TECHNOLOGY INTEGRATION REVIEW FOR NGNP AIR INGRESS

Workshop Minutes

March 31 & April 1, 2009
0800-1700 hours

Sundance Conference Room
City Center Marriott
Salt Lake City, Utah

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Executive Summary

The Next Generation Nuclear Plant (NGNP) project sponsored a technology integration workshop in Salt Lake City on March 31 and April 1, 2009. The purposes of the workshop were to: 1) integrate future and on-going air ingress work being performed by various stakeholders within the project; 2) perform a pilot of the technology integration review process (TIRP), and; 3) prioritize future issues for TIRP evaluation. Several air ingress technology issues require integration and resolution, including the determination of which phenomenon – molecular diffusion or density driven stratified flow - initiates air ingress following a postulated accident. Events considered are loss of helium and loss of forced flow within the primary pressure boundary of the reactor system. The workshop was attended by representatives from industry, academia, DOE, and NGNP Management, Licensing, Engineering, and Research and Development (R&D) organizations. All parties expressed very strong support for the TIRP, development of a single integrated response to air ingress and further integration of other cross-cutting issues.

Integration is needed to define the bases for future work. For example, at the German NACOK facility, graphite blocks held at high temperatures and relatively low oxygen concentrations and flow rates experienced significant oxidation. However, graphite at Hanford exposed to an acetylene torch and resulting temperatures of up to 1650°C experienced less than 3% material loss. The results of these experiments contradict each other, but the conditions for each – graphite type, specific test conditions, post-test examination, etc. – are not well known. Still, each test is referenced extensively when defining and evaluating impact from air ingress events.

Further, the assumed size and location of a leak initiating a postulated event significantly affect air ingress sequences and the results of any analysis. Work initiated at Oregon State University (OSU) by the Nuclear Regulatory Commission (NRC) is intended to develop an integral heat transport experiment and measure temperatures induced in core components by loss of helium and loss of flow events. These are the same type of events that would initiate air ingress. The results will significantly impact how the Nuclear Regulatory Commission (NRC) views technology development and subsequently, license applications. None of the industry partners at the workshop were aware of the OSU work or had been solicited for input to the experiment design. Interfaces and communications for this work should be carefully managed to ensure the results are relevant, well understood, and avoid the appearance of conflict of interest.

It is unlikely that research and evaluation of air ingress phenomena will result in successful design and licensing if the activities are not coordinated, and several examples of failures in other projects were discussed. Specific recommended activities to inform technology development with early NGNP project design information, and to inform design of ongoing technology development, were presented. Twenty-five specific recommended future activities were developed for better coordination and reduction of technology and project risk. They are

listed in Table 2 and assigned by area to Program Management, NGNP Engineering, Suppliers, NGNP R&D and Licensing. Some activities were grouped and eleven were identified as most important. They are listed in Table 4 with prime responsibilities listed by organization.

Several additional technology areas were prioritized for future workshops, with the expectation that they will be evaluated. As a result of the workshops, risk reduction activities will be developed that link research, engineering (including work by the reactor suppliers) and licensing to integrate the strategy for successful design and construction of the NGNP project. As a minimum, it is recommended that similar workshops address six areas, although the order of performance could be altered slightly for scheduling of key stakeholders and logistical considerations.

1. Fission Product Transport
2. Confinement/containment
3. Water ingress
4. Relationship between analysis uncertainty and fuel qualification (Localized hot-spots in the core)
5. Dust Transport and Impacts on Component Operability
6. Reactor Cavity Cooling System (RCCS) Experimental Needs

Recommendations for revisions to subsequent TIRP workshops were developed and will be incorporated in the TIRP workshop procedures and process flow diagrams. Development of a charter was specifically identified as a need by the group.

Background

The Next Generation Nuclear Plant (NGNP) project sponsored a technology integration workshop in Salt Lake City on March 31 and April 1, 2009. The NGNP project is in the conceptual design phase for deployment of a prototypical very high temperature gas-cooled reactor (VHTR) as authorized by the Energy Policy Act (EPAct) of 2005. The workshop topic was technology integration for NGNP air ingress phenomena and the purposes of the workshop were to:

1. Integrate future and on-going air ingress work being performed by various stakeholders within the project;
2. Perform a pilot of the technology integration review process (TIRP), and;
3. Prioritize future issues for TIRP evaluation.

Several air ingress technology issues require integration and resolution, including the determination of which phenomenon – molecular diffusion or density driven stratified flow - initiates air ingress following a postulated loss of helium and forced flow within the primary pressure boundary of the reactor system.

The TIRP is managed by NGNP Engineering as a means to identify varied stakeholder positions and opinions for a specific phenomena or issue related to VHTR research and development (R&D), design, and/or licensing. Stakeholders are identified to present relevant information in a structured workshop. After presentation and facilitated discussion, actions are identified and assigned to resolve technical differences, verify assumptions and reduce technology uncertainties. Information from assignments is routed back to the stakeholders to update technology development roadmaps (TDRMs), R&D goals, regulatory strategies, or design input. The goal of the process is to establish a single NGNP project position on how each topic will be addressed, ultimately reducing technology and project risk. Stakeholders will vary from workshop to workshop, depending on the topic. This workshop was attended by representatives from industry, academia, DOE, and NGNP Management, Licensing, Engineering and R&D organizations.

Meeting Objectives

The objectives of the TIRP workshop for air ingress were to:

1. Provide a means of presenting and discussing the various technical opinions regarding air ingress and related issues with project stakeholders to strengthen the project position;
2. Provide a means of informing technology development stakeholders of design needs, and in turn, informing designers of the results from technology development;
3. Develop a path forward to resolve specific air ingress issues, verify assumptions and obtain and evaluate data needed for successful design and licensing, and;
4. Provide a means to incorporate the developed path forward into the integrated project schedule to enable risk informed decisions regarding priorities and budget allocation.

Attendees

The following personnel from the NGNP project, Department of Energy (DOE), Industry and Academia attended the workshop. Key personnel from DOE Department of Nuclear Engineering (NE) were unable to attend due to schedule conflicts.

Table 1. Workshop Attendees

NAME	Org/ROLE	PHONE	E-MAIL
Collins, John	NGNP Engr, System Engineering	(208) 526-3372	John.Collins@inl.gov
Edmondson, Al	Industry/University	(509) 378-7852	adedmonds@aol.com
Fineman, Cliff	DOE-ID,	(208) 526-2753	finemacp@id.doe.gov
Garrett, Richard	NGNP Engineering	(208) 526-6766	Richard.Garrett@inl.gov
Gougar, Hans	NGNP R&D	(208) 526-1314	Hans.Gougar@inl.gov
Kadak, Andy	Industry/University		kadak@earthlink.net
Kinsey, Jim	NGNP Regulatory Affairs	(208) 526-6882	James.kinsey@inl.gov
Lommers, Lew	AREVA	(434)832-3687	lewis.lommers@areva.com
Lowry, Pete	NGNP Engr Safety Analysis	(208) 526-7101	Peter.Lowry@inl.gov
Oh, Chang	NGNP R&D	(208) 526-7716	Chang.Oh@inl.gov
Patterson, Mike	NGNP Engr, Technical Discipline Support	(208) 526-5525	MW.Patterson@inl.gov
Petersen, Per	Industry/University		peterson@nuc.berkeley.edu
Richards, Matt	General Atomics	(858) 455-2457	matt.richards@gat.com
Saurwein, John	General Atomics	(858) 455-2485	john.saurwein@gat.com
Schultz, Richard	NGNP R&D	(208) 526-9508	Richard.Schultz@inl.gov
Silady, Fred	PBMR Team	(858) 455-9500	silady@ti-sd.com
Stringer, Joe	AREVA	(704) 805-2711	joe.stringer@areva.com

Meeting Process

The meeting used computer-assisted facilitation with GroupSystems Meeting Room© software. Each participant had access to a computer, linked with other computers in the room. Information entered by the recorder or other participants appeared simultaneously on everyone's computer. Any ranking or scoring of items was done via the computers and the results were immediately available for review and discussion. Comments and scoring information were recorded anonymously unless otherwise specified by the facilitator. Information entered into the computers, including ranking or scoring information, is included in this meeting record.

The workshop opened with welcoming remarks from Richard Garrett and introductions were made. Key points from Richard's remarks include:

- This process needs to involve project the stakeholders and all attendees are considered stakeholders;
- This is not a "trial by jury" process - we want a questioning attitude to strengthen our program, and;
- This is a pilot of the TIRP workshop process - we will be working out the bugs as we go.

Meeting Presentations

Richard Garrett presented the background, objectives and the agenda for the workshop (Appendix A). During the agenda review, Richard was questioned if the objective of the workshop was to address the Air Ingress issue, develop a process for the Technical Integration Review Process (TIRP), or both. Richard and Mike Patterson explained the objective was to both refine the TIRP process and address a path forward for the Air Ingress issue.

Bryan Parker then explained the process for using the computers to capture comments and questions on the presentations. The computers remained closed during the presentations so the group could focus attention on the presentation. After the presentation the computers were opened for collecting comments and questions on the presentation. It was noted that the discussion following the presentations was very important and the use of the computers would limit the discussion. Bryan indicated that the process would accommodate both the discussion and the capture of comments in the computers. The group agreed and comments on the presentations were collected for each in general categories: Issues or Concerns, Assumptions, General Comments, and Uncertainty. Not all categories were used by participants when commenting and re-formatting of categories will be considered for the next TIRP workshop.

A series of five presentations were made to clarify air ingress issues and define the different stakeholder perspectives on each issue. The presentations are included as appendices to this report, along with the comments collected in the computers during and after the presentations. The five presentations were:

1. *Air Ingress: General Description of Phenomena* by R. R. Schultz (Appendix B) was a presentation comparing initiating phenomena - molecular diffusion versus density driven, stratified flow – for air ingress events. The criteria for stratified flow initiation and progression to natural circulation through the core were presented. Video of an air ingress simulation modeling a double-ended guillotine break initiated by stratified flow was shown and the basic physics underlying stratified flow were introduced.
2. *Current INL R&D Activities on VHTR-Air-Ingress Accident Analysis* by Chang Oh (Appendix C) was a presentation of recent CFD air ingress modeling based on the GT-MHR prismatic block reactor design. The presentation detailed the physics and analytical results of event initiation, concluding that stratified flow is highly dependent on design-specific geometry and configuration. The time to onset of convective cooling (natural circulation) then is also highly dependent geometry and leak location. Results of the analysis show early convective cooling (within minutes) for two leak scenarios - complete shear of the cross duct and complete break of the pressure relief line. During the period in which natural circulation is initiated, graphite temperature is still high which accelerates graphite corrosion. The CFD model results show extensive damage of structural damage for each postulated event. During the presentation, it was noted that the design-dependent location of check valve(s) and corresponding assumptions could also significantly affect the modeling results.
3. *Perspective on Air Ingress and Effect of Helium Injection on Natural Circulation in a Scaled Pebble Bed Reactor* by Andrew C. Kadak (Appendix D) was a presentation of the results from recent prominent experiments. Experiments conducted at the NACOK facility in Germany exposed graphite blocks held at high temperatures to air, resulting in significant damage to the graphite. A second set of experiments conducted by JAERI showed that air ingress would occur by molecular diffusion. Some inconsistencies between data and analytical models, geometry differences and uncertainty in boundary conditions were noted. Specifically, the need to characterize graphite corrosion properties for different graphite grades at varied temperatures and gas compositions, before and after irradiation, was identified as the largest uncertainty related to air ingress.
4. *Design and Development Process with Air Ingress Example* by Fred Silady (Appendix E) was a presentation of industry's perspective of air ingress as related to pebble bed VHTRs. While the importance of air ingress and other phenomena to design were noted, the designers' perspective is that research and development should be design-informed. Significant research and modeling has been and is being performed that is design specific. Without sufficient information to identify the sequence of events and their probability, modeling specific phenomena adds little value and can result in misleading conclusions. Modeling should be deferred until designs are mature enough to determine what additional

experimentation and modeling, if any, are needed. The PBMR design process was presented, identifying how design-informed R&D was integrated to meet design requirements. The flow down from high level requirements, such as maintaining public safety during a postulated event, may include air ingress but may also include multiple other phenomena. The requirements flow down is intended to ensure the design mitigates the impact of all of the phenomena for credible event sequences.

5. *Overview of Air Ingress Issues Prismatic Block Core Designs* by Matt Richards (Appendix F) was a presentation of industry's perspective of air ingress as related to prismatic core VHTRs. The design process is very similar to that presented for pebble bed reactors, although the requirements flow down process for design-informed R&D is more detailed. The results of design-specific research and modeling, as related to air ingress phenomena, were presented. These included experiments performed at LANL and Hanford where graphite was exposed to temperatures up to 1650°C in air with minimal oxidation. Generally, event sequences from past designs, similar to NGNP, concluded that large air ingress accidents were well beyond the design basis.

At the conclusion of the presentations, the group discussed to what extent and when air ingress occurs, and how to determine if the issue or event needs to be addressed. Also discussed was the possibility that the TIRP may inflate regulator and public perception of the impact of air ingress events. The group agreed that the TIRP needs to clearly assess the risk of air ingress to determine if it is a problem that needs to be addressed, and that misperceptions of risk (impact and probability) should be managed with clear and consistent communications. Some of the group believes that NGNP needs to design only for the design basis and consider beyond design basis events until after the design substantially matures. To extensively evaluate phenomena that are well beyond the design basis may confuse the clear communications noted above and will dilute critical resources needed for design and licensing activities.

Industry and Academia Feedback

Richard Garrett then asked Per Petersen and Andy Kadak for their impressions, experience, and feedback on the presentations and discussion. Their perspectives were captured by the facilitator in Appendix G. The group was given time to comment on the perceptions, and those comments can also be found in Appendix G. Key points from their perspectives are summarized as follow:

- It is import to understand the correct scaling approach for the processes and to make sure the distortions in any experiment are identified and compensated for. It is also important to understand, in detail, what is happening at the postulated leak location.
- 3-D CFD will play an important role in modeling the systems so it is important to understand the limitations of 3-D modeling.
- NGNP resources should be devoted first to risk-significant issues
- Employing a best estimate mechanistic approach to air ingress then this should minimize this issue for licensing and maintain focus on evaluating the technical issues.

Al Edmondson was also asked to provide his impressions, experience, and feedback which were then commented on by the group. Al's impressions and the group's comments are contained in Appendix G. Key points from his perspective are summarized as follows:

- There is a need to establish some guidance on the team's strategy and work plan, including a strategic plan on how interaction will occur with the NRC.
- For air ingress, the leak-before-break philosophy appears to be a key position of the project. There needs to be some stress analysis to support this position.
- The team should consider performing a benefit/cost review for each issue to inform decisions regarding the probability and cost of success.

Prior to adjourning for the day, the group was informed that Mike Patterson would take the comments entered into the computers during the day and identify major issues for inclusion in his presentation to start the second day.

The group then adjourned for the day.

Day 2 – Presentation and Discussion Summary

To begin the second day of the workshop, Mike Patterson presented what is going to happen with NGNP over the next 6-18 months and a summary of the major issues from the previous day (see Appendix H). Comments on his presentation, as captured by the facilitator, are included in Appendix H with key points summarized as follows:

- The team needs to find the best way to use the universities, and for what scope, so they are not on the critical path. It is recommended that universities address long-term enhancement activities, not near-term enablement activities. Coordination with universities that conduct research for both the NGNP and the NRC is a potential conflict-of-interest issue.
- Project and equipment systems requirements need to be kept in mind by the NGNP when prioritizing research activities.
- The most important thing is to identify all of the issues to produce an integrated, prioritized plan - not to identify one issue, solve it, and then look for the next issue.

Based on the comments and concerns with the TIRP flow diagram, a new TIRP flow diagram based on the comments and discussion was developed in parallel by a sub-group, presented and discussed, before the end of the day. It is presented later in Figure 1 with discussion comments.

The group then discussed the draft list of air ingress activities developed by Mike and presented in his slide presentation. Activities developed in the TIRP workshop are intended to integrate the project's approach. In this case, it was intended to develop a consensus approach to air ingress. The group modified the list of activities and placed them into five categories of Program Management, NGNP Engineering, Suppliers, NGNP R&D, and Licensing. The category indicates who has the ultimate responsibility for the action. For the purposes of this discussion, independent reviews (i.e. academics/industry) will be considered as part of the NGNP engineering category.

The group broke for a working lunch, and topic is discussed in the next section. After lunch, the group reviewed potential criteria for prioritizing the activities. The potential criteria were:

1. Impact to licensing (licensability)
2. Impact to design (including performance, availability, investment protection, safety)
3. Impact to schedule
4. Impact to plant economics
5. Impact to marketability

The group debated their ability to explicitly assess each activity against the criteria. After some discussion, the group agreed to evaluate the activities in two passes. The first pass would rank order the activities, within a category, based solely on the importance of the activity. The second pass would then look at how urgent is the activity. During each pass the group would keep the explicit criteria in mind as they ranked the activities. The group then rank ordered the activities, from most important to least important within the five categories.

