Safety Issues for High Temperature Gas Reactors

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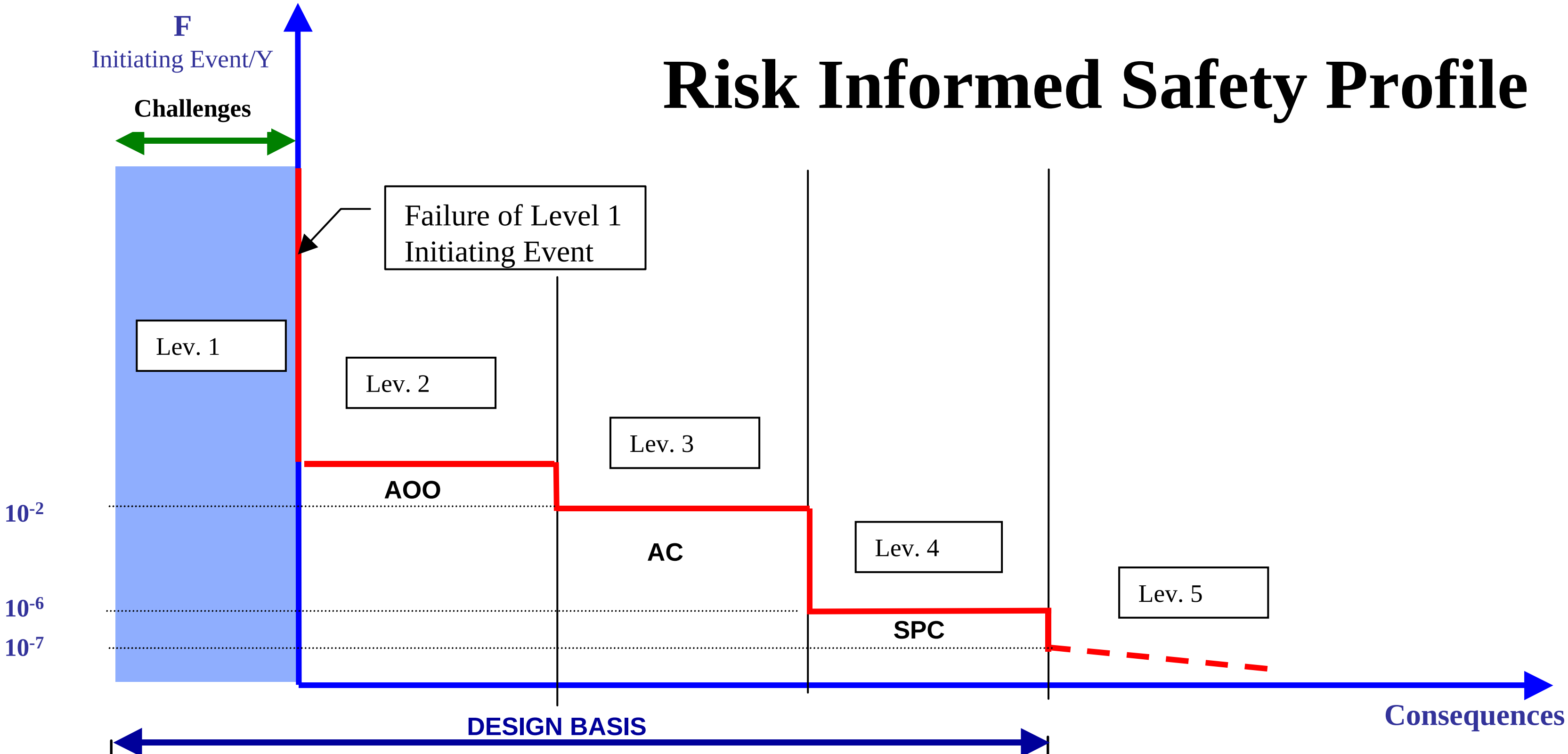
Major Questions That Need Good Technical Answers

- Fuel Performance
  – Normal operational performance
  – Transient performance
    - Ejected Rod (maximum energy insertion capability)
    - Reactivity insertions (seismic, water)
  – Accident Performance
  – Weak fuel issues
  – Mechanistic source term for high burn-up fuel
  – Fuel fabrication quality assurance

- Risk Dominant Accident Sequences
  - Establish risk informed design to identify risk dominant accident sequences to be analyzed.
  - Use either IAEA[1] or NRC[2] risk informed approach to establish safety requirements of plant.
  - Use of safety goal as a design guide
  - Application of risk informed “Defense in Depth”
  - Scope of risk analysis may be easier due to inherent robustness of basic design.

1. “Development of Technology Neutral Safety Requirements for Innovative Reactors”, IAEA TECDOC Draft Dec. 2004
2. “Regulatory Structure for New Plant Licensing, Part 1: Technology Neutral Framework, Dec. 2004, Draft, US NRC.

Risk Informed Safety Profile



Plant conditions / Consequences	Normal Operations (NO)	Anticipated Operational Occurrences (AOO)	Accident conditions (AC)	Severe plant conditions* (SSPC)		
Doses to Operators	50 mSv/a ALARA (5 mSv/a target)	50 mSv/a 20 mSv/a (average 5 y) (5 mSv/a target)	50mSv/a (Could be exceeded for rear recovery events)	500 mSv (limit) (This value derived from Finnish regulation)	**NOTE 1: Doses for NO, AOO, AC are derived from IAEA-SS No 115**	
Doses to the public	1 mSv/a (10 µ Sv/a –target)	5 mSv/a 1 mSv/a (average 5 y)	5 mSv/a (For 1 year period following the accident)	5 mSv/a (For 1 year period following the accident)	**NOTE 2: Doses are derived from IAEA-SS No 115**	
Off-site Actions			**No off-site actions beyond defined distance from the plant**	**Minimal emergency actions beyond defined distance from the plant**		

*** Severe challenge to the Fission Products Confinement Function**

LEVELS OF DEFENCE IN DEPTH (From INSAG-10)

Levels of defence	Objective	Essential means	Acceptable failures of the Level of Defence (events/year)
Level 1	Prevention of deviations from normal operation and failures	Conservative design and high quality in construction and operation	
Level 2	Control of deviations from normal operation and detection of failures	Control, limiting and protection systems and other surveillance features	$< 10^{-2}$
Level 3	Control of accident conditions within the design basis	Engineered safety features and accident procedures	10^{-2}- 10^{-6}
Level 4	Control of severe plant conditions	Complementary measures and accident management	10^{-6}- 10^{-7}
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response	$< 10^{-7}$

- Expected Significant Accident Sequences
  - Air Ingress
  - Water Ingress (reactivity insertion)
  - Seismic Events (reactivity insertion)
  - Loss of Load
  - Rod Ejection (more significant in block reactors)
  - Failure of reactor cavity cooling system
  - Recuperator By-pass events (overcooling)
  - Graphite dust, plate-out, lift off
  - Impact of Terrorism
  - Identification of “cliff edge” effects

Knowledge Required

- Improved understanding of core behavior
- Improved understanding of heat transfer in core and vessel - pebble and block - bypass flows
- Materials behavior at high temperature in helium (plus contaminants) including radiation effects and chemical attack on graphite
- Blow down loads and timing of accident event sequences.
- Behavior of fuel, fission product release behavior in reactor building and structures under accident conditions.
- Development and validation of computer codes used in the analysis
- Validation of passive performance of safety systems - natural circulation - heat conduction and convection.

