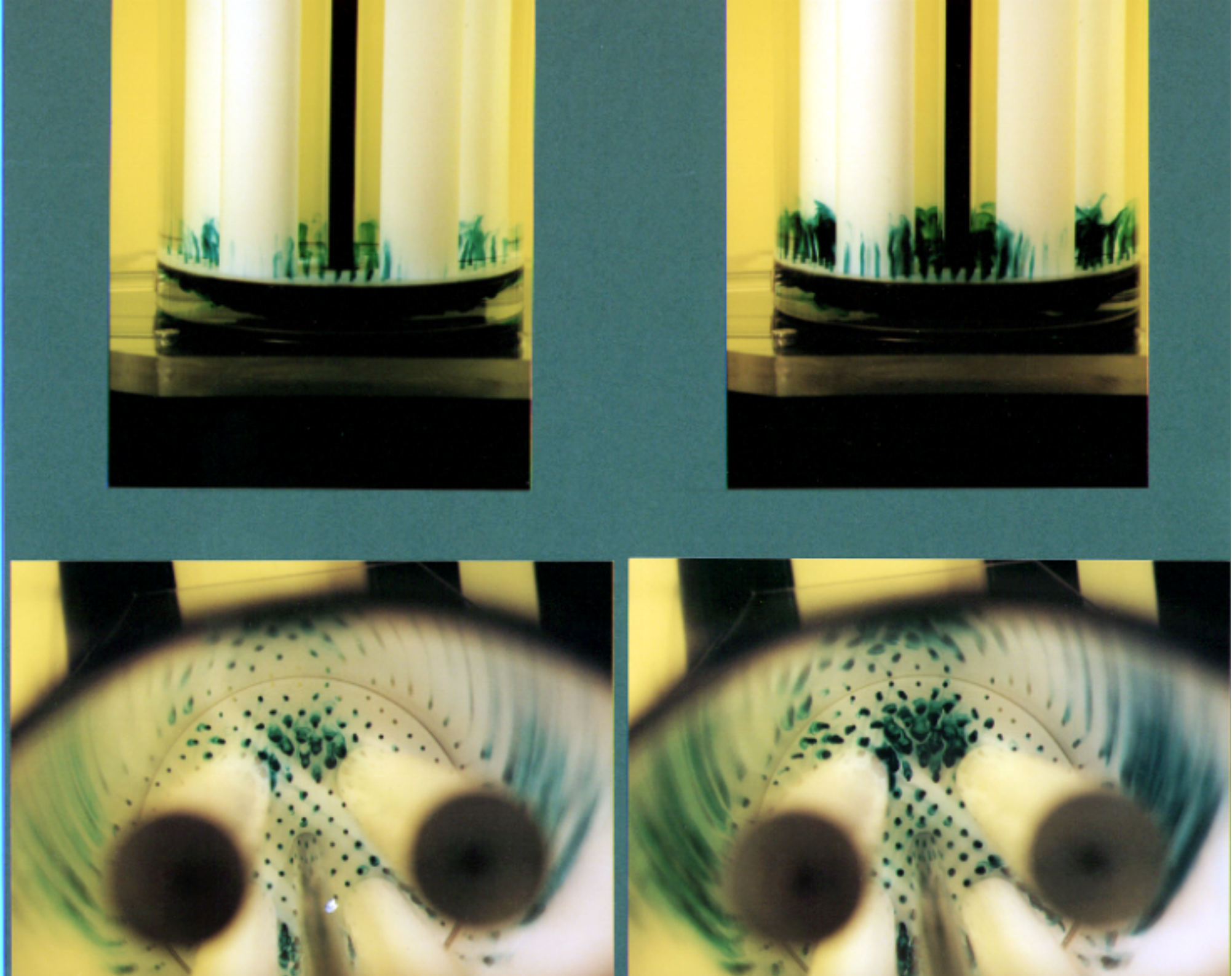


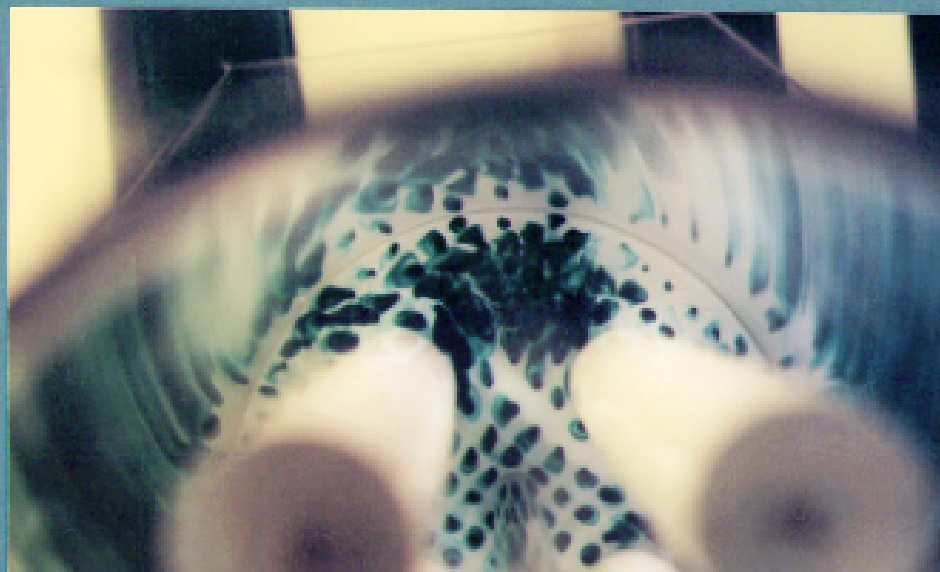



3"
5"
3.5"
4' - 0


18"
1"
3"
3.5"
5"
4' - 0
5' - 0
2"







Future Work:

- Perform more validation tests to ensure the proper synchronization of the cameras and frame grabbers in the multi-image mode and ensure the integrity of the images.
- Port the 3-D PTV analysis software under the new operating system environment (Win '95). This task is viewed as a simpler task than the crucial image acquisition step described above.

Sequence of photographs showing introduction of dye into mock spent nuclear fuel storage canister. Scale: 1:4. Inlet pipe Reynolds number is 2,500. Porous support plate open area is 4%.

The flow initially enters the main chamber from the area between the mock fuel rods. While the dye fills the main chamber, recirculation zones develop above and below the porous support plate.