Table 2 on the next page shows the rank sum results for the activities within each category. Detailed ranking information can be found in Appendix J of this record. The group reviewed and discussed the results and agreed they were an accurate representation of the group's ranking of the importance of the activities.

Table 2. Activity Importance Ranking

Primary List Importance	Rank Sum
1 Program Management	
1.1 Establish interface between R&D review boards and vendors	40
1.2 Resolve interface between the R&D done to support NGNP and the R&D done to support DOE/NRC	29
1.3 Integrate TIRP activities in project schedule	28
1.4 Update participants i.e. for end user requirement changes	23
2 NGNP Engineering	
2.1 Resolve the apparent differences between the NACOK/other experimental results and the applicability of results to NGNP design	44
2.2 Review of graphite chemical, physical, mechanical corrosion design data needs test plans, and test specs	42
2.3 Provide Input from vendor conceptual designs and design basis to R&D/methods development	37
2.4 Develop revision to the DDN's and their relationship to prior PIRTs on air ingress	35
2.5 Develop a white paper on the relative importance to the NGNP of the He pressure boundary and its requisite reliability.	22
3 Suppliers	
3.1 Develop scenario definitions from scoping PRA for spectrum of events involving air ingress	116
3.2 Determine time/state at which air ingress occurs for the spectrum for the size and location	105
3.3 Determine The initial Air/Helium concentration, temp, and pressure in the reactor building for the spectrum of events	88
3.4 Classify event into AOO's, DBE's and beyond design basis events	85
3.5 For the design basis event develop the approach to air ingress prevention and mitigation.	75
3.6 Know the composition and temp of the atmosphere (mixed, stratified, etc.) of the reactor building	69
3.7 Determine if we have a DDN to experimentally confirm density driven flow phenomena, if yes establish the test plan	63
3.8 Seismic analysis of large earthquake and the impact on a cross vessel	59
3.9 Review of Chang's December report	49
3.10 Determine the effect of the reactor plenum flow field on local mass transfer and oxidation.	45
3.11 Suppliers define what would be included in the definition "dynamic effects" as used in LLB design criteria for pipe breaks.	38
4 NGNP R&D	
4.1Perform a comparison using the best available data to determine what to expect on the oxidation damage for the MHTGR design bases 10 and 11.	35
4.2 Update and obtain TIRP team input on the development of OSU facility and test plans	33
4.3 Perform corrosion test as identified by tech plans/specs and identified gaps	29
4.4 Peer review of Chang Oh's air ingress December report	23
5 Licensing	
5.1 Address regulator questions regarding composition and temperature of atmosphere in reactor building.	12

Because of time limitations, Richard Garrett asked the group to forgo scoring the activities for urgency and instead review the revision of the TIRP process based on the discussion held earlier in the morning. The revised TIRP process flow is presented in Figure 1.

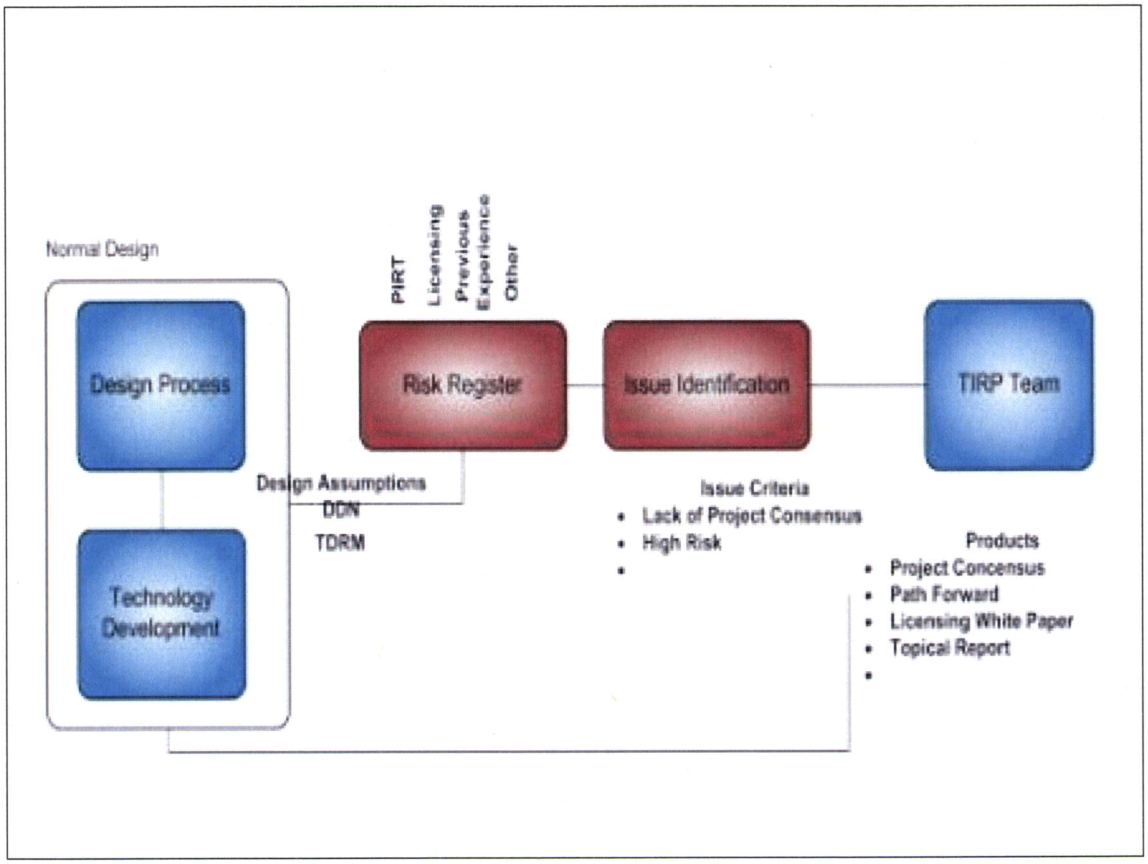

Figure 1. Revised TIRP flow diagram

The group agreed that the revision was on the right track, but requested more detail on the Risk Register, Issue Identification, and TIRP Team functions. It was suggested that a feedback loop to licensing also needs to be included in the process. There was a general belief that a more detailed TIRP flow diagram combined with a TIRP charter would alleviate many of the uncertainties this group was experiencing with regards to purpose and process of the TIRP.

Working Lunch - Discussion Summary

The working lunch started with a briefing/discussion led by Richard Schultz regarding the Oregon State University (OSU) facility and NRC. The OSU facility is a planned integral test facility meant to validate models of temperature distributions from the fuel to the pressure vessel. The facility and validation is planned to encompass loss of forced convective cooling during pressurized and depressurized conditions. Testing is meant to address leak sizes that vary from the double-ended guillotine break to sizes similar to instrument lines. Discussion centered around concerns that the OSU facility would not accurately reflect actual dimensions, conditions and scaling, generating validated models that would have to be modified and re-validated at a later date. Consensus was reached on the general concept that input from the suppliers in setting test conditions and functional requirements would improve model and validation quality and limit subsequent re-work. Further, the potential for confusing or seemingly contradictory results would be limited with additional design input. Finally, concern was expressed that multiple customers ranging from regulator to designer could create the perception of a conflict of interest. Resolution of this concern will remain unresolved until the INL identifies how interfaces and communications between multiple customers and organizations will be managed.

After lunch, the group reviewed the raw data from the first day of the workshop and verbally added additional items to the air ingress activity list. The categories, actions and participant comments on the activities can be found in Appendix I of this record.

Topics for Future TIRP Workshops

The group then discussed future TIRP issues, starting with a list provided by Richard Garrett and adding to it. These are issues that should be addressed by other TIRP teams utilizing the process prototyped in this meeting and refined by the TIRP process flow and charter. A total of eleven future issues were identified and placed in rank order from the most important to the least important. The results of this initial rank order are shown in Appendix K.

The group reviewed and discussed the issues ranking results, providing comments on the ranked issues (see Appendix K). The group then re-ranked the future issues based on the discussion and comments provided on each issue (see Table with details in Appendix L). It should be noted that scheduling of subsequent TIRP workshops will follow the priority listing to the largest practical degree. However, while this exercise identified the highest priority issues, subsequent TIRP workshops may not precisely follow the priority list due to scheduling conflicts for key stakeholders and logistics.

Table 3. Future TIRP Issues ranked in order of importance, round 2

Rank Sum	Future Issue
144	1. Fission Product Transport
140	2. Confinement/containment
131	3. Water ingress
127	4. Relationship between analysis uncertainty and fuel qualification (Localized hot-spots in the core)
100	5. Dust Transport and Impacts on Component Operability
84	6. RCCS Experimental Needs
82	7. Core Bypass Flow
68	8. RPV material issues (e.g. constructability, materials, classification, operating in He environment etc.)
44	9. Specific high temperature design and materials issues including an evaluation of the need for composites
39	10. First of a kind instrumentation
31	11. PIRT reactivity transients (rod ejection)

On reviewing the re-ranked issues, the group noted that some issues swapped places but there was no major reordering of the list.

Near Term Activities and TIRP Meetings

Following the meeting the individual the activities identified in Table 2 were reviewed, consolidated as appropriate based on additional team comments, and separated in three areas based on the nature of the activity (Programmatic, Licensing related, or Air Ingress specific). The near term activities (FY09) with the highest priority in each area are identified below.

Table 4. Near Term Activities

Activity Id.		Responsibility
	Programmatic Activities	
1.1 4.2 1.2	Establish an interface process between R&D review boards and vendors. Develop a NGNP position on and a strategy for the Oregon State University HTTF. Update and obtain TIRP team input on the development of the OSU facility and test plans. Identify and resolve interface between the R&D done to support NGNP and R&D done to support other DOE/NRC activities.	NGNP-Engr
2.3	Provide input from vendor conceptual designs and design basis to R&D and methods development.	NGNP-Engr
1.3	Integrate TIRP activities in project schedule.	NGNP-Engr
1.4	Update participants on end user requirement changes. Identifying end user requirements (by interface with SAG or other review groups) and disseminating that information to groups performing TIRP activities.	NGNP-Engr
	Licensing Related Activities	
2.5	Develop a white paper on the application of the LBB (leak before break) criteria to the HTGR specific design features to aid in defining the credible leak size and orientation and the relative importance to the NGNP of the He pressure boundary and its requisite reliability.	NGNP-Licensing
5.2*	Develop a white paper Methodology for Classification of events into AOO's, DBE's and beyond design basis events	NGNP-Licensing
	Air Ingress Resolution Activities	
4.1	Do a comparison using the best available data to determine what to expect on the oxidation damage for the MHTGR design bases 10 and 11.	NGNP R&D
2.1	Resolve the apparent differences between the NACOK/other experimental results and the applicability of results to NGNP design	Suppliers
2.2 4.3	Perform a review of graphite chemical, physical, mechanical corrosion design data needs test plans, and test specs to identify gaps. Perform corrosion test as identified by revised test plans/specs to resolve identified gaps	NGNP-SE NGNP R&D
2.4	Review and identify gaps in current DDN's based on PIRT review. Initiate revision to DDNs to as appropriate to identify gaps on air ingress issues.	NGNP-SE
4.4	Peer review of Chang Oh's air ingress December report	Suppliers

* New Activity in support of Activity 3.4.

In support of closure of the identified Future Issues, the following TIRP meeting schedule is proposed based on the issue ranking, resource availability, and expected data collection and presentation preparation times to support the TIRP meeting.

Table 5. Proposed schedule for next TIRP Workshops

Issue	Proposed TIRP Meeting
Water ingress	June
Confinement/containment	July
Fission Product Transport	September

Additional Actions and Meeting Conclusion

The following actions (not captured within the specific activities identified in the Meeting Summary) were identified during the workshop:

- Develop a glossary of terms and an anti-glossary of terms for use in future TIRP meetings and Project Documents (NGNP Engineering).
- Develop a more detailed process flow diagram of the TIRP diagram revised during the meeting (Figure 1) and link it to the supplier design logic flow diagrams. (NGNP Engineering)
- Develop a charter for the TIRP (NGNP Engineering).
- Provide typical break cases to NGNP R&D for future analyses (Suppliers).

Richard Garrett closed out the meeting with comments and observations about the workshop as follow:

- The workshop has had very beneficial dialogue,
- The workshop has been a good use of time,
- This meeting helped breakdown stovepipes, and the TIRP process will help us continue to breakdown stovepipes,
- Everyone has had a good questioning attitude,
- NGNP will take this information and feed it into the integrated project schedule,
- This group has brought up valid concerns on communicating divergent information to the NRC,
- Overall this workshop has surpassed expectations.

Mike Paterson added that he appreciated all the patience and restraint from the participants. Others added that vendors can gain a lot from each other through the discussion of common technical issues. The meeting concluded with participants completing a workshop evaluation.

The workshop adjourned at about 5:00 PM.

Technology Integration Review Process (TIRP) Charter

Purpose

The Technology Integration Review Process (TIRP) provides the Next Generation Nuclear Plant (NGNP) project with a method to consolidate engineering, technology development and licensing activities related to cross-cutting phenomena or issues into a single, integrated project response. Implementation of the TIRP enables design-informed research and development (R&D) and provides design direction and updates from the R&D results. This iterative approach reduces project risk by resolving technical uncertainties, validating design assumptions and developing licensing strategies based on integrated planning to meet the following objectives:

1. Provide a means of presenting and discussing the various technical opinions and related issues with project stakeholders to strengthen the project position;
2. Provide a means of informing technology development stakeholders of design needs, and in turn, informing designers of the results from technology development;
3. Develop a path forward to resolve specific issues, verify assumptions and obtain and evaluate data needed for successful design and licensing;
4. Provide a means to incorporate the developed path forward into the integrated project schedule to enable risk informed decisions regarding priorities and budget allocation, and;
5. Inform and update licensing strategies communicated through white papers or topical reports to the Nuclear Regulatory Commission (NRC).

TIRP Scope

The TIRP is managed by NGNP Engineering as a means to identify varied stakeholder positions and opinions for a specific phenomena or issue related to NGNP R&D, design, and/or licensing. Stakeholders are identified to present relevant information in a structured workshop. After presentation and facilitated discussion, actions are identified and assigned to resolve technical differences, verify assumptions and reduce technology uncertainties. Information from assignments is routed back to the stakeholders to update technology development roadmaps (TDRMs), R&D goals, regulatory strategies, or design input. Stakeholders vary from workshop to workshop, depending on the topic.

TIRP Board Composition and Responsibilities

Potential TIRP topics have been identified and prioritized. A topic-specific board will be assembled and TIRP workshop conducted for the highest priorities. The TIRP board consists of representatives selected for their expertise related to the pertinent technology issue. Typical workshops may be attended by representatives from industry, academia, and NGNP Management, Licensing, Engineering and R&D organizations. The Department of Energy (DOE) may be represented by personnel from the Nuclear Engineering (NE) department and/or Idaho field office (DOE-ID). NGNP Engineering will identify potential board members and select the board based on input from NGNP R&D, NGNP Licensing, and DOE. Availability and logistics will be considered. Responsibilities of the board are identified in Table 1.

Table 1. TIRP Board Composition and Responsibilities

Member Organization	Responsibilities
NGNP Engineering	1. Primary responsibility for developing board membership and conducting TIRP workshops 2. Evaluation of recommended responses based on technical risk and schedule/cost impact 3. Incorporation of responses (cost/schedule/scope) from the workshop into the NGNP baseline (as approved) 4. Coordination of TIRP activities, milestones, deliverables and dissemination of results 5. Function as the owner's engineer in developing recommendations and reviewing/coordinating activities 6. Integrate TIRP activities into the project risk register and risk response plans
NGNP R&D	1. SME for specific phenomena 2. Interface and coordination with international and university R&D initiatives 3. Coordination of INL and other DOE lab R&D activities
NGNP Management	1. TIRP Process sponsor 2. Provide resources for TIRP workshops and board formation consistent with activity priorities and project risk 3. Review recommended responses and provide resources consistent with activity priorities and project risk
NGNP Licensing	1. SME for specific phenomena with regard to licensing impact 2. Coordination of NGNP and vendor activities with NRC 3. Integrate TIRP activities with and into NGNP licensing plan 4. Oversight and direction of white papers and/or position papers developed as a result of TIRP activities
NGNP Vendors	1. Serve on NGNP R&D advisory boards as SMEs for specific phenomena with regard to design 2. Provide design data needs (consistent with design maturity) to organizations performing TIRP activities 3. Integrate TIRP activities into supplier licensing plans 4. Provide design information to developers of white papers and/or position papers
Department of Energy DOE-NE:	1. Sponsor for NGNP and integration with NRC 2. Evaluate recommendations and incorporate in Program Direction
Department of Energy DOE-ID:	1. Implementation of Program Direction from NE 2. Monitoring of contractor's performance with regard to program direction

NGNP Engineering has overall responsibility for managing the TIRP process and will propose topics and participants. Topics were developed and prioritized during the first workshop. This prioritized list will be updated as new topics are identified and as a minimum, will be reviewed at each subsequent workshop. The need for TIRP workshops, at least on an ad hoc basis, is anticipated to last through NGNP final design.