Issues

- Fuel Temperature limits (1600 C ?)
- Regulatory Credit for Basic Design Strengths
- Need new risk informed licensing process to allow credit for innovative systems.

Containment

- Based on design and accident analysis of source term and sequences - a containment of radioactive materials strategy is developed to assure that safety goals are met.
  - Full pressure containment
  - Confinement - low pressure - not pressure tight
  - Dynamic containment/confinement (time dependent)
  - Performance is quite different than water reactors.

Classification of Safety “Systems”

- Ideally safety system classification should be done on importance to safety function in a risk informed manner.
- Some “systems” are not components but parameters in analysis for passive performance (ex. emissivity of reactor vessel).

Expectations

- Water Ingress - generally understood and can be limited by amount of water ingress - some German experience at AVR
- Seismic - reactivity simulations can assess reactivity impact.
- Rod ejection - more significant for block reactors but fuel energy limits like for LWRs can be established for rod worths.
- Testing on heat transfer and flow can be verified by South African tests and Chinese pebble bed reactor including reactor cavity cooling systems.
- Fuel behavior data to be provided by past German and focused South African and US testing programs

Challenges

- Verification of high temperature material behavior (fuel, graphite, metals, carbides)
- Validation of analysis tools
- Air ingress
  – Most visible concern among the public
  – Most significant in terms of potential offsite consequences
  – Can not be eliminated by “design”

Air Ingress Status

- Most "eliminate" connecting "vessel" failure as too low a probability event (10^{-8}).
- Break sizes limited to largest connecting "pipe".
- Two breaks (top and bottom) considered unlikely but are analyzed (chimney effect)
- Graphite corrosion behavior not well modeled in existing codes.
- CFD analysis and confirmatory experiments needed.

Air Ingress Tests

- Japanese series on prismatic configuration
  - Diffusion
  - Natural Circulation
  - Corrosion (multi-component)
- German NACOK tests - pebble bed
  - Natural circulation
  - Corrosion
- MIT CFD (Fluent Methodology Development)