TIRP Workshop Process

Design activities conducted by design suppliers lead to identification of specific design data needs (DDNs). Design-informed responses – studies, analysis, or experimental validation – are performed to support the design suppliers and reduce project risk. Ultimately, the activities inform the NGNP license application. For particularly high risk or contentious activities or phenomena, a workshop is held to develop a consolidated project approach to reducing the risk. The workshop is the key component of the TIRP process. By itself, a single path forward reduces risk because it minimizes conflicting communications with stakeholders and regulators and is the most efficient use of resources.

Results of the TIRP process (if the activities are not already included in test plans and schedules) are incorporated in the NGNP baseline as part of the project schedule and can be communicated to the NRC as white papers or topical papers to reduce risk through early identification. A graphical representation of the process is shown in Figure 1 below.

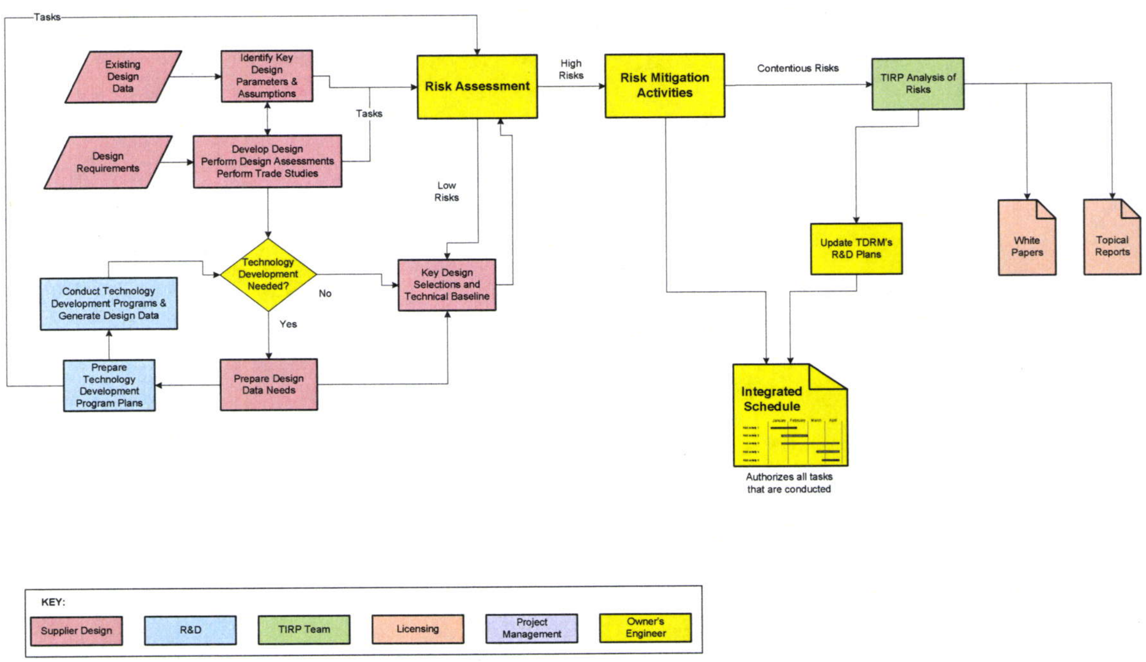

Figure 1: Graphical Representation of TIRP

Once it has been determined that a TIRP workshop is required for a particular issue, the procedure below is used to complete the workshop and implement the recommended actions. The procedure represents a guideline for completing the green block ("TIRP Analysis of Risk") in Figure 1.

1. Identify topic, presenters and potential SMEs
2. Inform participants via e-mail
3. Procure technical resources as needed
4. Develop presentations
5. Assign homework to invited stakeholders
6. Conduct workshop
7. Issue minutes
8. Present results to process sponsors
9. Develop cost estimates/schedules via NGNP trend process
10. Incorporate approved actions into NGNP baseline
11. Update risk register and risk mitigation plans
12. Monitor progress, distribute results from assigned actions per updated baseline schedule
13. Conduct subsequent workshops as needed and as determined by NGNP Engineering and Project Management
14. Close TIRP process when criteria in risk register is met

Workshop Location

Workshop sessions will typically be held at an off-site location with good access for participants. Adequate Internet connectivity, teleconferencing equipment, video projection capability, and recording media (e.g., electronic whiteboards, flip charts, etc.) will be provided. A systems engineering tool such as GroupSystems Meeting Room© in a facilitated format will be used.

Workshop Results

Meeting minutes from the workshop will be distributed for comment to participants, although comments will be limited to corrections in the meeting record. Recommended actions from the meeting will be presented to NGNP management using the trend process. Approved trends will be incorporated in the NGNP baseline by baseline change control (BCP), drawing funds from management reserve, or by including the work in the subsequent fiscal year work plan. Risk registers and DDNs will be updated based on the implemented actions and results from the activities. Approaches to design and licensing will be communicated to the NRC by white paper or topical report, as coordinated with NGNP licensing and approved by NGNP management. Once the activities have become part of the baseline, stakeholders will be updated via normal project communications.

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Rev. 03

NEXT GENERATION NUCLEAR PLANT PROJECT INFORMATION INPUT SHEET

1. Document Information

Document ID: CCN 218092 Revision ID: ______ Project Number: 23843

Document Title/Description: Contract Number DE-AC07-05Id14517 - Air Ingress Technology Integration Review Process

Sub-Project No.: ______

Date of Record: 07/23/09

Document Author/Creator: Richard Garrett

OR

Document Owner: Richard Garrett

Date Range:

Originating Organization: INL

From: ______ To: ______

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Category: ☒ General Record ☐ Quality Assurance ☐ Controlled Document

If QA, Record, QA Classification: ☐ Lifetime ☐ Non-Permanent

Uniform Filing Code: 0100 Disposition Authority: A23-1-a Retention Period: Cut off at the end of the year. Destroy when 2 years old, .

Keywords: Technology Integration Review for NGNP Air Ingress Workshop Minutes; Technology Integration Review Process (TIRP) Charter; RG-01-09

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Air Ingress: General Description of Phenomena

NGNP Methods R&D
Presented by R. R. Schultz

Each VHTR scenario must be evaluated in context of…

Relevant potential accidents:

- Phenomenology & sequence timing
  - What happens when?
  - Influence of geometry, break size , break location (orientation)
  - Graphite structural material (nuclear or non-nuclear)
- Are there factors that may combine to cause unexpected result, e.g., "cliff-edge" behavior or unanticipated turn of events?

Impacts: type of system

Design implications:

- Mitigation systems?
- Accident management procedures?

Nature of system: redundancies, diversities, etc

Credible break sizes:

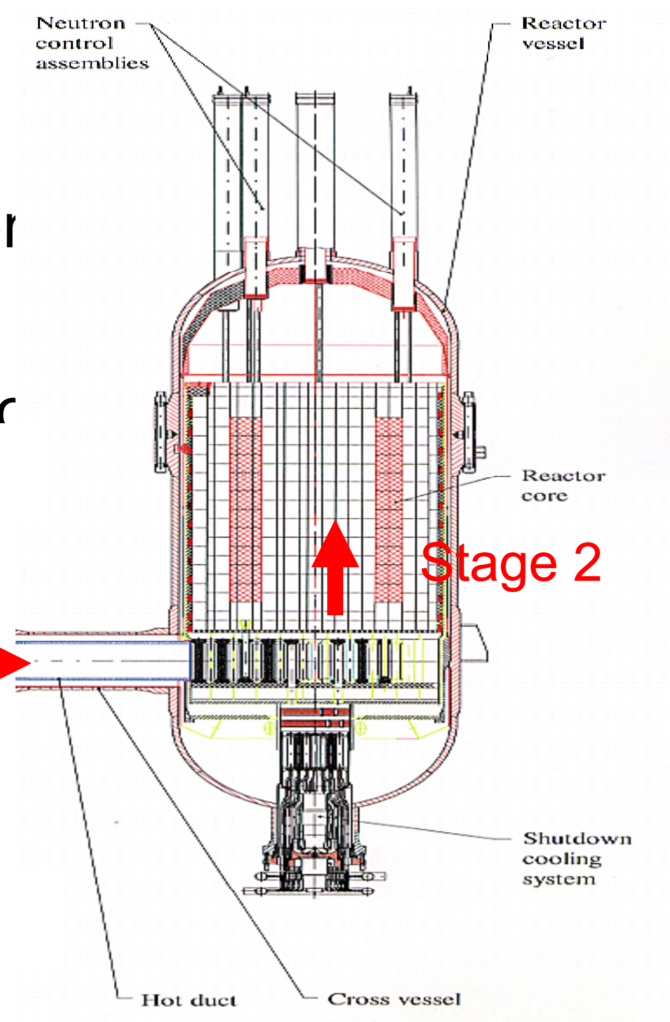
- Design basis?
- Beyond design basis?
- Best Estimate or conservative approach (Appendix K?)
- Acceptance criteria?

The Air Ingress Scenario…

Is divided into 2 parts:

1. Stage 1: Air moves into lower plen

2. Stage 2: Air moves into core regio



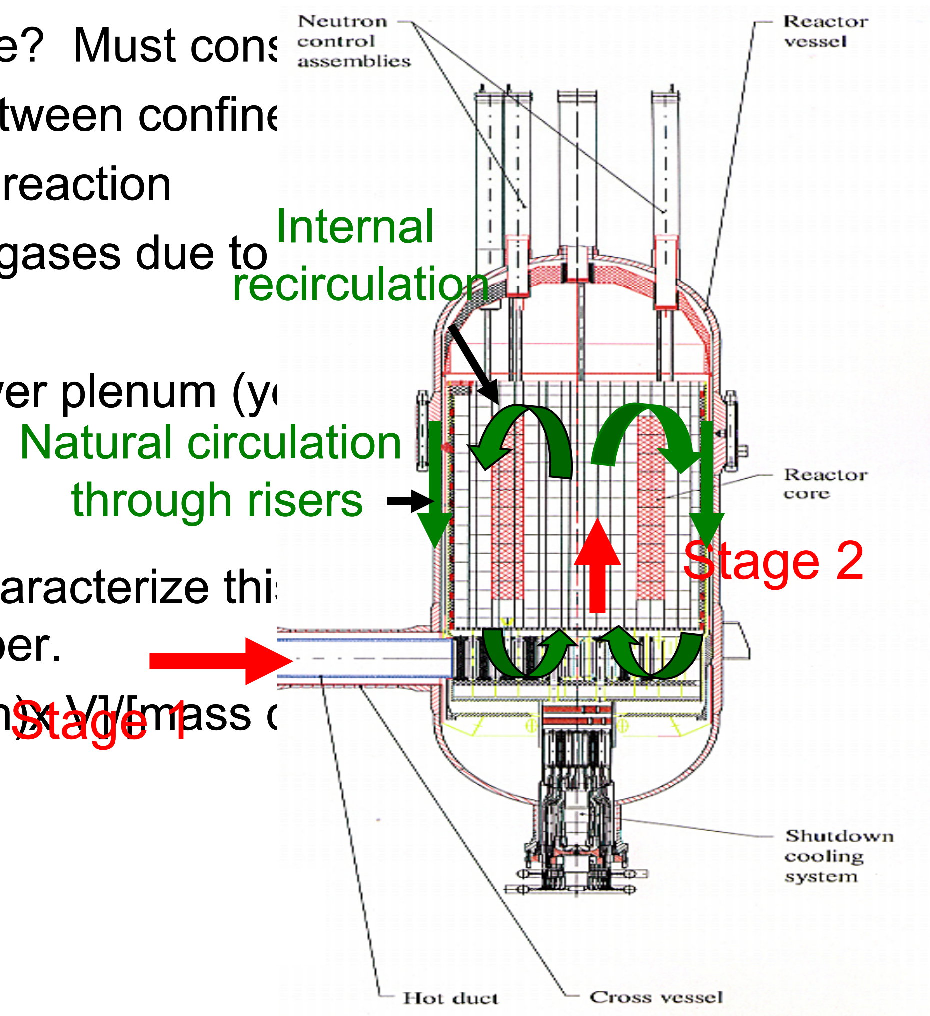
Stage 1…

- How does the air move into the lower plenum if a leak causes the system to depressurize?
  - Density-gradient stratified flow? Occurs if break orientation meets key criteria and densimetric Froude number is less than 1.
  - Or Diffusion?
- Densimetric Froude number is helium velocity (V) divided by wave velocity = $[g'L]^{1/2}$ where

  $g' = g\,(\rho_{air} - \rho_{helium})/\,\rho_{helium}$
- The physics of the air ingress scenario are very similar to the stratified flow phenomena we've been aware of and analyzed for advanced LWRs—since the mid-90s.

Stage 2…

- What causes air to move into the core? Must cons
  - Manometric pressure balance between confine
  - Momentum induced by oxidation reaction
  - Decreasing density of ingressed gases due to
  - Chimney effect.
  - Circulation between core and lower plenum (ye probably no for pebble-bed)
  - Diffusion
  - Nondimensional numbers that characterize thi Peclet number and Nusselt number.
- Peclet no = [(characteristic dimension) x V]/[mass c



Air Ingress Scenario—

- Occurs as part of depressurized conduction cooldown scenario (DCC).
- DCC caused by pipe leak where leak size ranges from small crack in piping to full pipe rupture (double-ended guillotine).
- DBA presently undefined—may be a small area leak
- Most likely scenario is a crack in piping.

Depressurization & Leak Spectrum…

- Scenario begins with depressurization where rate of depressurization is dictated by leak size and geometry.

- System depressurizes to confinement pressure

- DEGB is well defined and is based on unobstructed blowdown through full pipe area of largest pipe or hot duct into confinement. Depressurization is very short. Air ingress initiated earliest point in time.

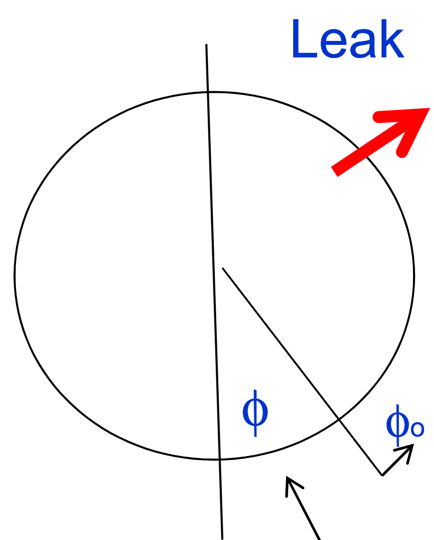
- Small flow area leaks will likely be a “crack” in a system pipe. Leak may still be horizontally-oriented—located perhaps on hot duct or instrument line at upper elevations.

Leak Orientation Greatly Influences Air Ingress Scenario

Leak orientation and size determines:

1. Magnitude and timing of density-driven stratified flow
2. Dust transport characteristics

End view of horizontally-oriented pipe.



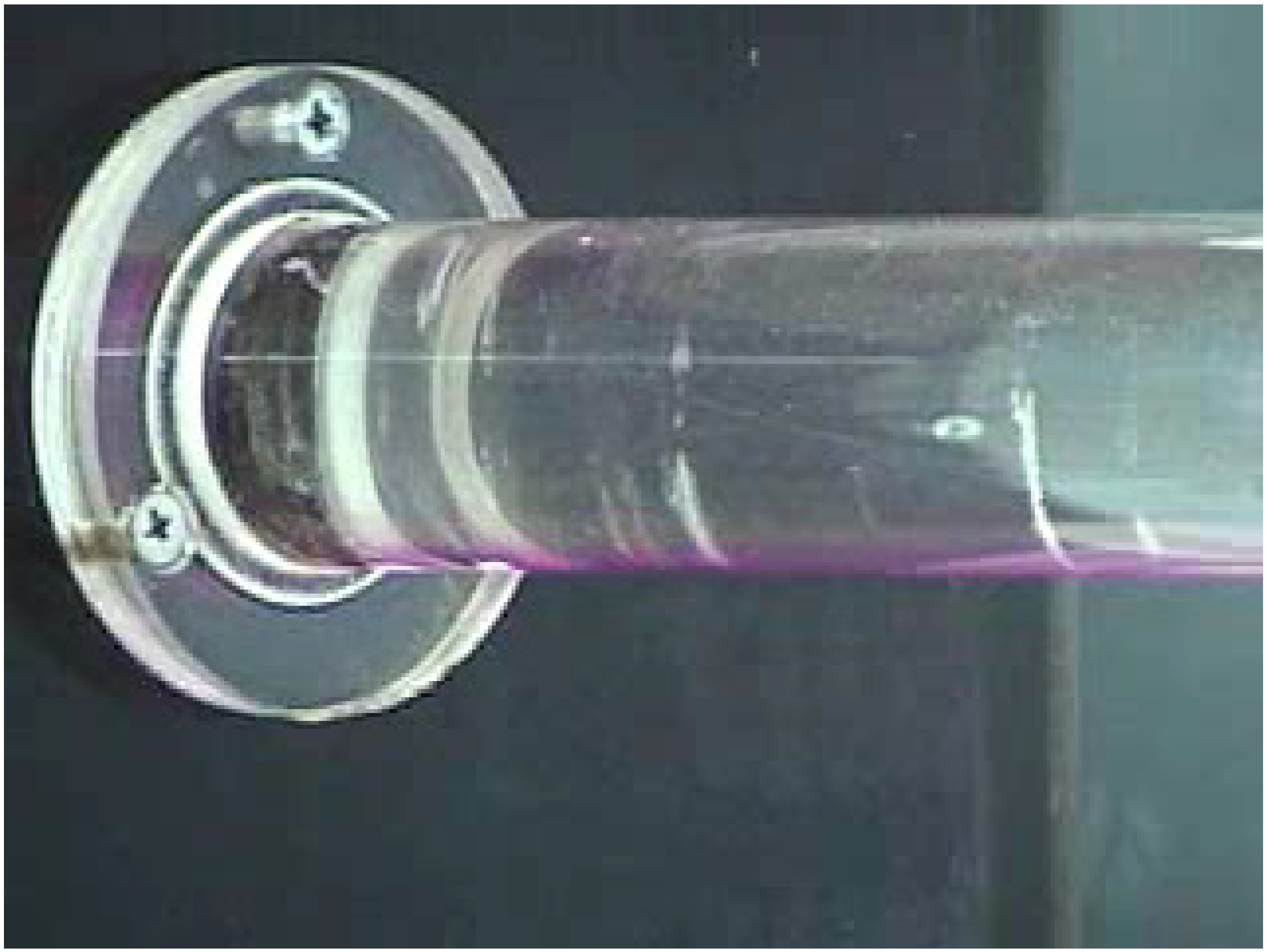
Horizontally-oriented leak pipe will have larger rate of air ingress than vertically-oriented leak. Density-gradient driven flow important factor for ϕ greater than ϕ_o

Zone where density-driven stratified flow has no influence.

Progression of DCC & Transition to Air Ingress—

- Blowdown is initiated: Leak (break) is choked.
- Depressurization almost over—break unchokes.
- Flow influenced more and more by density gradients. Densimetric Froude number signals when countercurrent stratified flow may begin. Pressure level near atmospheric.
- For leaks conducive to stratified flow, air will begin moving into vessel only a short time after the depressurization is over. Rate of air ingress dictated by break characteristics and orientation.

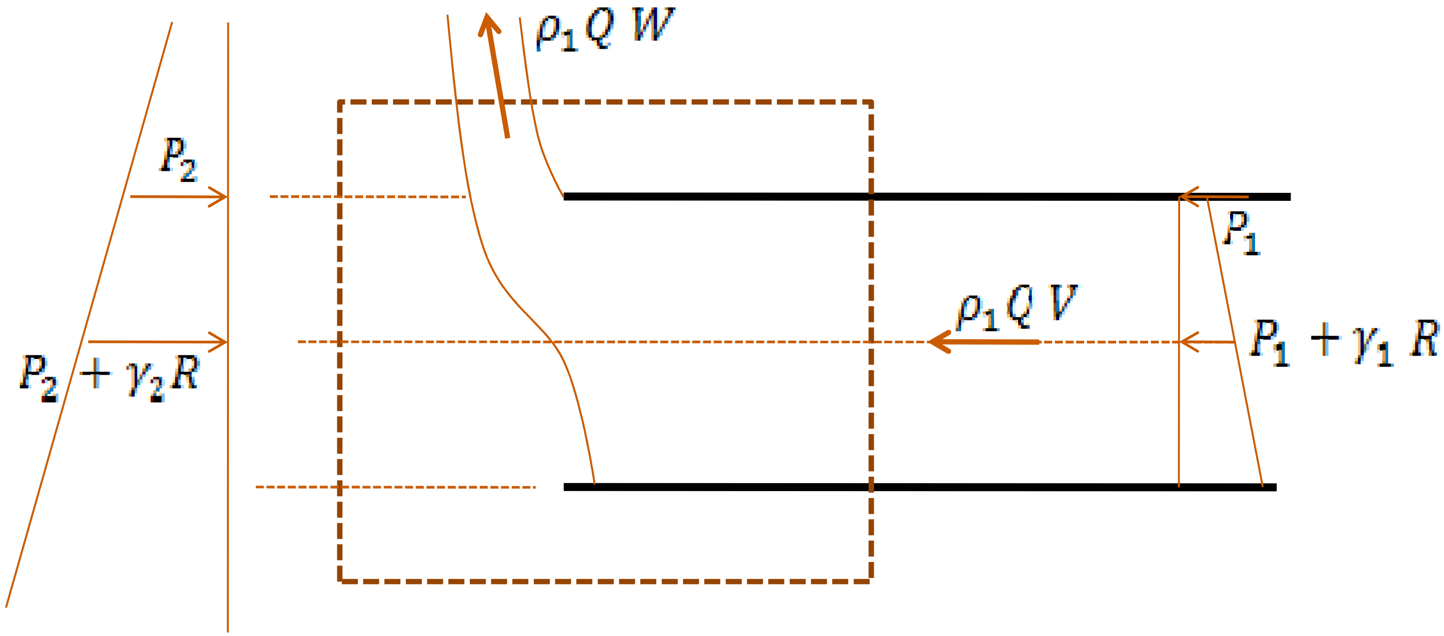
Quasi-Static Wedge Intrusion



Video by:

Professor Jim Liou,
University of Idaho

Onset of Intrusion
Momentum Principle



Control volume

Criterion for the Onset of Intrusion

Assume ambient hydrostatic condition…

$$(P_2 + \gamma_2 R)\pi R^2 - (P_1 + \gamma_1 R)\pi R^2 = \rho_1 Q V$$

$$\frac{V^2}{g' R} = 1 - \frac{P_1 - P_2}{(\gamma_2 - \gamma_1) R}$$

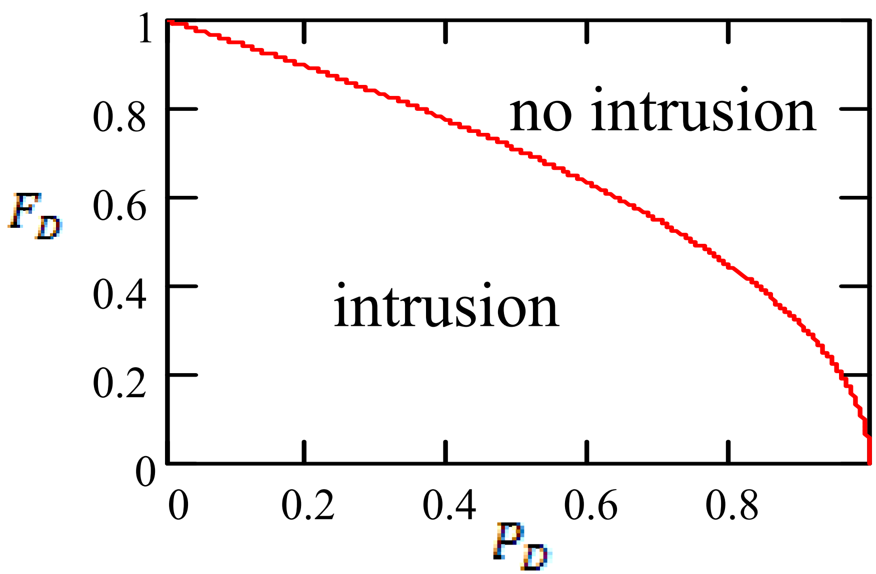
$$g' = \frac{\rho_2 - \rho_1}{\rho_1} g = reduced\ gravity$$

Criterion for the Onset of Intrusion (2)

$$F_D = \sqrt{\frac{V^2}{g'R}} = \sqrt{1 - \frac{P_1 - P_2}{(\gamma_2 - \gamma_1)R}} = \sqrt{1 - P_D}$$

$$F_D = densimetric\ Froude\ number$$

$$P_D = \frac{P_1 - P_2}{(\gamma_2 - \gamma_1)R} = scaled\ pressure\ difference$$

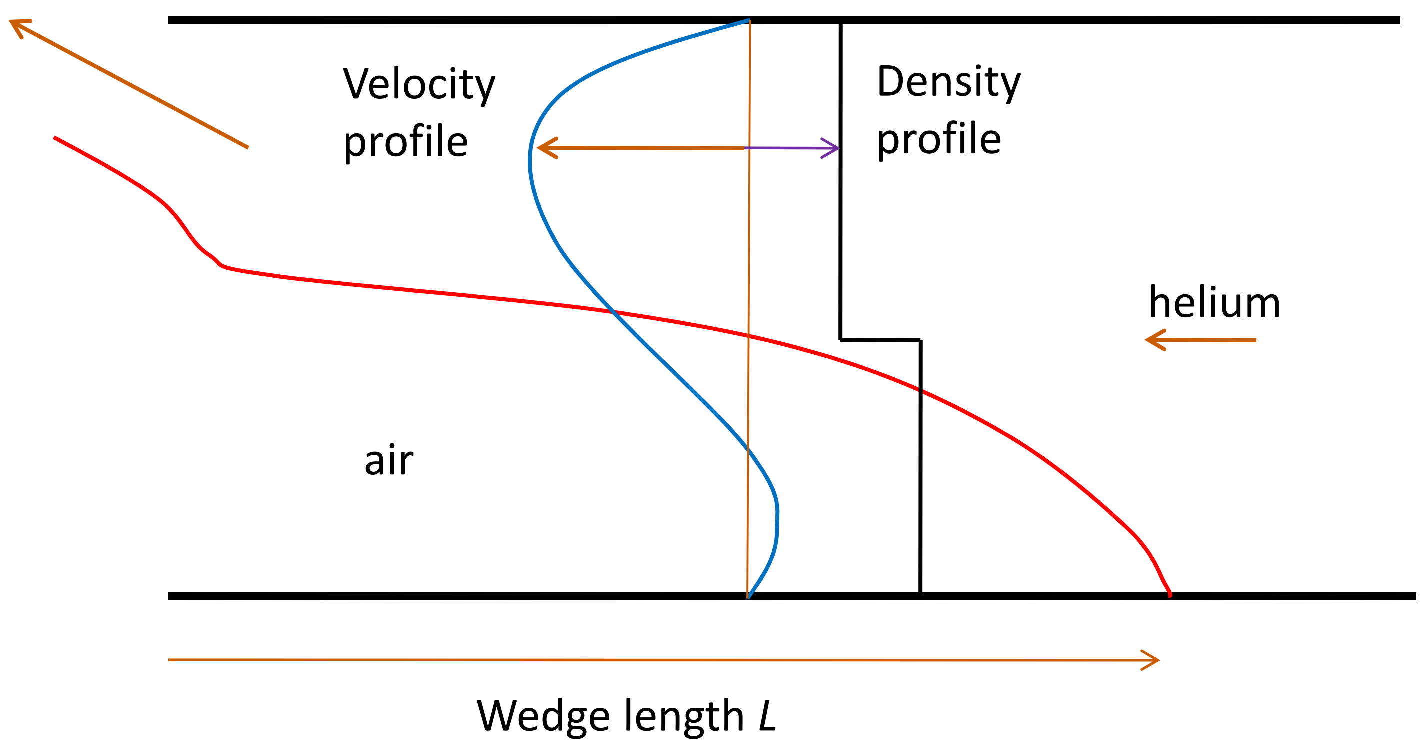


Criterion developed by Professor Jim Liou, University of Idaho

Interpretation of the Criterion

- When P_D exceeds unity, no inertia force of the helium is needed to prevent intrusion
- As P_D decreases toward zero, the required inertia force to prevent intrusion increases
- When P_D reaches zero, the inertia force needs to equal or exceed gravitational (buoyancy) force of the air in order to prevent intrusion
- Since the inertia force is derived from the pressure differential, intrusion is inevitable as P_D diminishes

Intrusion as a Wedge (A static equilibrium)

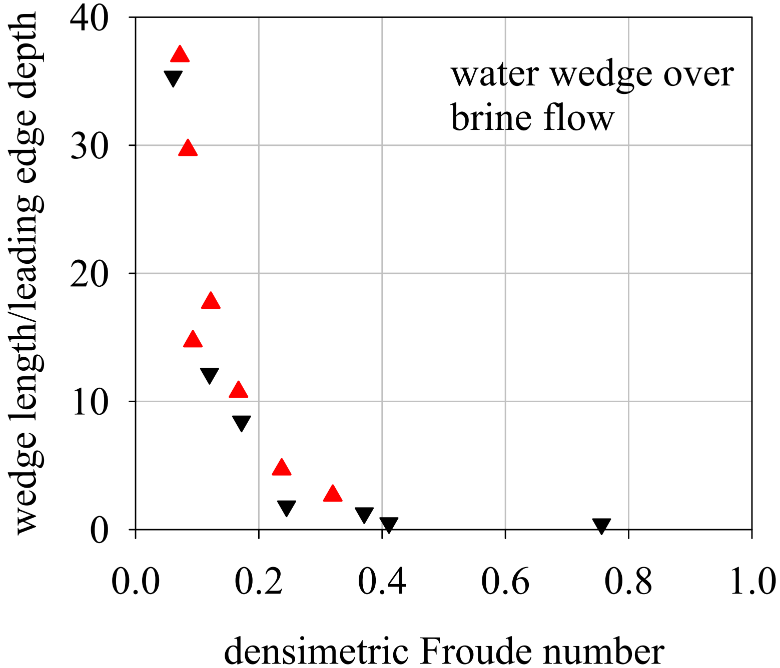


Mechanism of Wedge Formation

- The vessel-to-containment pressure gradient drives the helium flow
- The helium flow exerts a shear stress and pressure on the interface
- The interface adjusts its shape so that local longitudinal gradient of gravitational force in air balances the stresses on the interface
- The shape of the wedge is determinable by the momentum conservation principle

Extent of Wedge Intrusion

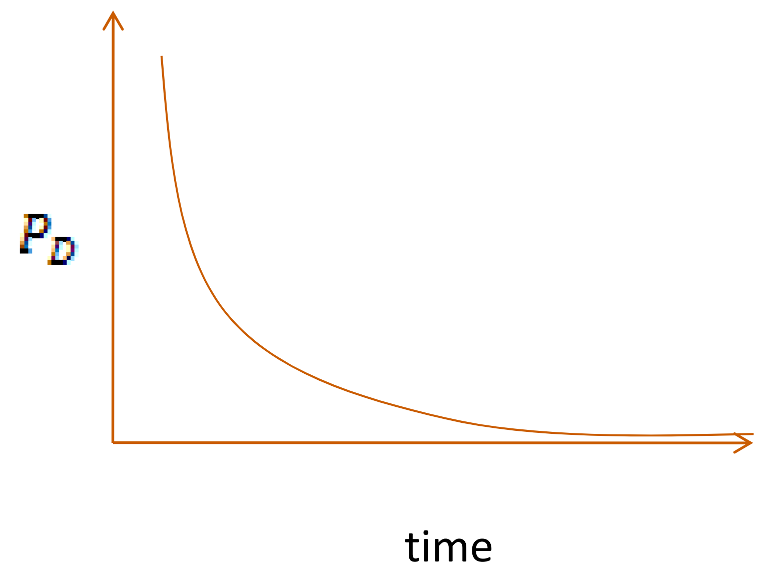
- The extent of intrusion is a function of the densimetric Froude number



Liou, et. al., ICONE13 - *50450*

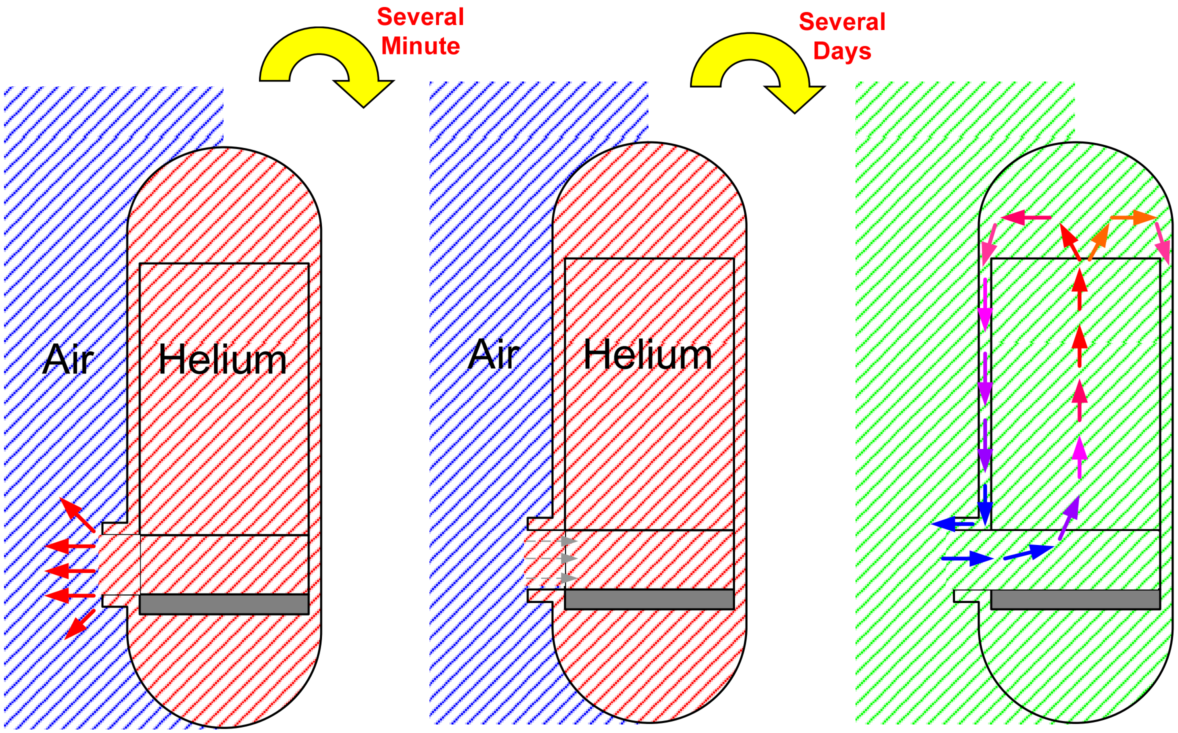
Speed of Wedge Intrusion

- The speed of Intrusion depends on the rate of decrease of P_D to maintain static equilibrium