Experimental Apparatus - Japanese

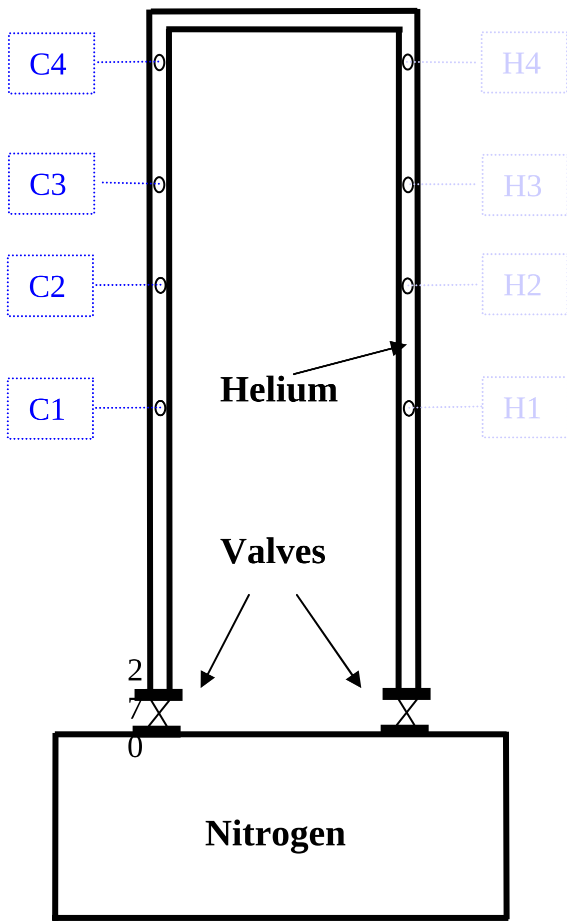


Figure 16: Apparatus for Isothermal and Non-Isothermal experiments

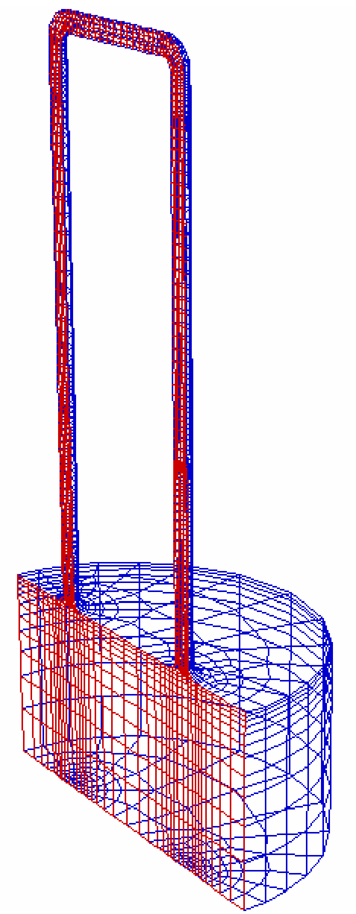


Figure 17: Structured mesh

Isothermal Experiment

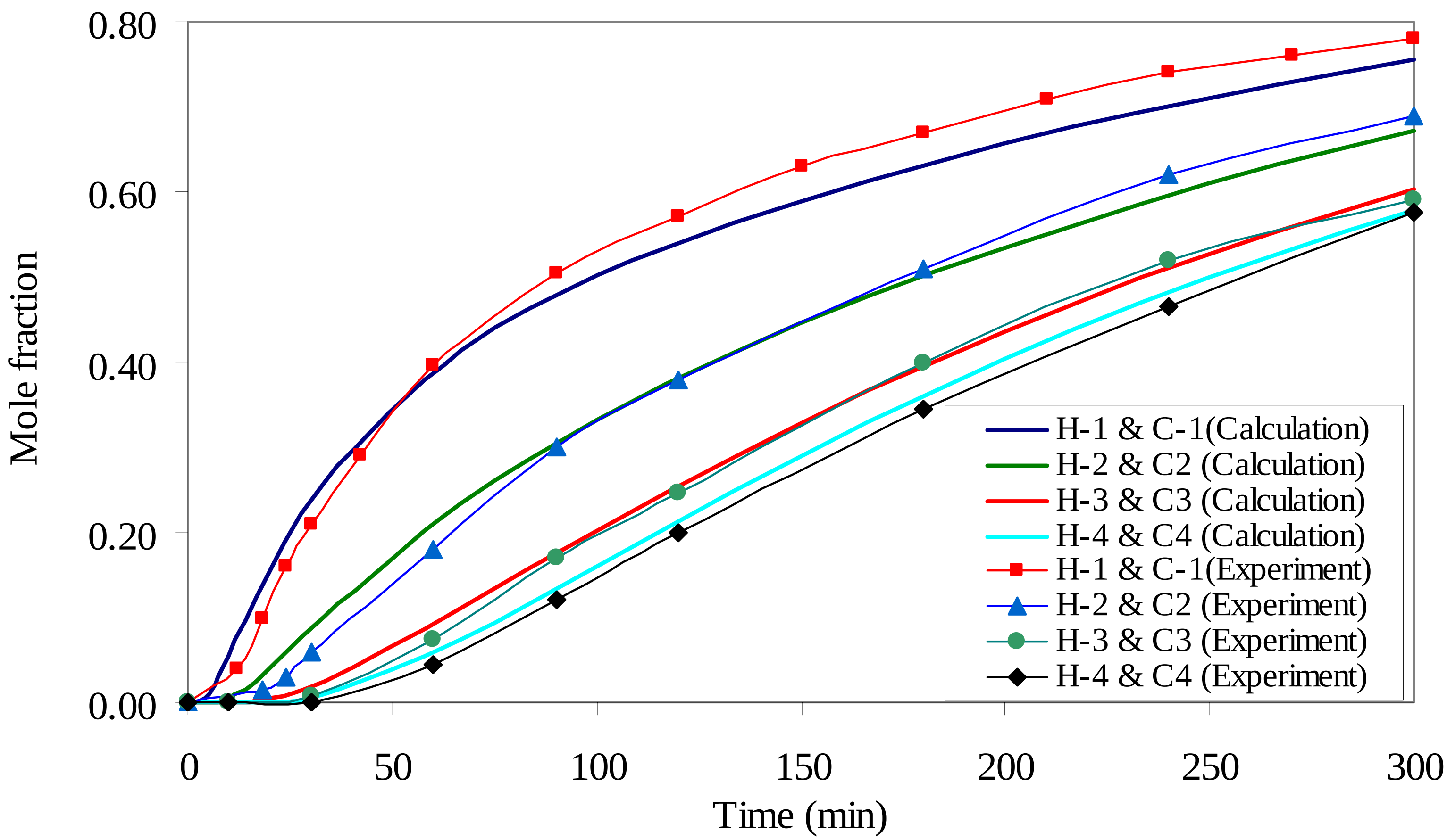


Figure 18: Mole fraction of N_2 for the isothermal experiment

Thermal Experiment

- Pure Helium in top pipe, pure Nitrogen in the bottom tank
- N_2 Mole fractions are monitored in 8 points
- Hot leg heated
- Diffusion Coefficients as a function of temperature