Air Ingress Scenarios

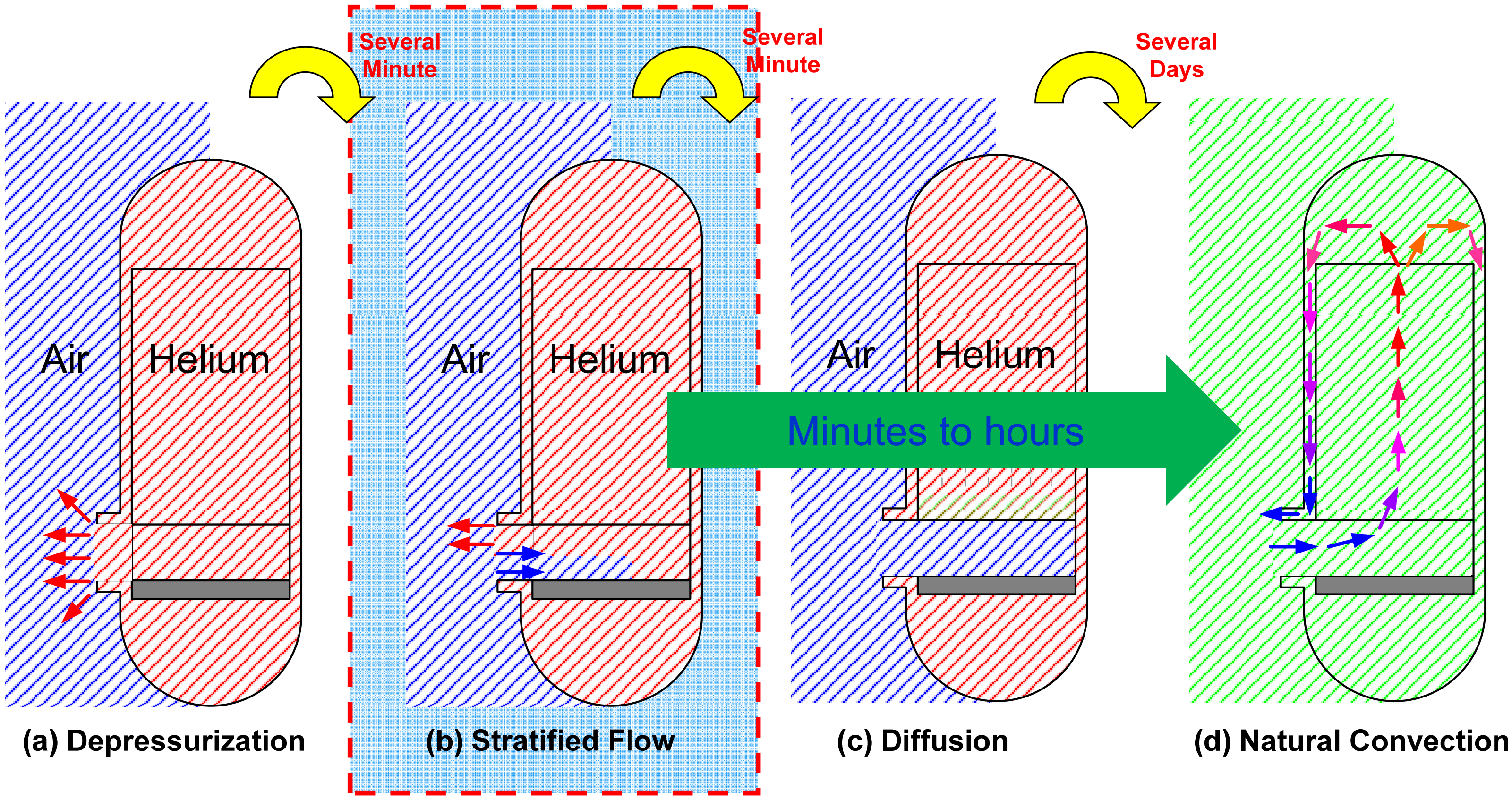
Original Scenario: Diffusion Dominated Air Ingress



(a) Depressurization **(b) Diffusion** **(c) Natural Convection**

Air Ingress Scenarios

New Scenario: Stratified Flow Dominated



Air Ingress Scenario—Key Variables for Air Entry During Stratified Flow Phase

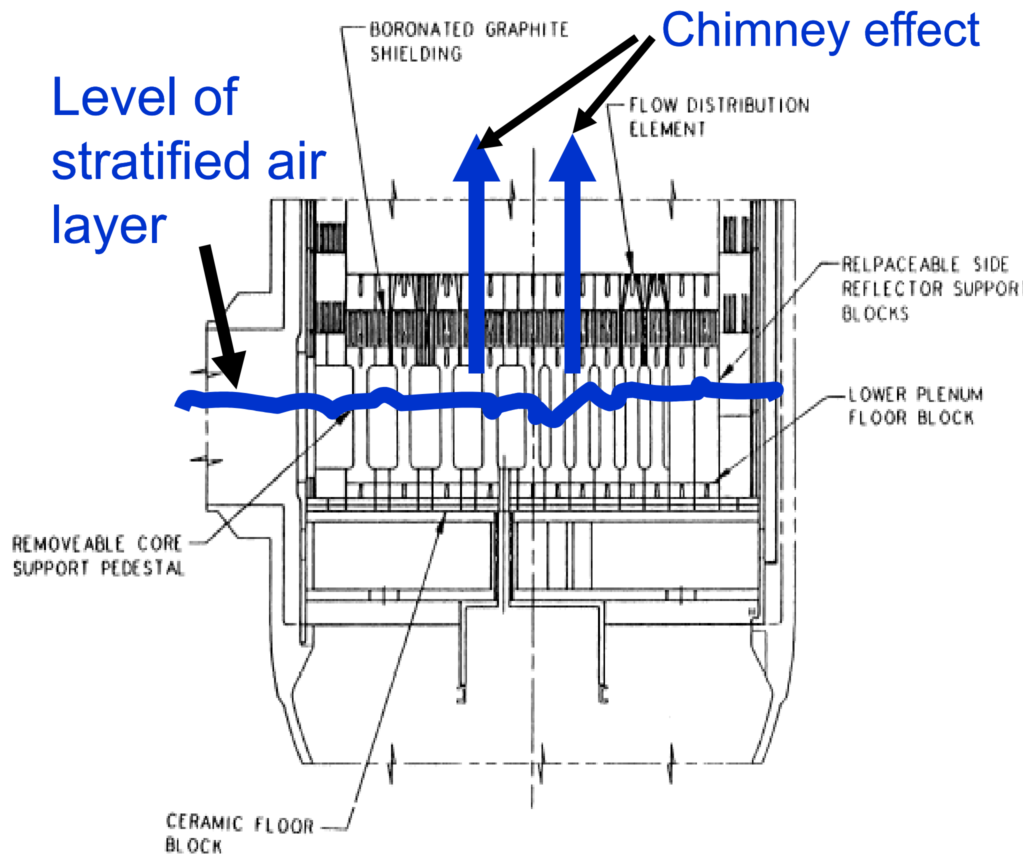
- Size and orientation of break; horizontally-oriented pipe is ideal for stratified flow.
- Volume of confinement and quantity of air in confinement
- Ratio of reactor vessel volume to confinement volume
- Operational conditions of reactor vessel when break occurs, e.g., quantity and energy level of helium

Air Ingress Scenario—Key Variables for Air Entry During Stratified Flow Phase (cont)

- Head of gas volume in confinement, i.e., relative hydrostatic heads in confinement vs. reactor vessel
- Confinement relief valve (blowout panels) characteristics, i.e., lift pressure, leakage, etc
- Temperature of graphite that interacts with incoming air
- Type of graphite (nonnuclear graphite used in Ft. St. Vrain lower plenum—and it is more reactive than nuclear-grade).

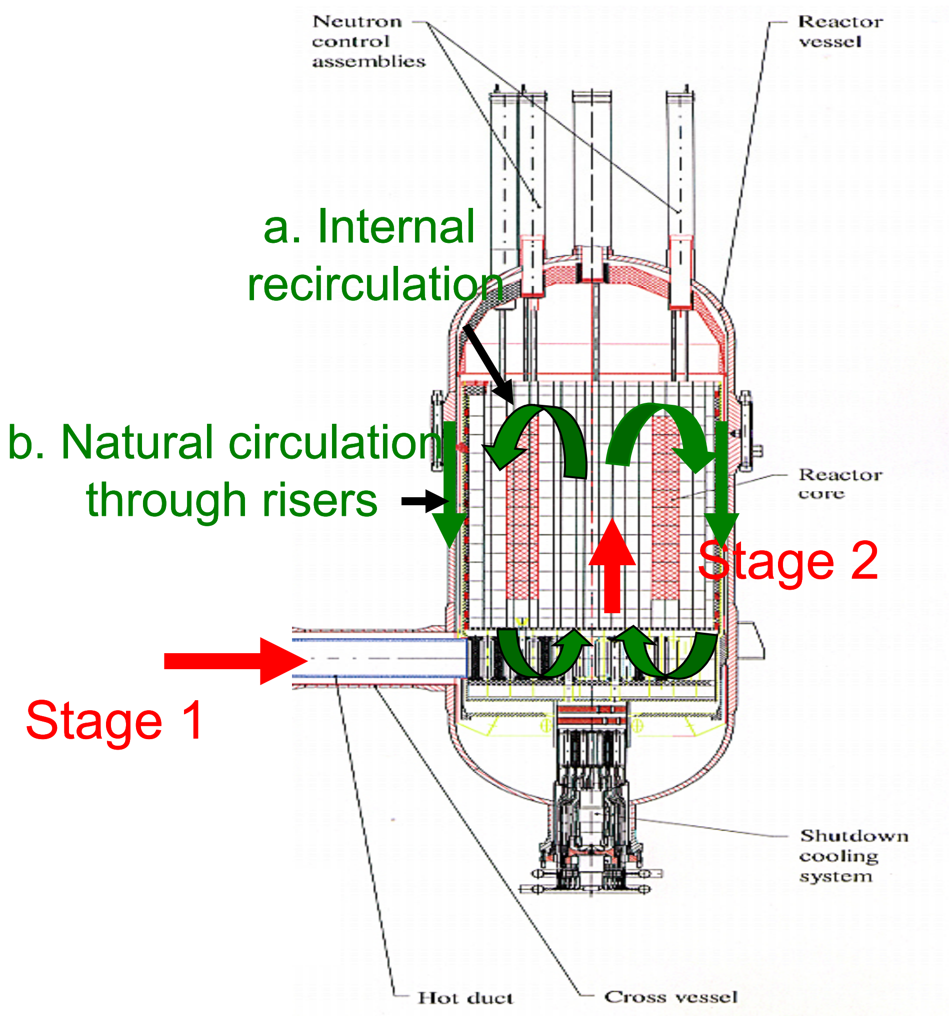
Air Ingress Scenario—Considering Stratified Flow—Stage 2

- Air entering reactor vessel is heated via contact with extremely hot graphite surfaces
- Momentum imparted to air via exothermic oxidation reaction in lower plenum and heating
- Lower density air and oxidation products are drawn into core via chimney effect



Air Ingress Scenario—Considering Stratified Flow—Stage 2 (cont)

- Sufficient air intrudes into core that natural circulation begins:
  a. Within the reactor vessel itself and/or
  b. From lower plenum to upper plenum to risers and then out into confinement.
- Quasi-steady-state pressure balance (equal hydrostatic heads) achieved between confinement and reactor vessel



Key Considerations that Affect Initiation of Natural Circulation…

- Level of air layer that has moved into lower plenum: The level is dictated by friction balanced against manometric head between conditions in confinement and lower density gases in lower plenum and core.

- Natural circulation of the air layer: It will be induced by heating from hot structures and environmental heat losses considering the buoyancy forces. Also of potential importance is the oxidation reaction and the potential to impart momentum to the contact gases.

- Natural circulation of the helium: The chimney effect, caused by heating of the helium will draw gases into the core from the lower plenum. Air near the lower reflector will be drawn into core.

Chang will Quantify Stages 1 & 2 for a Small Leak & DEGB scenario…

- By giving:
  - A comparison of a hand calc to some of the CFD output.
  - Give relative magnitudes of manometric heads and time scales.

NGNP Technology Integration Review Process Meeting
March 31, April 1, 2009

Current INL R&D Activities on VHTR-Air-Ingress Accident Analysis

Presented by
Chang Oh

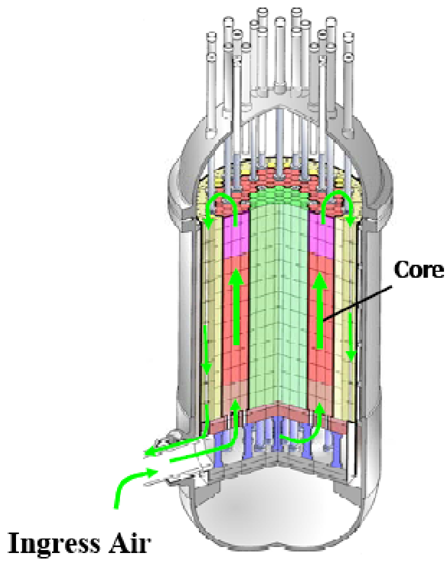
Overview

1. *Introduction*
2. *Past Understanding on Air-ingress Accident Scenario*
3. *Current Understanding on Air-ingress Accident Scenario*
4. *Density- Gradient Driven Stratified Flow*
5. *Analytical Models: Qualitative Understanding*
6. *CFD Simulations (2-D and 3-D): Quantitative Assessment*
7. *Summary*

2. Past Understanding on Air-ingress Scenario

Most of the previous analyses to date are based on the molecular diffusion dominated air-ingress scenario.

" GA-911128 [2008], Reactor containment, Embedment depth, and Building Functions Study"

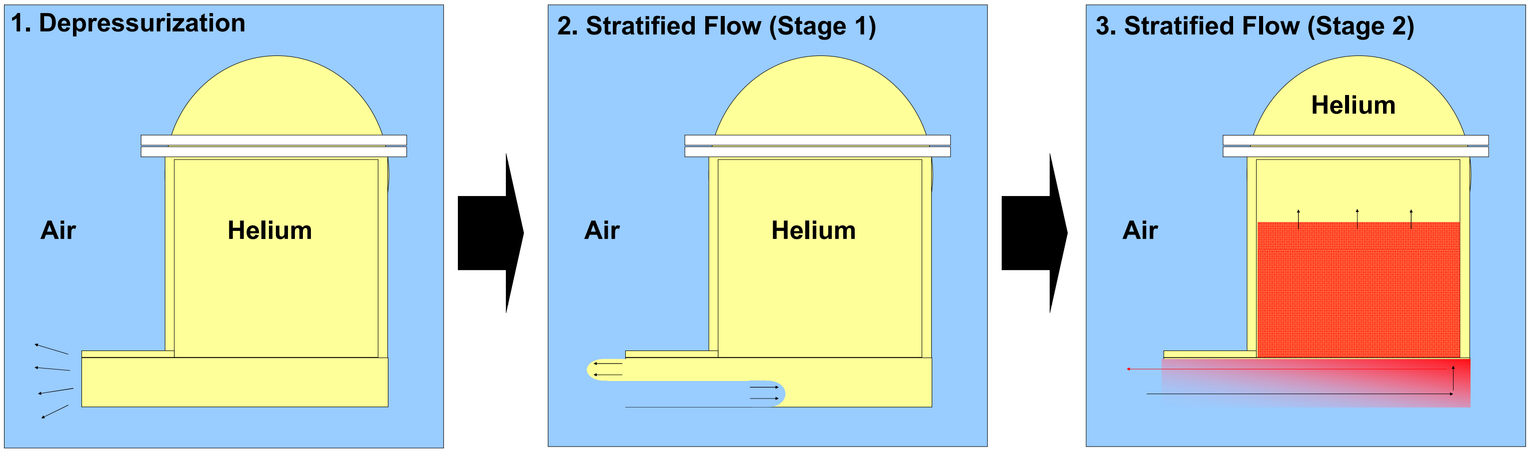


Path of air ingress due to natural circulation

- 1st Phase – Rapid Depressurization
  - Pressure balances between inside and outside of the RPV.
- 2nd Phase – Molecular Diffusion
  - The air enters the RPV gradually by molecular diffusion. Graphite oxidation during this phase is negligible.
- 3rd Phase – Natural Circulation
  - Natural circulation eventually established after air concentration in the RPV becomes sufficiently large.

3. Current Understanding on Air-ingress Scenario

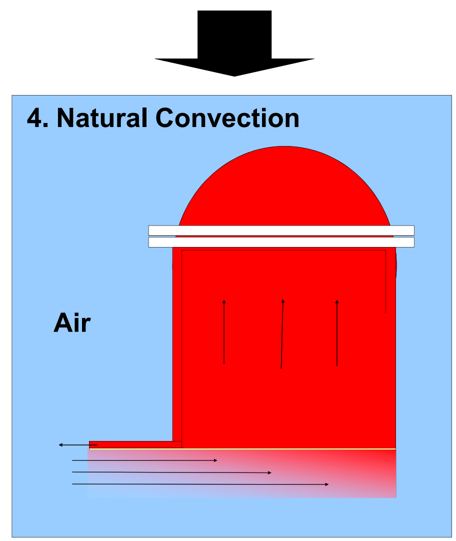
Density gradient between reactor inside and outside will drive convective flow much faster than molecular diffusion in GT-MHR



Stratified Flow

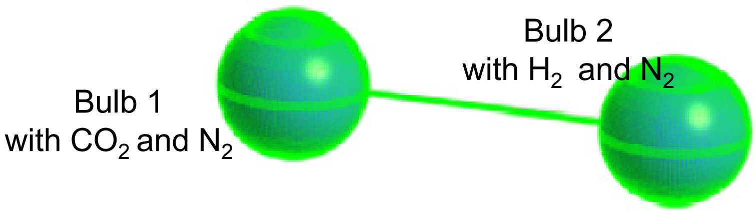
Stage-1: *Initially density gradient is driven by a factor of 26 and temperature (25^0 C vs. 900^0 C (750^0 C considered later).*

Stage-2: *Air moves up into the reactor core and initiates the Onset of Natural Convection.*



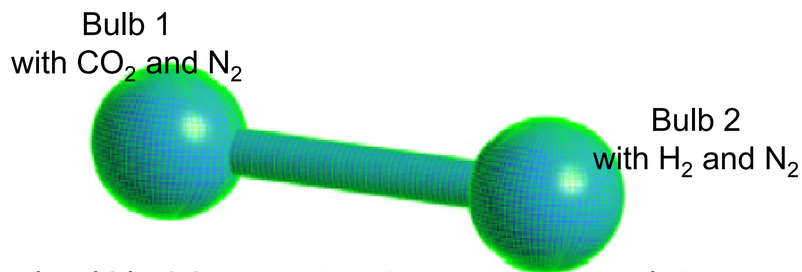
3. Current Understanding on Air-ingress Scenario Dependent on Geometry (Cont.)

Molecular diffusion experiments conducted by Duncan & Toor using a 2 mm tube were compared with CFX Code simulations with a 2 mm tube and a 16 mm tube.



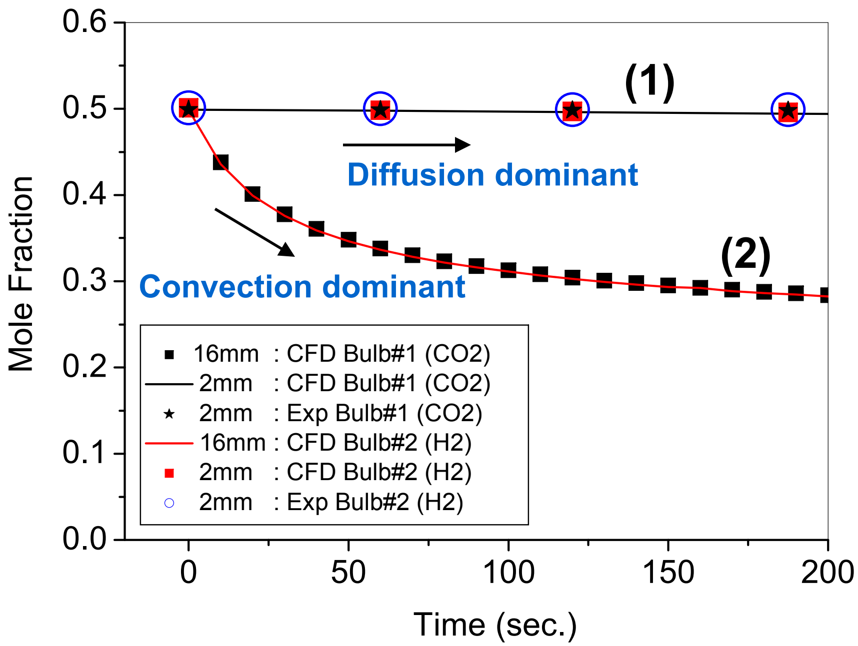
(1) 2 mm horizontal pipe (exp. & sim.)

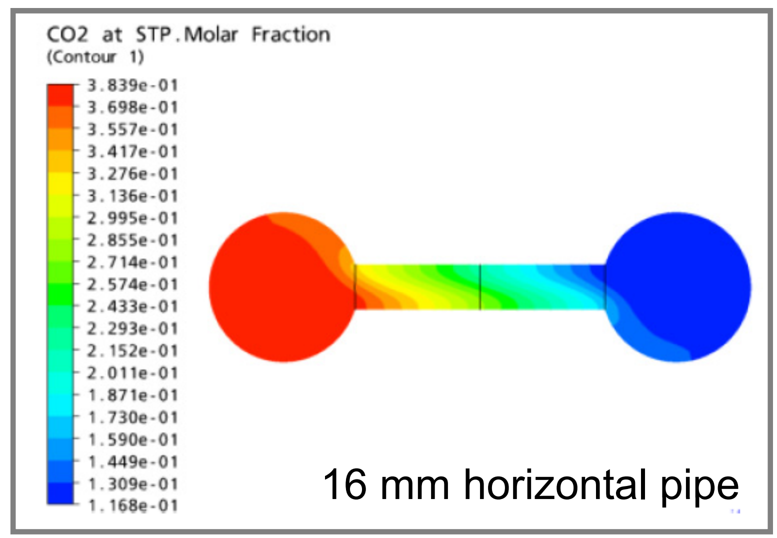
L/D = 44.5



(2) 16 mm horizontal pipe (sim. only)

L/D = 5.5





4. Density Gradient Driven Stratified Flow

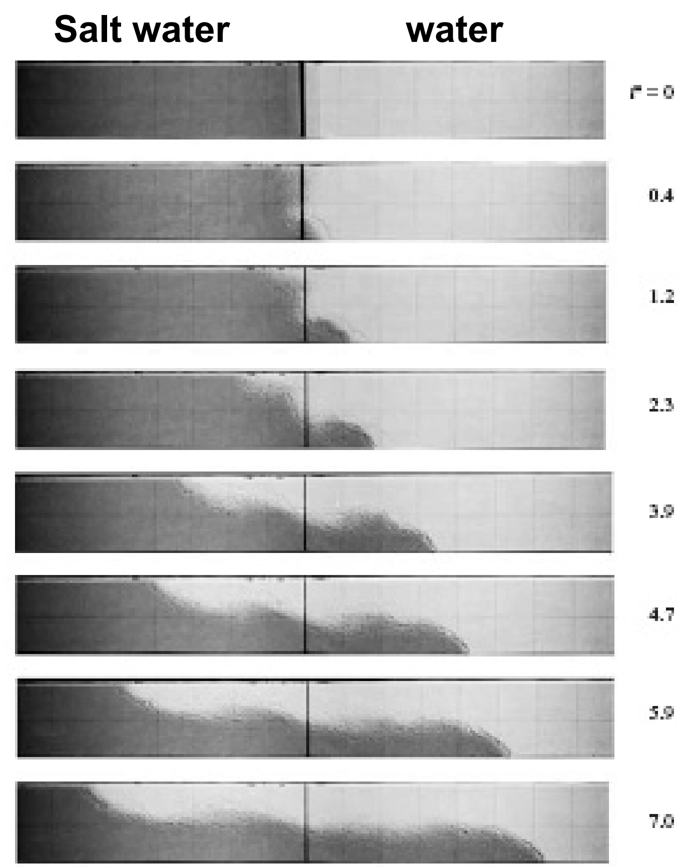
Stratified Flow

- Density-gradient stratified flow known as gravity current can happen when a heavy fluid intrudes into lighter fluid.

- After depressurization, a large density gradient exists between reactor inside (Helium) and outside (Air).

- The gravity current flow can accelerate the air-ingress process.

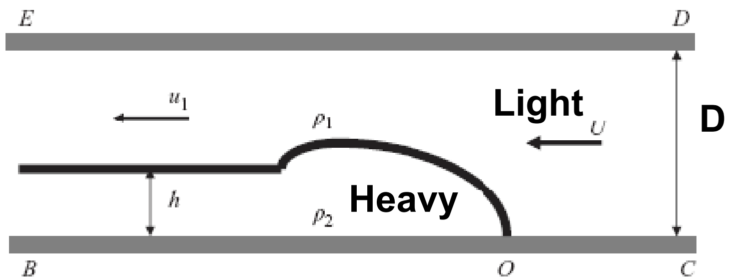
- Density gradient driven flow is very common phenomena which can be observed in the PWR.

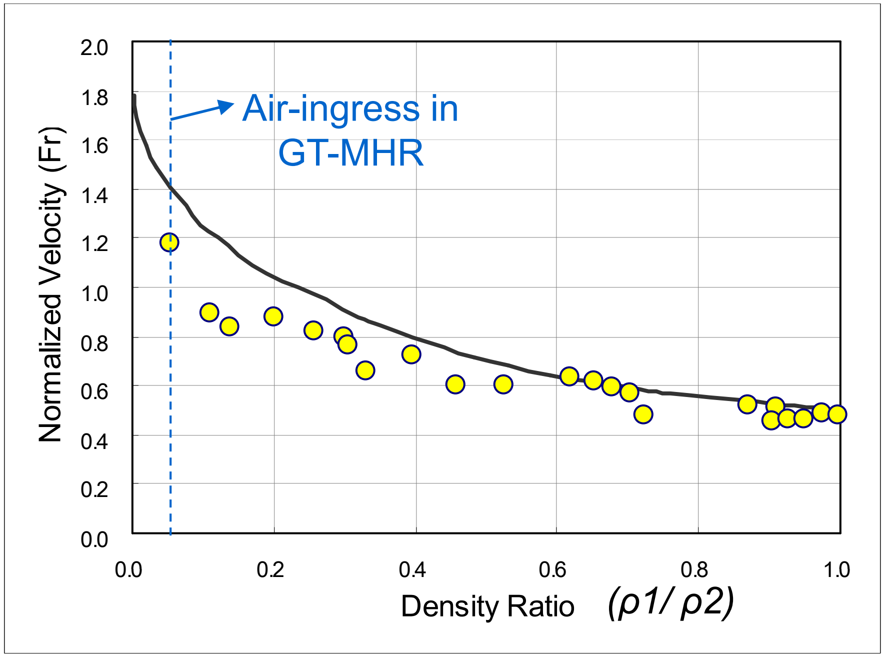


Density gradient driven stratified flow experiment with a lock gate (Shin et al. [2004])

5. Analytical Estimation on Stratified Flow

Air velocity to the lower plenum was estimated from Lowe's gravity current experiment.



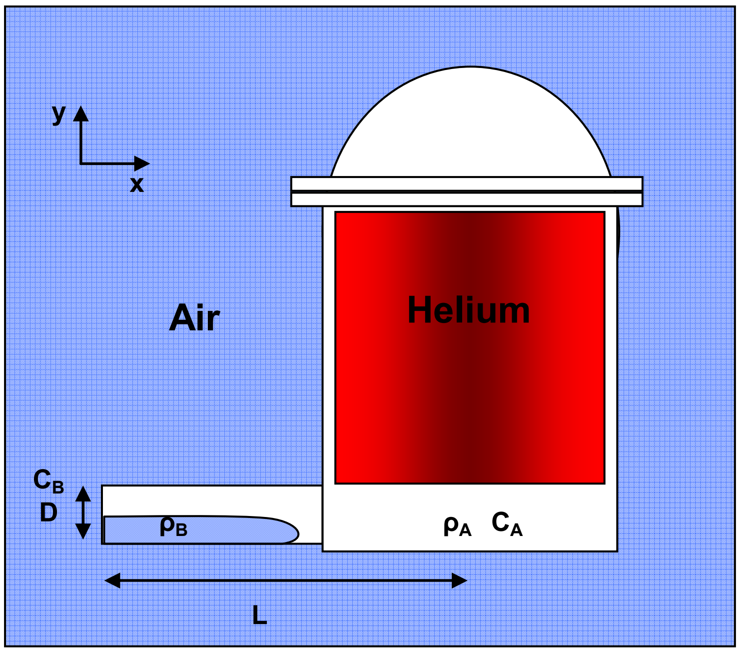


5. Analytical Estimation on Stratified Flow (Cont.)

Time-scale Comparisons in Stage 1

Time-scales of stratified flow and diffusion were compared to determine the dominant process.

Stage 1. Stratified Flow
by Air and Helium Density Differences



(1) Time-scale for stratified flow

$$U = \sqrt{(1-\gamma)gD}\left[\frac{1}{\gamma}\frac{h}{D}\left(2-\frac{h}{D}\right)\frac{1-h/D}{1+h/D}\right]^{1/2}$$ (Lowe et al. [2005])

$$U_x = \frac{U \cdot h}{D} = 0.21\, m/s \qquad (U = 5.27 m/s)$$

$$\Delta t_{gc} \sim L_1 / V = 3.4\, m / 0.21\, m/s = 19.5 \sec$$

(2) Time-scale for diffusion

$$D_{AB} = \frac{18.58 \cdot T^{3/2}\left[\frac{1}{M_A}+\frac{1}{M_B}\right]}{P \cdot \sigma_{AB}{}^2 \Omega_D}$$

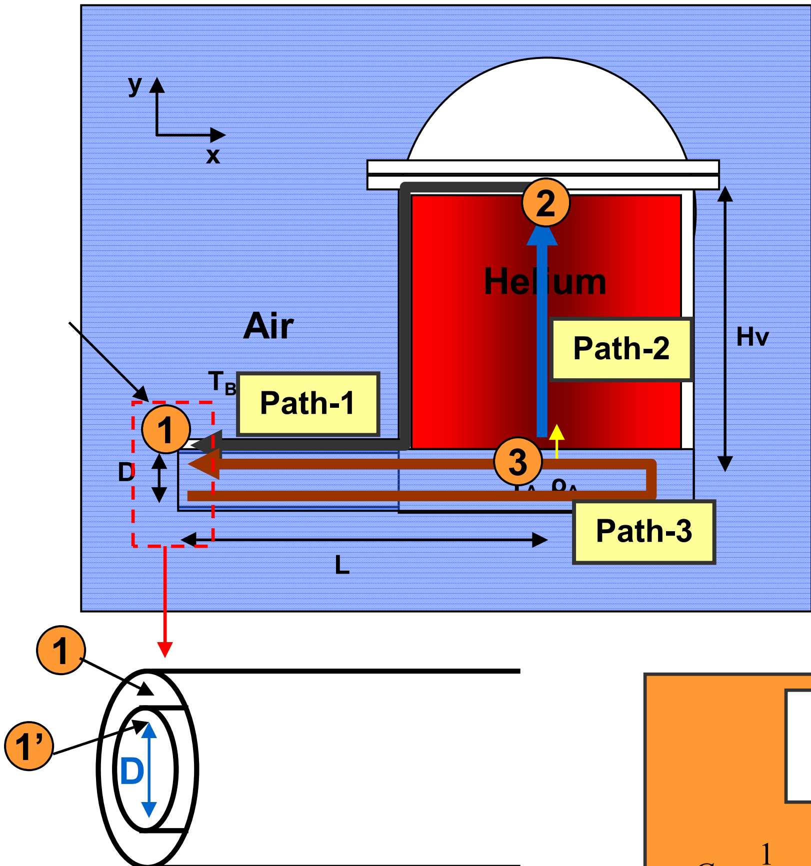
$$\left(\frac{C_{Air}(z,t) - C_{Air,0}}{C_{Air,s} - C_{Air,0}}\right)_{average,LowerPlenum} = \frac{1}{D_{LP}} \int_{LowerPlenum} 1 - erf\left(\frac{z}{2\sqrt{D_{AB}t}}\right) \cdot dz$$

$$t = \Delta t_d = 1.29 \times 10^4 \sec$$

In the Stage 1, time-scale of the stratified flow is much smaller than that of diffusion so that the diffusion can be neglected.