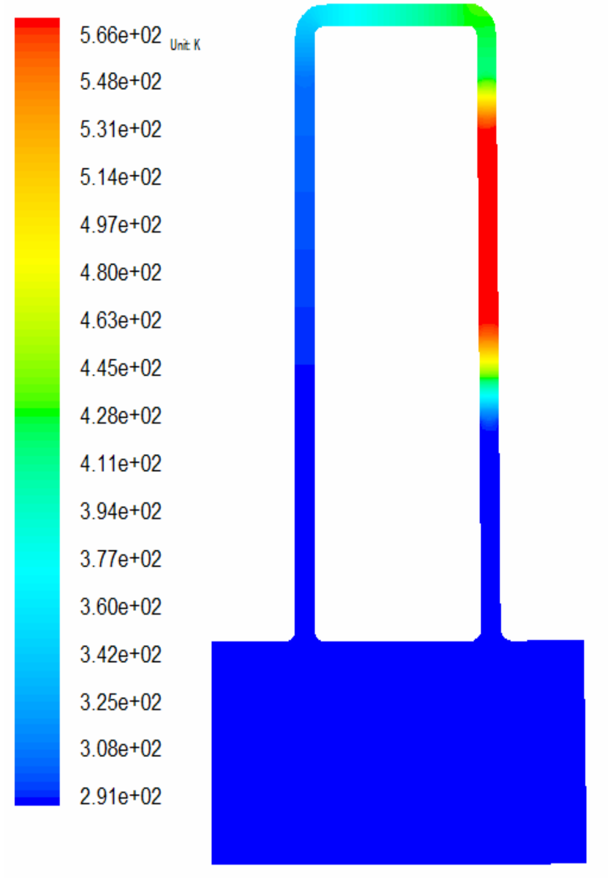


Figure 19: The contour of the temperature bound4ary condition

Thermal Experiment

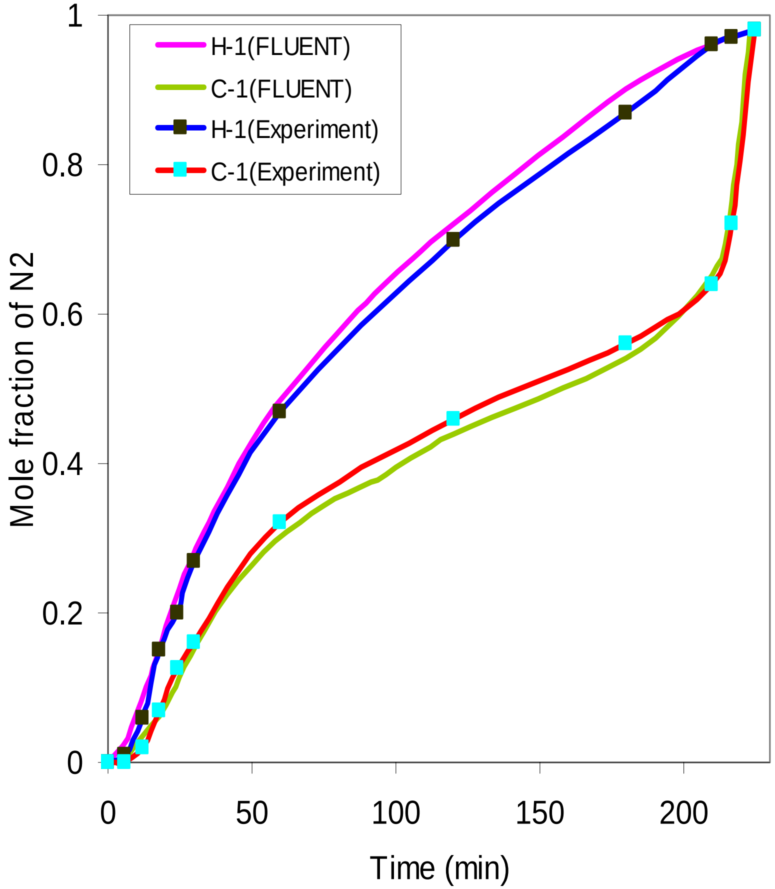


Figure 20: Comparison of mole fraction of N_2 at Positions H-1 and C-1

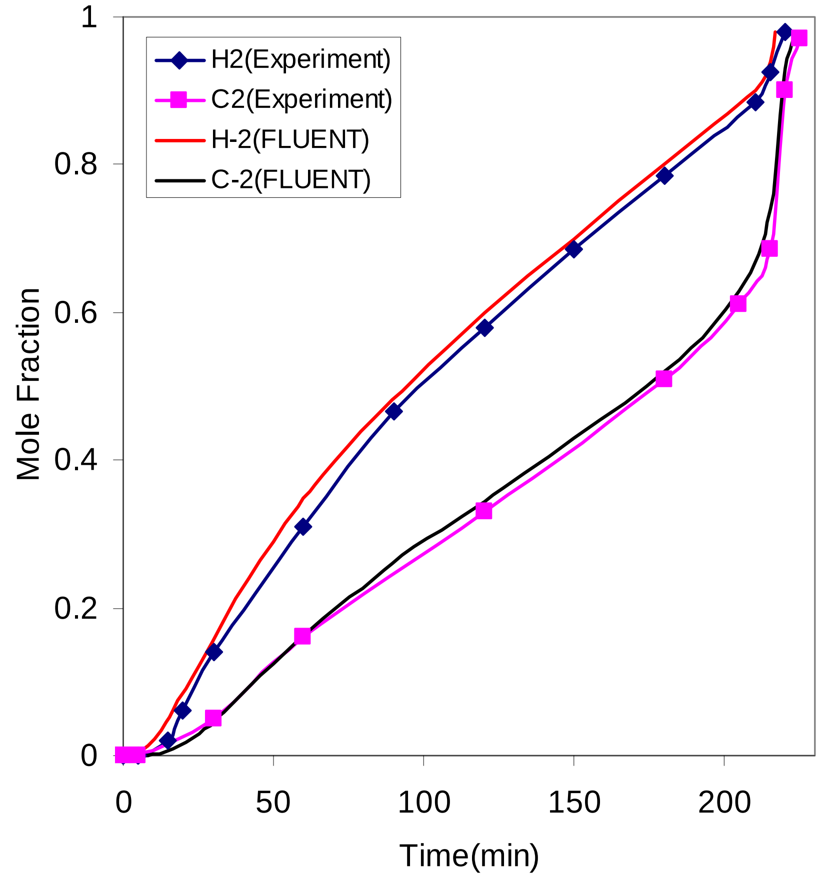


Figure 21: Comparison of mole fraction of N_2 at Positions H-2 and C-2

Thermal Experiment (Cont.)

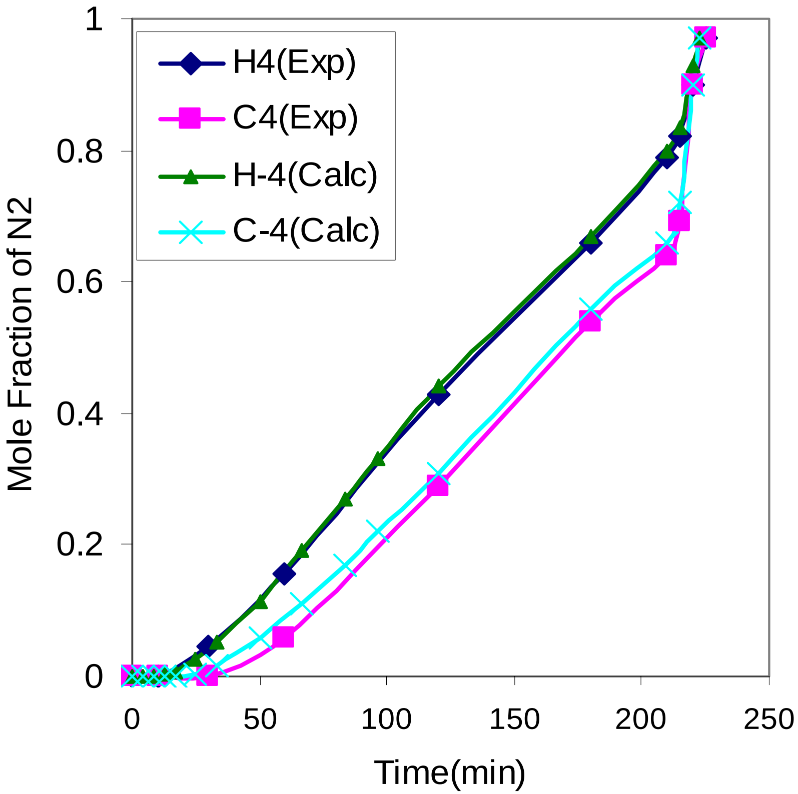


Figure 22: Comparison of mole fraction of N_2 at Positions H-1 and C-1

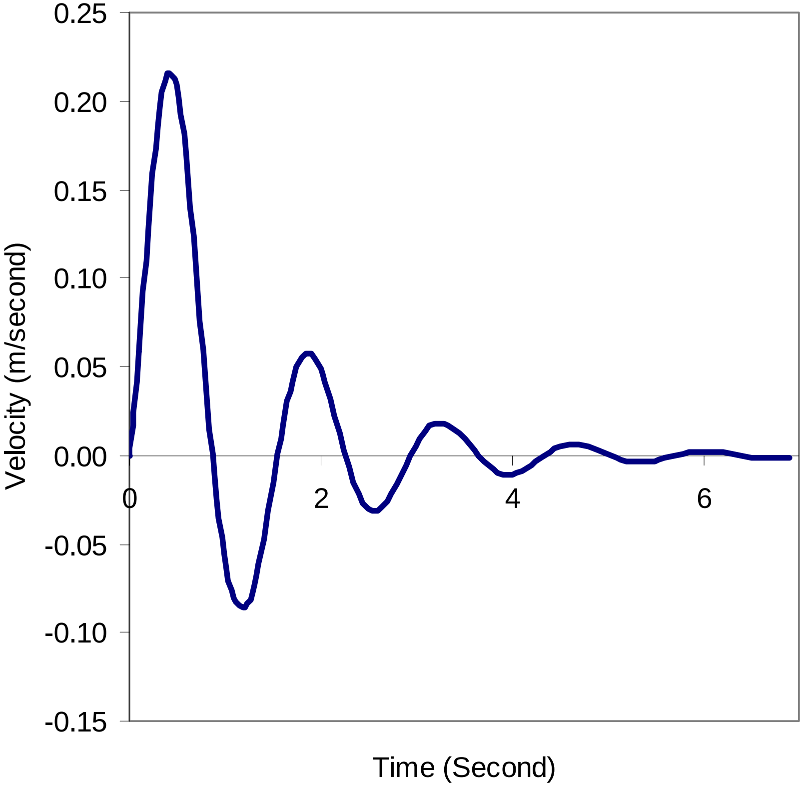


Figure 23: The vibration after the opening of the valves.