5. Analytical Estimation on Stratified Flow (Cont.)

Momentum Conservation in Stage 2



Path-1 (from point 2 to point 1)

$$P_2 - P_1 = \frac{1}{2}\rho_1 \cdot u_1^{\,2} - \frac{1}{2}\rho_2 \cdot u_2^{\,2} - \rho_{riser} \cdot g \cdot H_v$$

Path-2 (from point 3 to point 2)

$$P_3 - P_2 = 32\frac{\mu \cdot u_{core} \cdot H_v}{d^2} + hydrostatic\ head$$

Path-3 (circulation in the lower plenum)

$$P_1' - P_3 = \frac{1}{8}\rho_3 \cdot \left(\left(1-\gamma\right)\cdot g \cdot D\right)\cdot\left(\frac{1}{\gamma^3} - 1\right)$$

P_1' is assumed to be the same as P_1 at the break point.

$$C_1 \cdot u_2^{\,2} + C_2 \cdot u_2 + C_3 = 0$$

$$C_1 = \frac{1}{2}\rho_2 \cdot \left(\left(\frac{A_2}{A_1}\right)^2 - 1\right) \qquad C_2 = 32\frac{\mu \cdot H_v}{d^2}$$

$$C_3 = \frac{1}{8}\rho_3 \cdot g \cdot D \cdot (1-\gamma)\cdot\left(1 - \frac{1}{\gamma^3}\right)\cdot \eta + (\rho_c - \rho_A)\cdot g \cdot H_v$$

U_2: Flow Velocity in the Core

5. Analytical Estimation on Stratified Flow (Cont.)

Criteria for Stage 2

Stage 2 - Stratified Flow

- Temperature gradient drives cold air into the lower plenum.
- Cold air expands in the lower plenum by heating.
- If the pressure build-up by the expansion is larger than the static head of the core, air can move into the core.

dP > Static Head : Convection Dominant
dP < Static Head : Diffusion Dominant

Pressure Build-up [Pascal]:

$$dP = \frac{1}{8}\rho \cdot ((1-\gamma) \cdot g \cdot D) \cdot \left(\frac{1}{\gamma^3} - 1 \right)$$

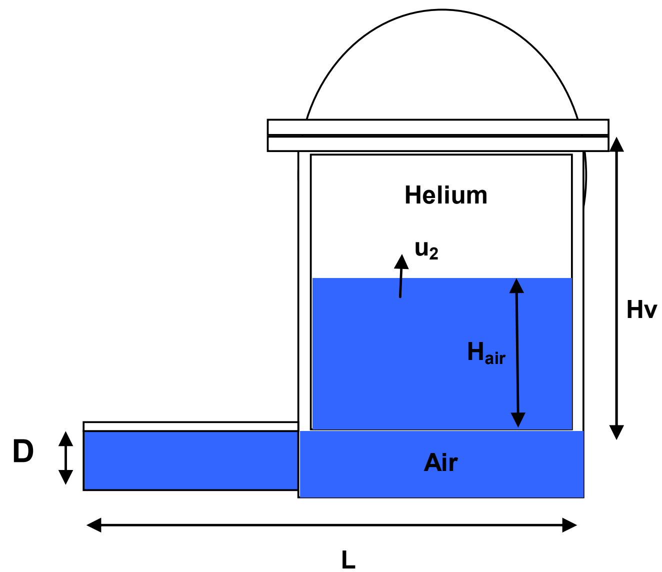
Static Pressure [Pascal]:

$$Static\ Head = (\rho_{core} - \rho_{riser}) \cdot g \cdot H_v$$

	GT-MHR	NACOK
Air Density Ratio (γ)	*0.253*	*0.323*
Pipe Diameter (D)	*1.5 m*	*0.125 m*
Core Height (H_v)	*11 m*	*7.334 m*
Pressure Build-up (dP)	*24.18 Pa*	*1.101 Pa*
Static Head	*10.01 Pa*	*9.6 Pa*

5. Analytical Estimation on Stratified Flow (Cont.)

Time-scale Comparisons in Stage 2

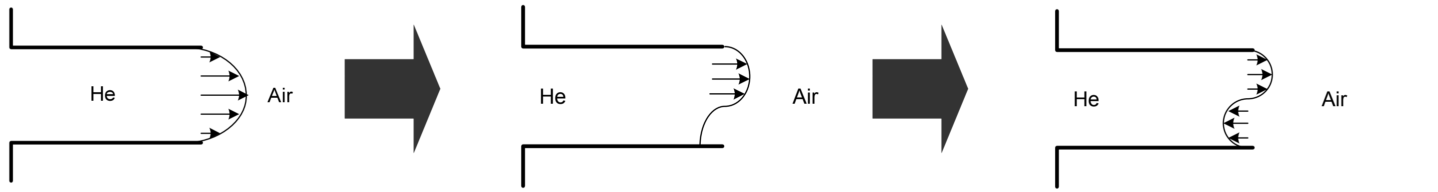


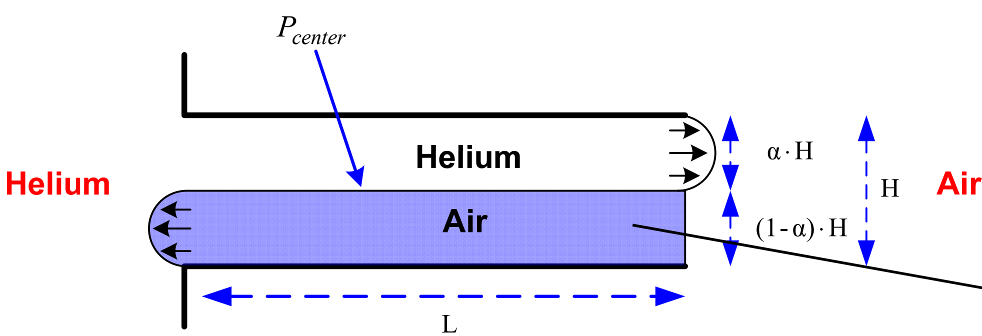
Calculation of timescales for GT-MHR (Stage 2)

	GT-MHR 600 MWt
Channel Depth (D) (m)	1.5
Core Height (Hv) (m)	11
Average core flow velocity (m/s)	**0.26**
Convection Timescale (tc) (sec) (within H_{air})	42
Diffusion Timescale (td) (sec)	2.70e4
td / tc	**642**

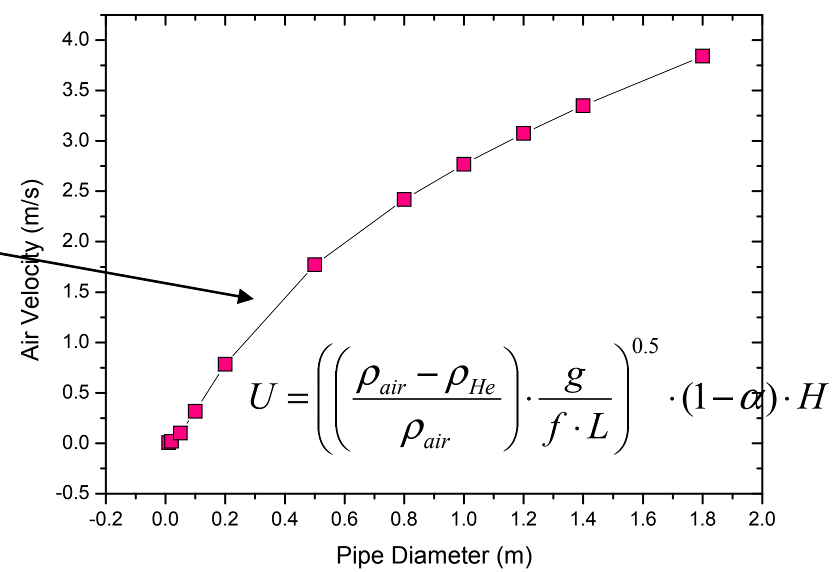
5. Analytical Estimation on Stratified Flow

(1) Depressurization ***(2) Onset-of Flow*** ***(3) Density-driven Flow***





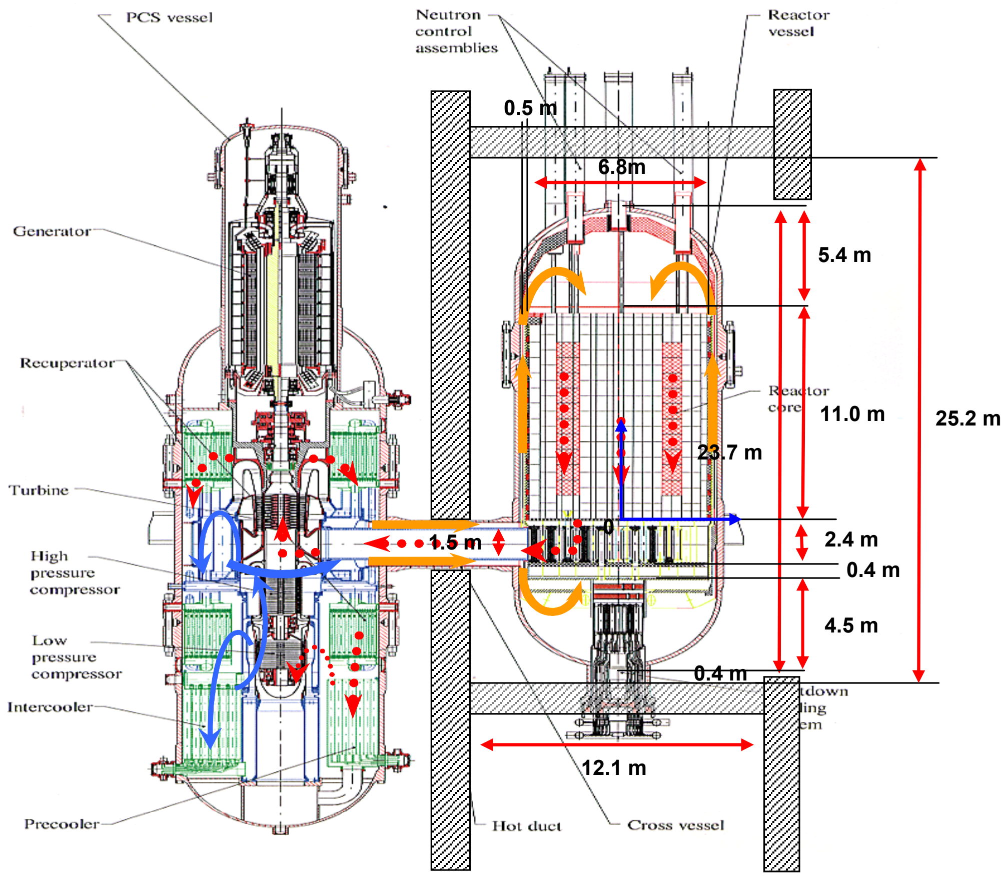
Air ingress velocities by density driven flow



$$U = \left(\left(\frac{\rho_{air} - \rho_{He}}{\rho_{air}} \right) \cdot \frac{g}{f \cdot L} \right)^{0.5} \cdot (1-\alpha) \cdot H$$

6. CFD Simulations for Air-ingress Accident
- Double Ended Guillotine Break

In the previous 1-D/2-D/3-D air-ingress analyses by other researchers, interactions between the confinement and the reactor vessel were not considered.

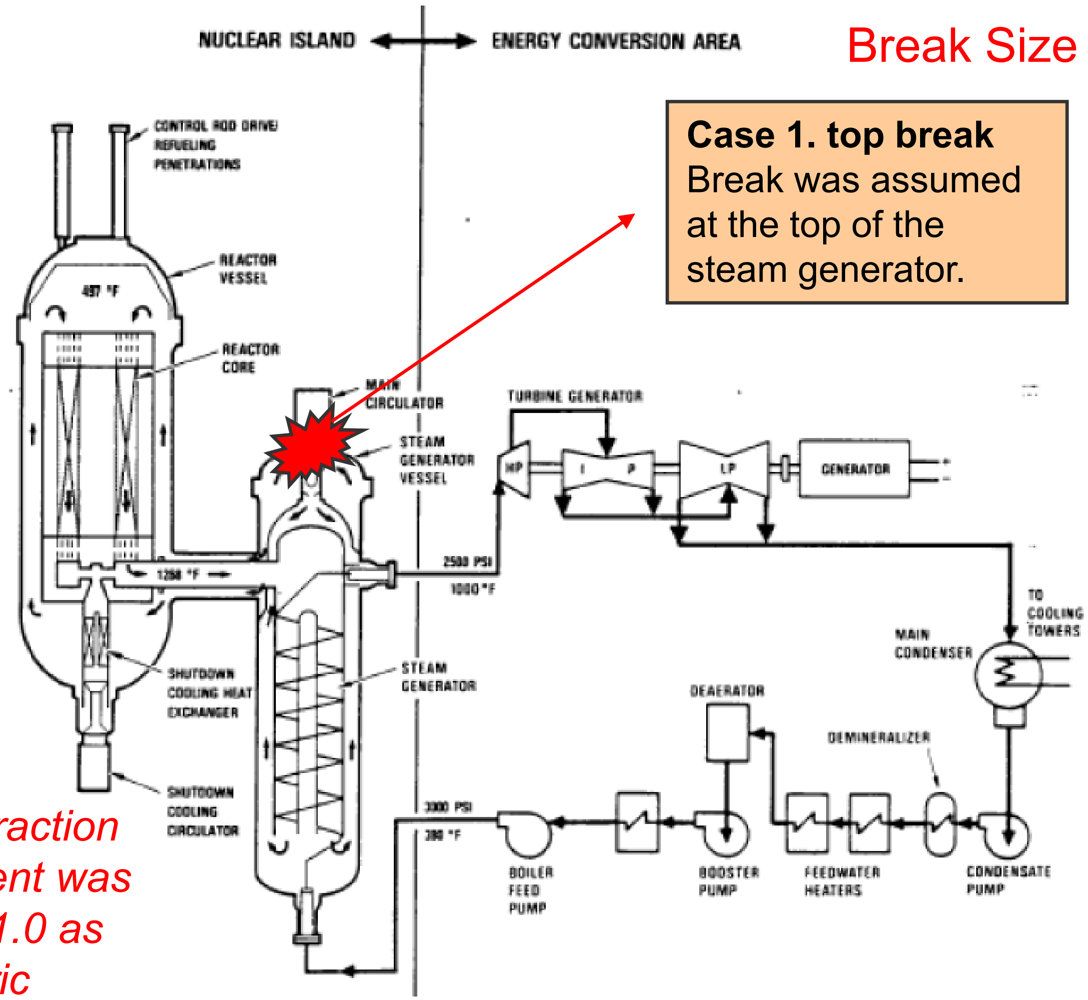


GT-MHR 600 MWt

6. CFD Simulations for Air-ingress Accident (Cont.)
- Small Break

Break Size = 86 cm^2

Case 1. top break
Break was assumed at the top of the steam generator.

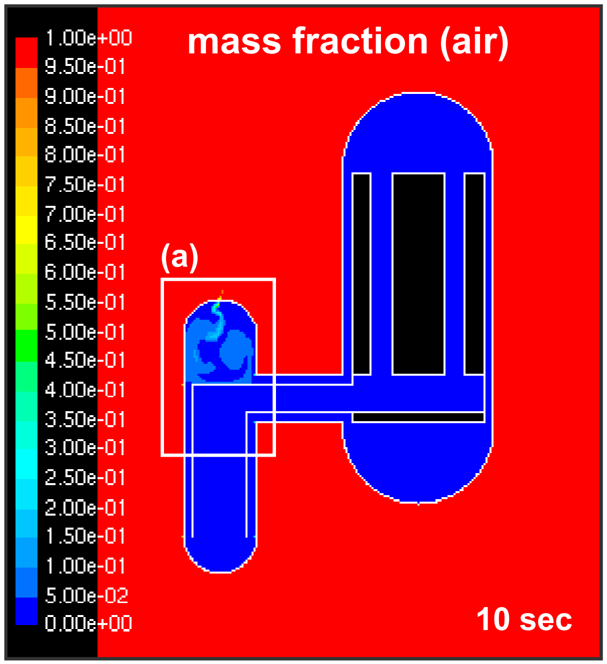


Initial air mass fraction in the confinement was assumed to be 1.0 as part of parametric studies

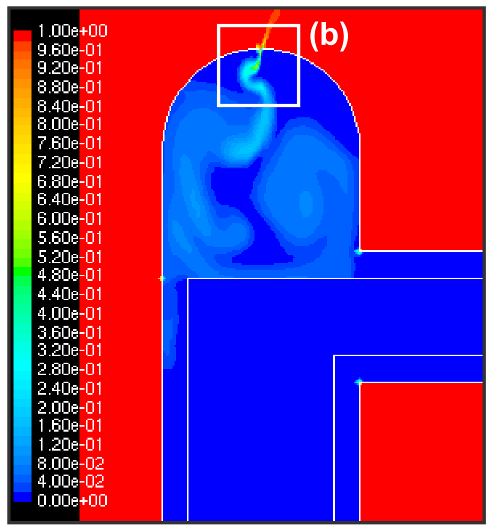
6. CFD Simulations for Air-ingress Accident (Cont.)