Multi-Component Experiment

- Graphite Inserted
- Multiple gases: O_2, CO, CO_2, N_2, He, H_2O
- Mole fraction at 3 points are measured
- Much higher calculation requirements
- Diffusion Coefficients

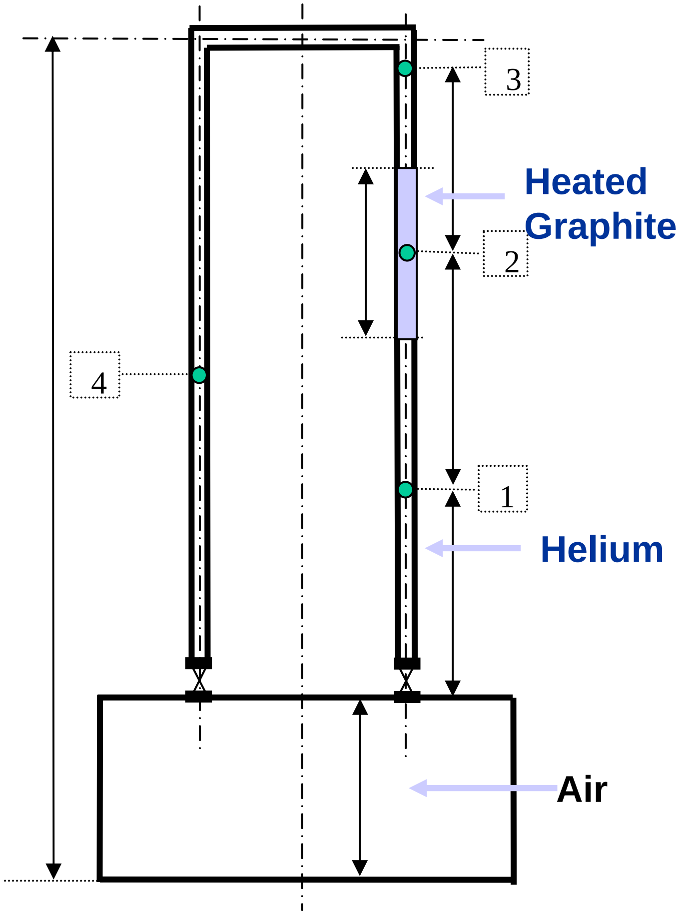


Figure 34: Apparatus for multi-Component experiment of JAERI

Multi-Component Experiment(Cont.)

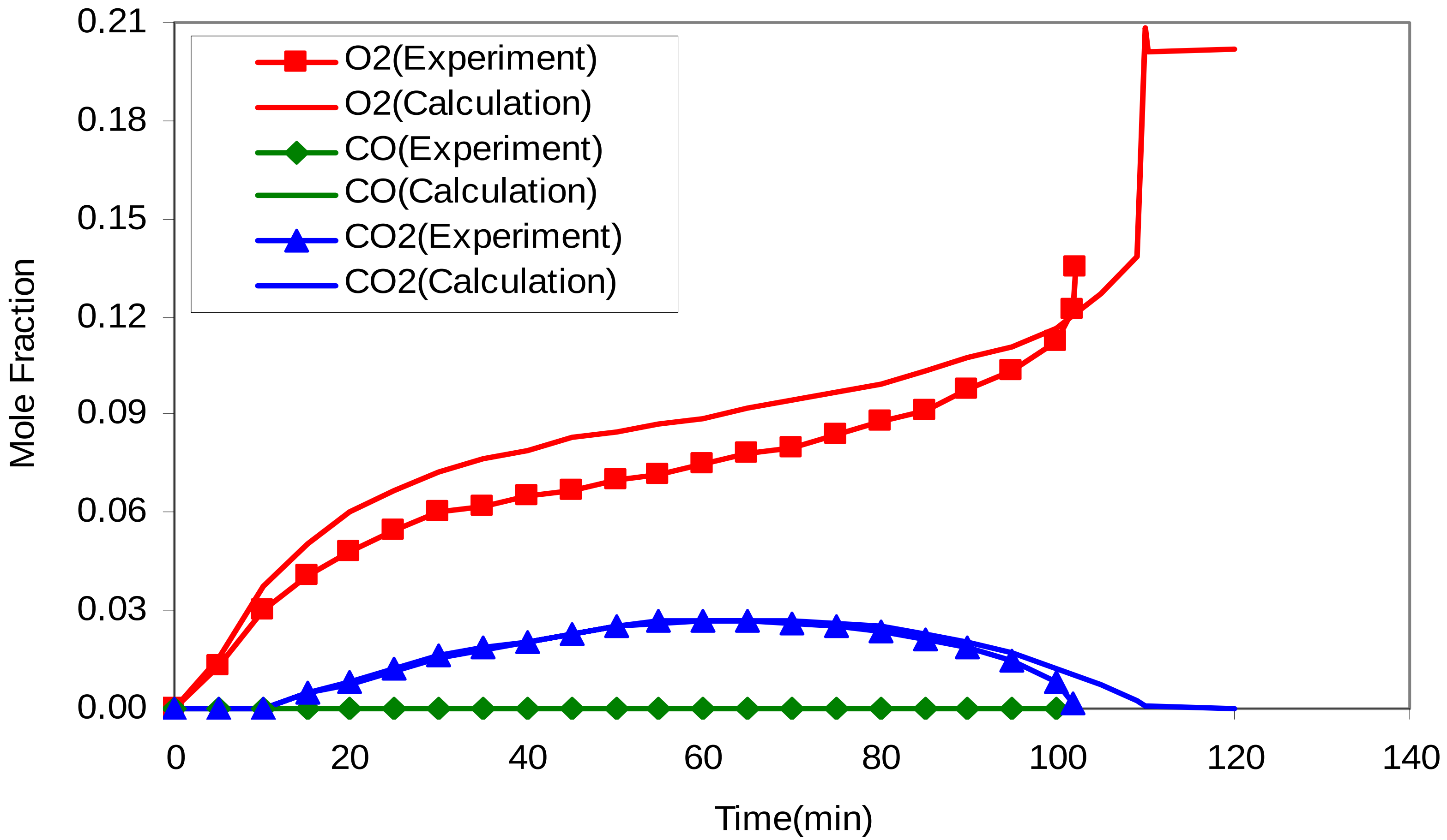


Figure 36: Mole Fraction at Point-1 (80% Diffusion Coff.)

Multi-Component Experiment(Cont.)

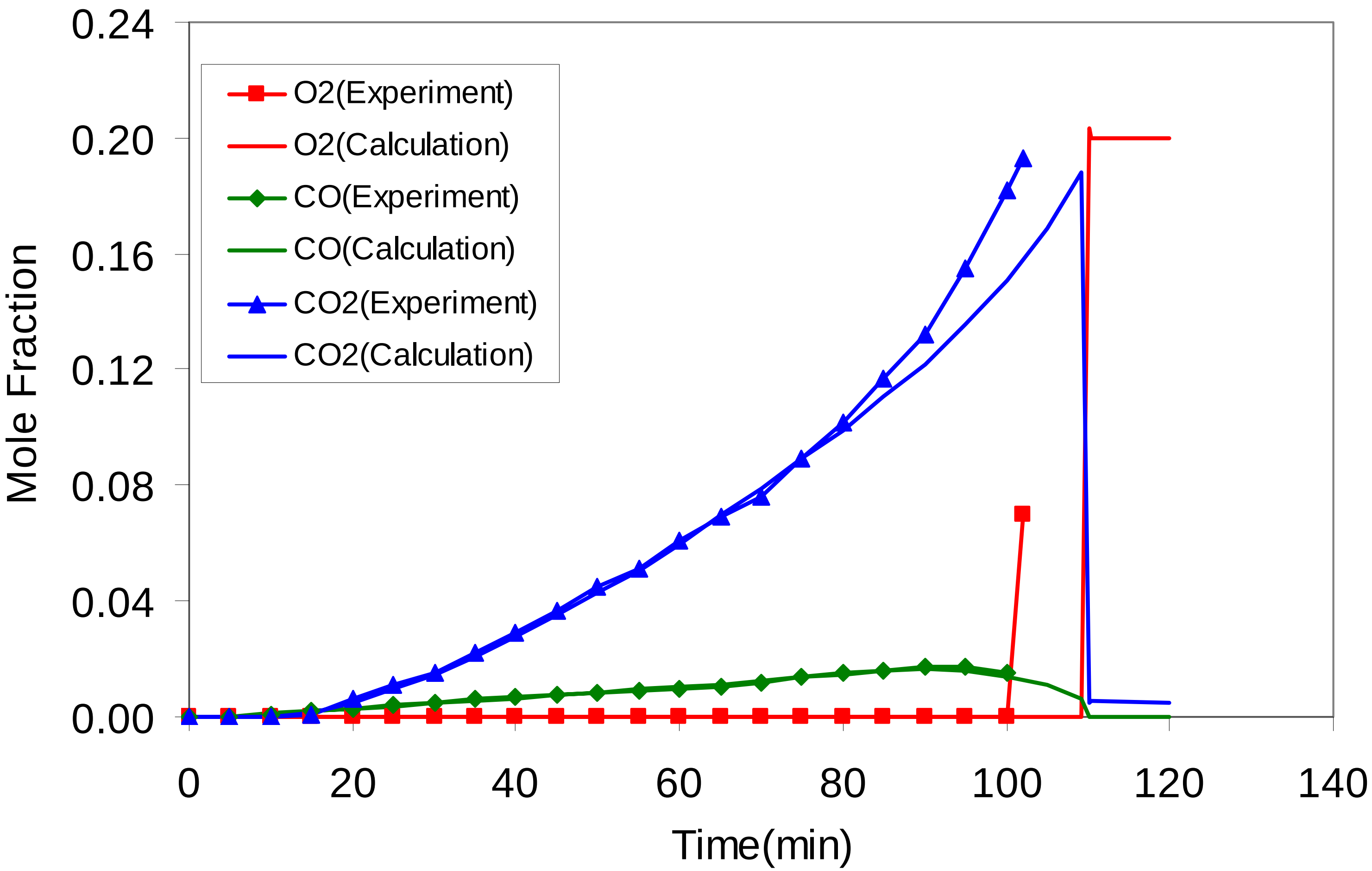


Figure 37: Mole Fraction at Point-3

Multi-Component

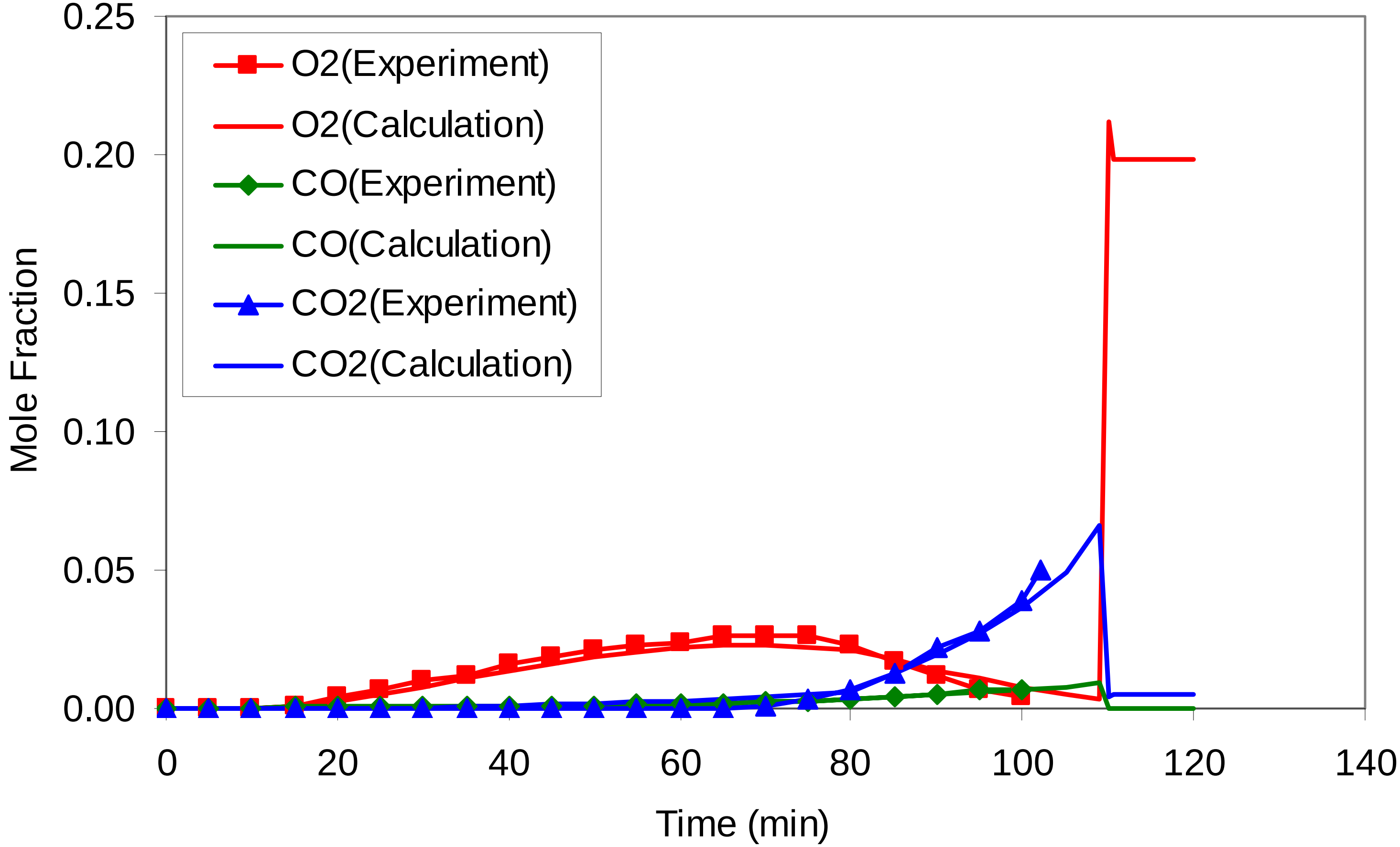


Figure 38: Mole Fraction at Point-4

NACOK Natural Convection Experiments

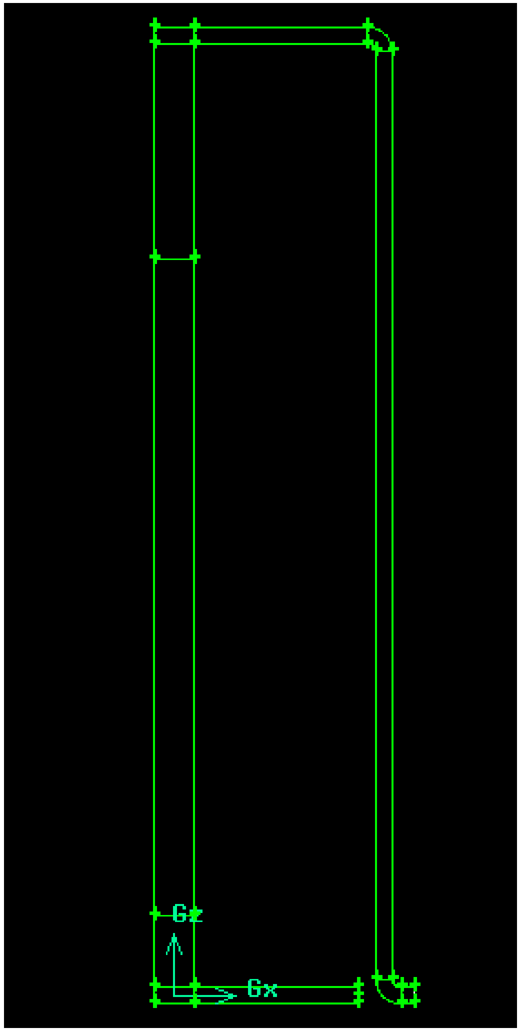


Figure 39: NACOK Experiment

Boundary Conditions

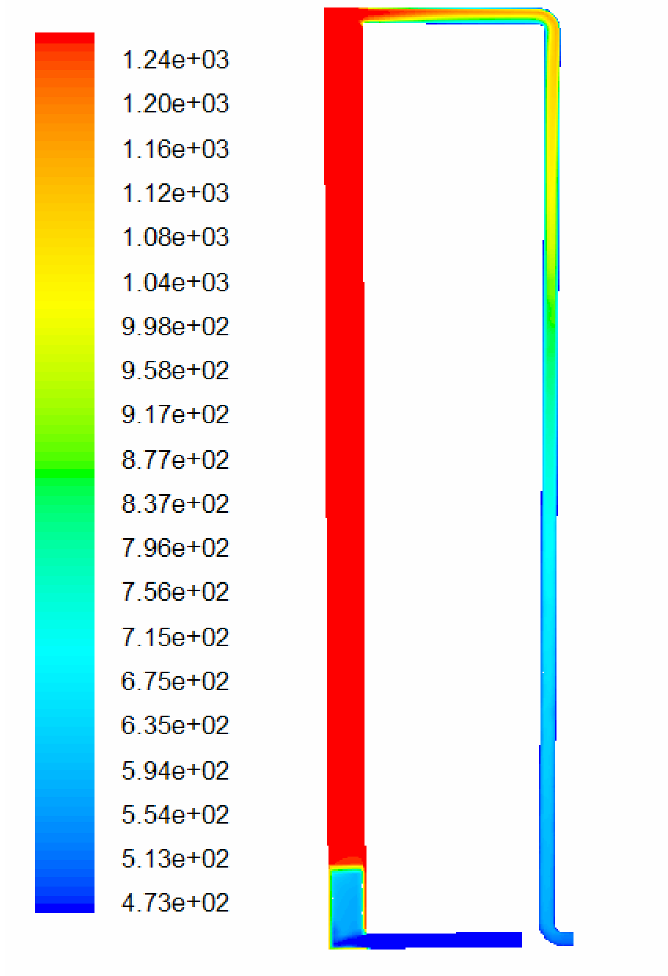


Figure 41: Temperature Profile for one experiment

The Mass Flow Rates

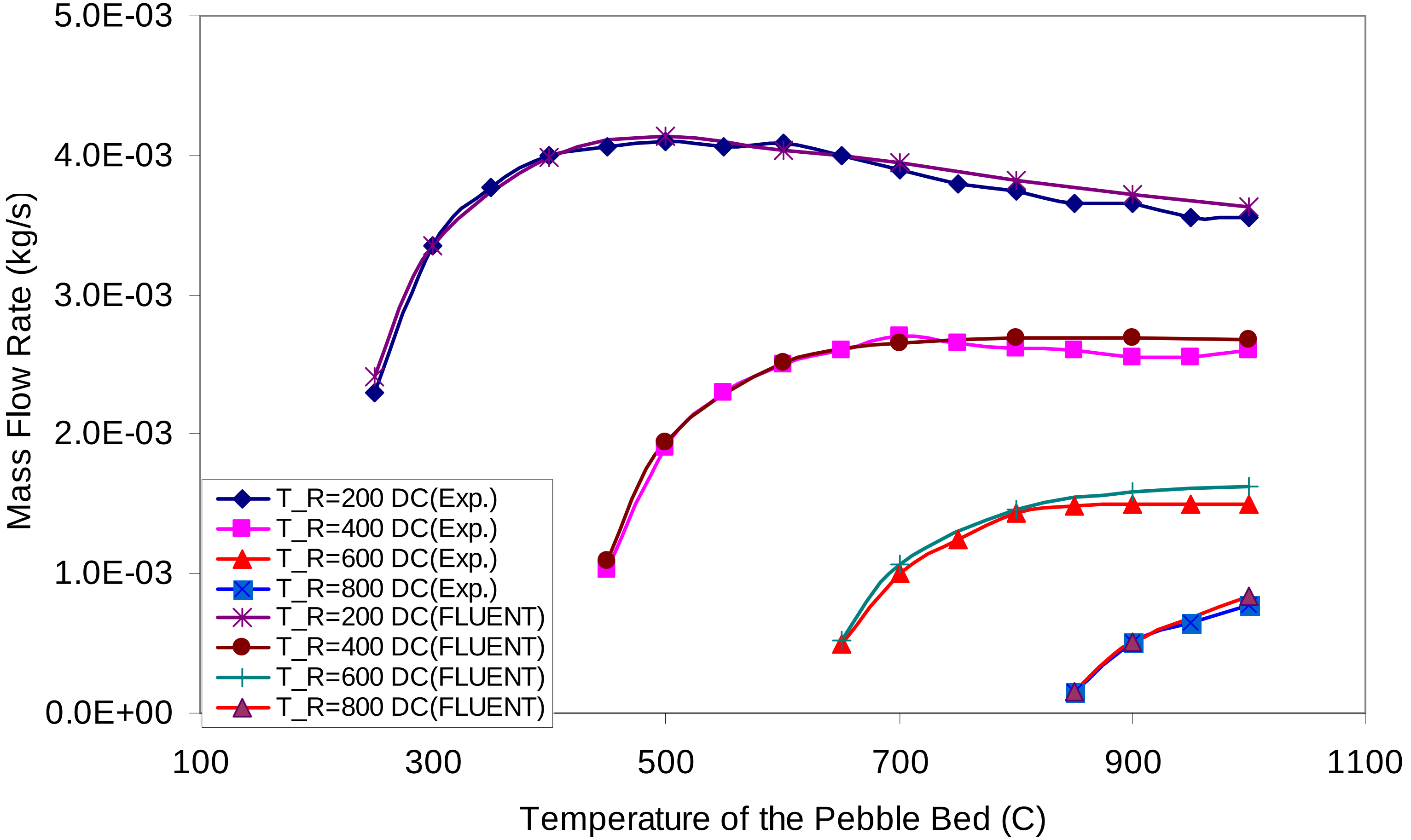


Figure 42: Mass Flow Rates for the NACOK Experiment

Future NACOK Tests

- Blind Benchmark using MIT methodology to reproduce recent tests.
- Update models
- Expectation to have a validated model to be used with system codes such as RELAP and INL Melcor.

Air Ingress Mitigation

- Air ingress mitigation strategies need to be developed
  - Realistic understanding of failures and repairs
  - Must be integrated with “containment” strategy to limit air ingress
  - Short and long term solution needed

Overall Safety Performance Demonstration and Validation

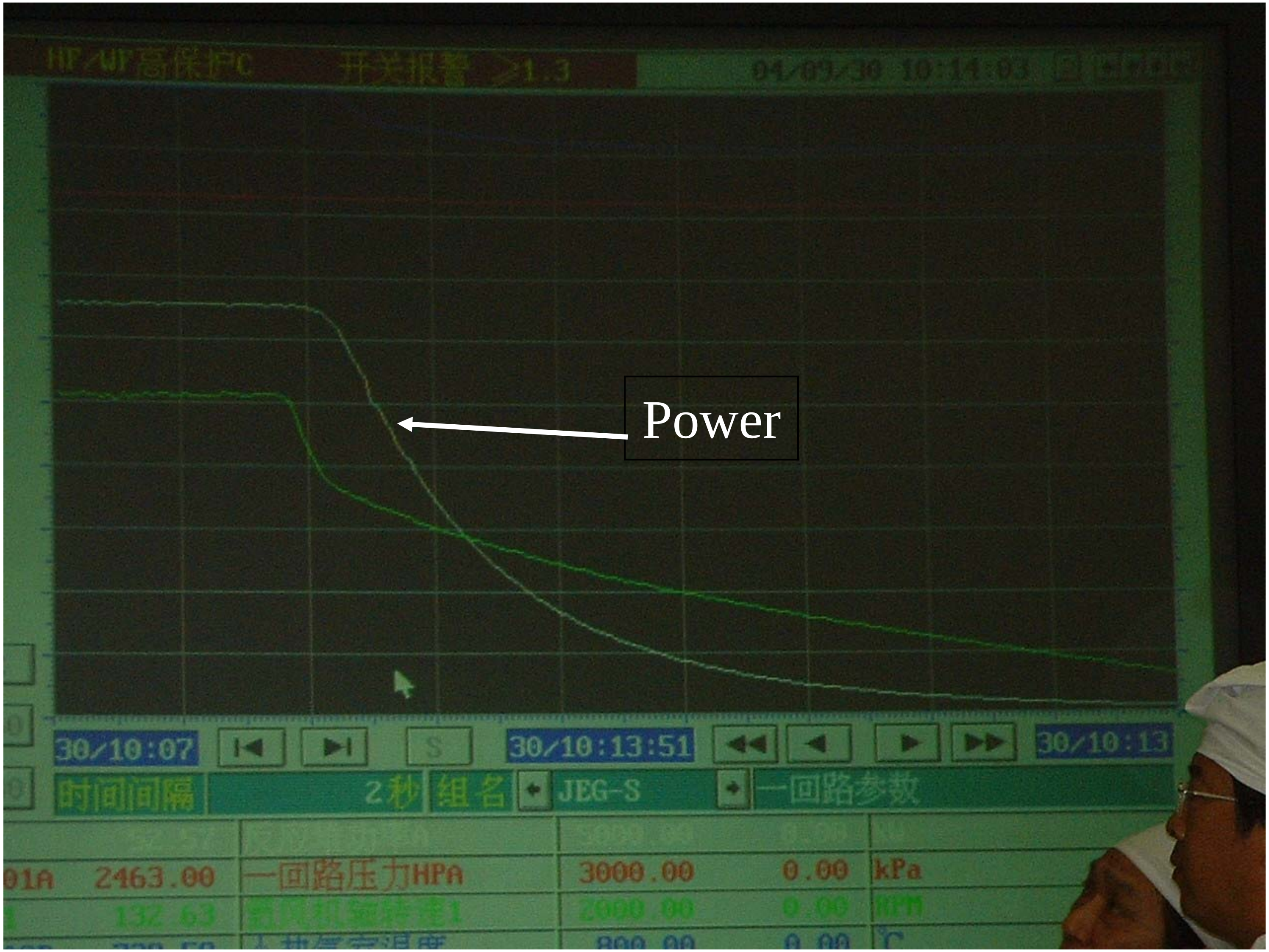
- China’s HTR-10 provides an excellent test bed for validation of fundamentals of reactor performance and safety.
- Japan’s HTTR provides a similar platform for block reactors.
- Germany’s NACOK facility vital for understanding of air ingress events for both types.
- PBMR’s Helium Test Facility, Heat Transfer Test Facility, Fuel Irradiation Tests, PCU Test Model.
- Needed - open sharing of important technical details to allow for validation and common understanding.

Chinese HTR-10 Safety Demonstration

- Loss of flow test
  - Shut off circulator
  - Restrict Control Rods from Shutting down reactor
  - Isolate Steam Generator - no direct core heat removal only but vessel conduction to reactor cavity

Video of Similar Test

Loss of Cooling Test



Loss of Cooling Test

Summary

- Safety advantages of High Temperature Reactors are a significant advantage.
- Air ingress most challenging to address
- Fuel performance needs to be demonstrated in operational, transient and accident conditions.
- Validation of analysis codes is important
- Materials issues may limit maximum operating temperatures and lifetimes of some components.
- International cooperation is essential on key safety issues.