- Small Break (top break)- 2-D FLUENT CFD Model

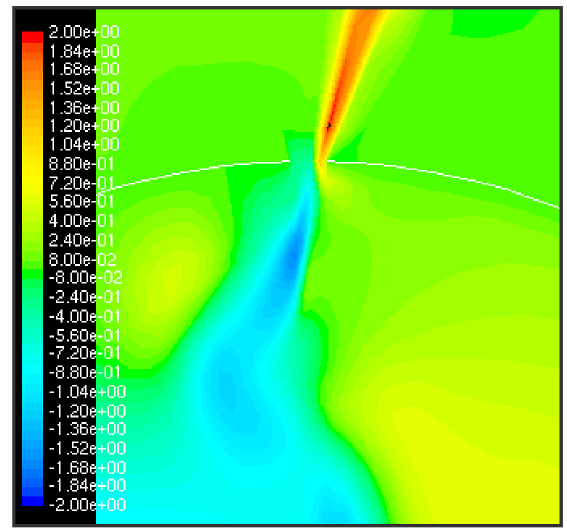
Flow was assumed to be laminar.



(a) air mass fraction



(b) y-velocity

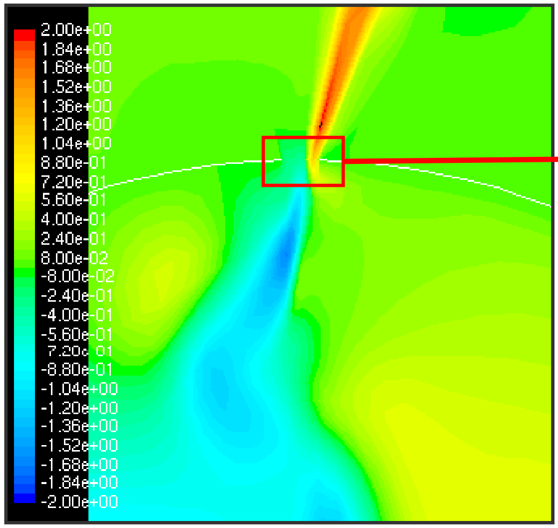


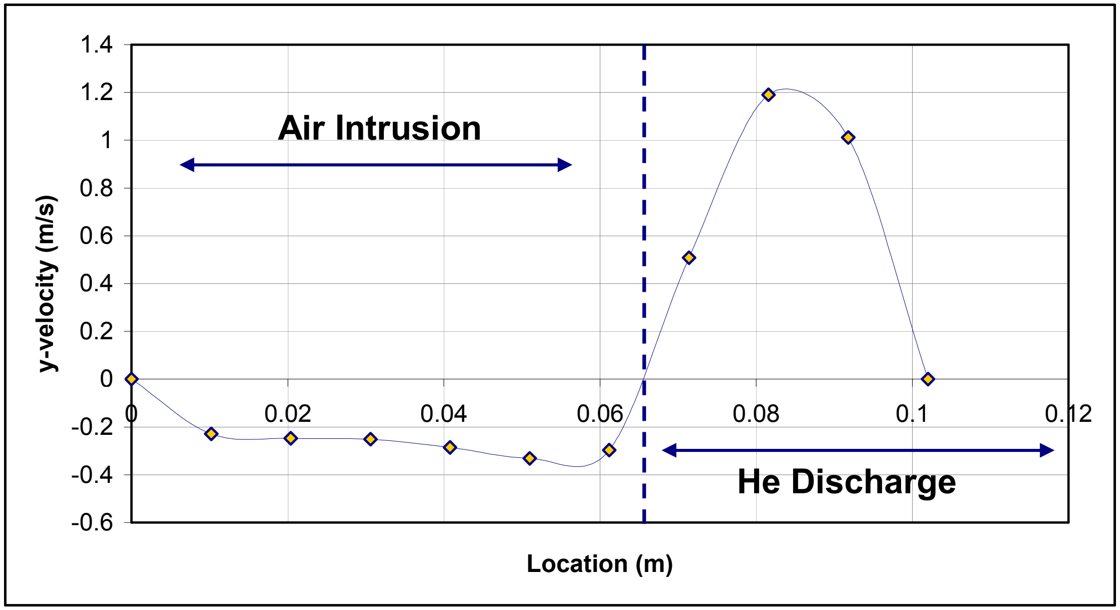
- Simulation was started after depressurization.
- Initial air mass fraction in the reactor outside was assumed to be 1.0 as a parametric scoping analysis. The air concentration depends on the size of the confinement.

6. CFD Simulations for Air-ingress Accident (Cont.)

- Small Break (top break)- 2-D FLUENT CFD Model

(a) y-velocity

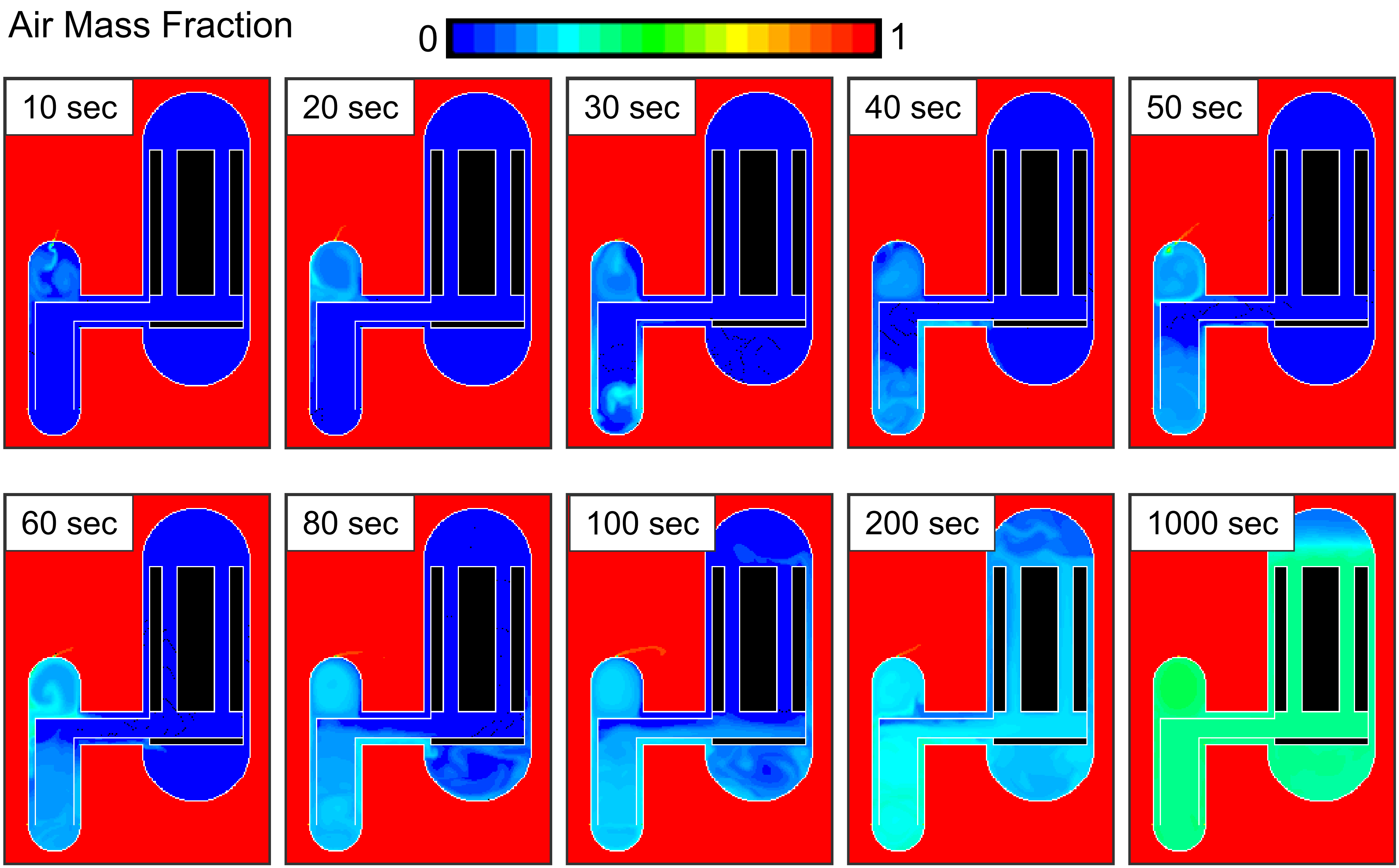




Flow velocity at the break location

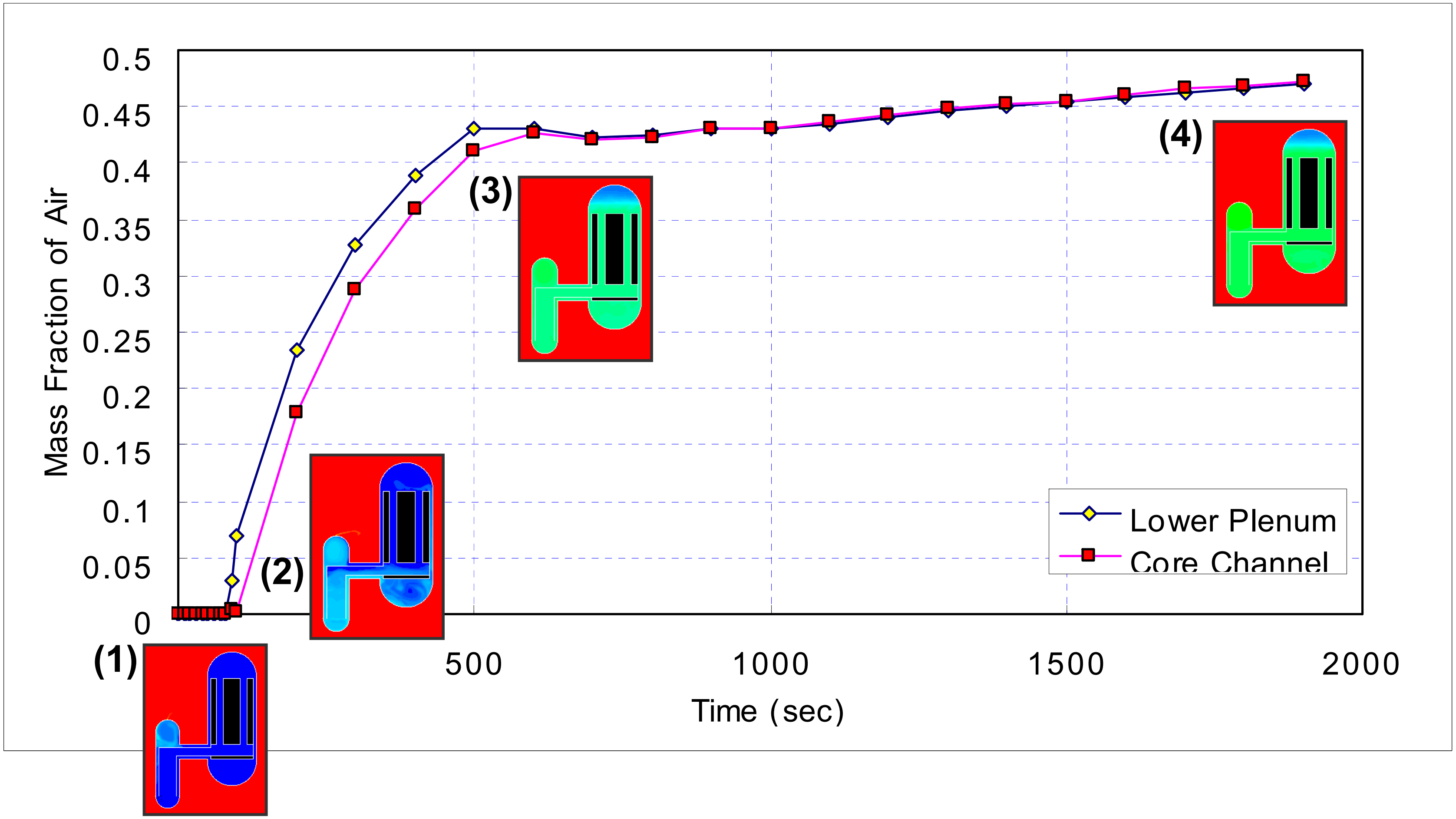
6. CFD Simulations for Air-ingress Accident (Cont.)

- Small Break (top break)

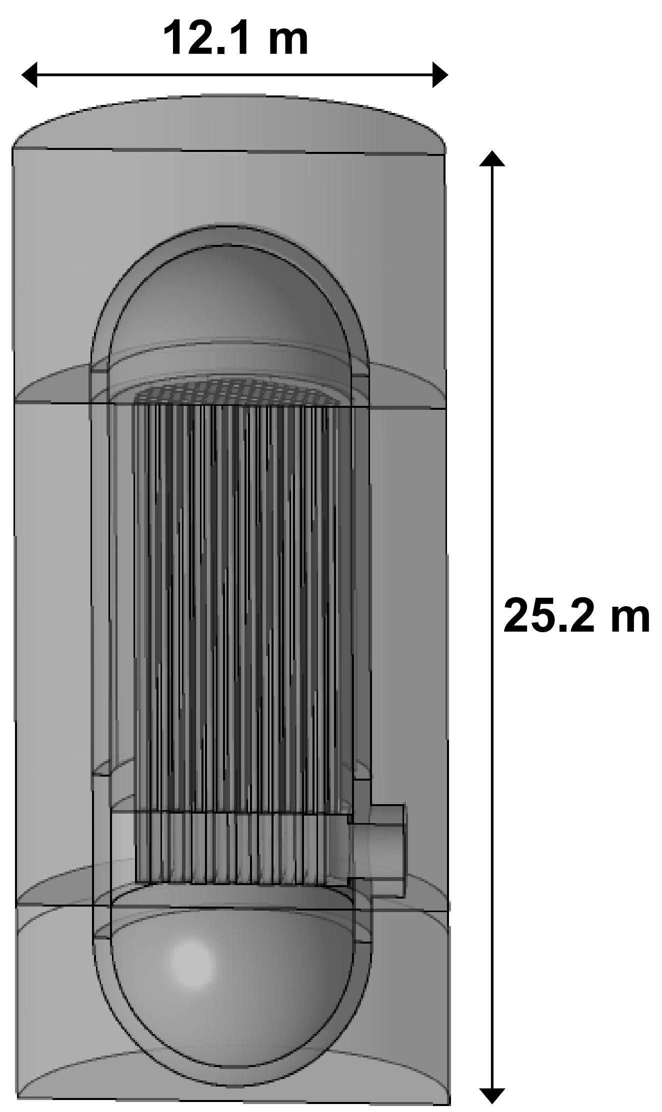


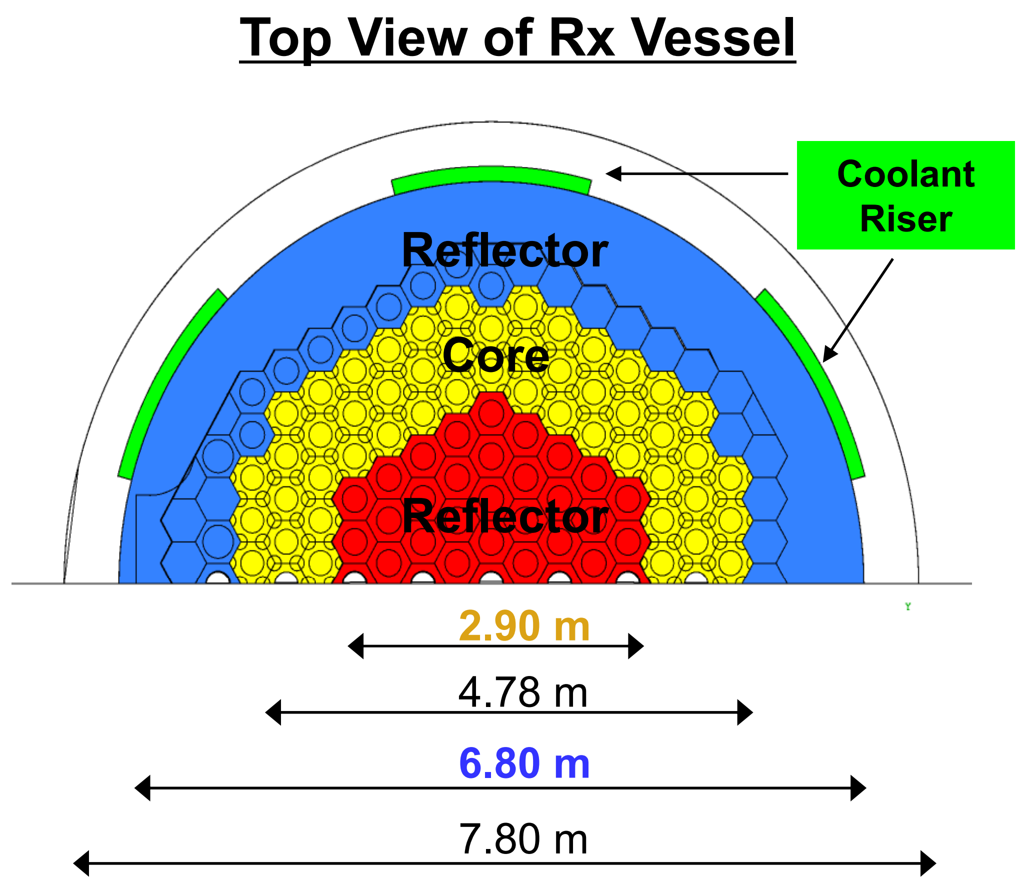
6. CFD Simulations for Air-ingress Accident (Cont.)
- Small Break (top break)

Average Air Mass Fraction in the Core and the Lower Plenum

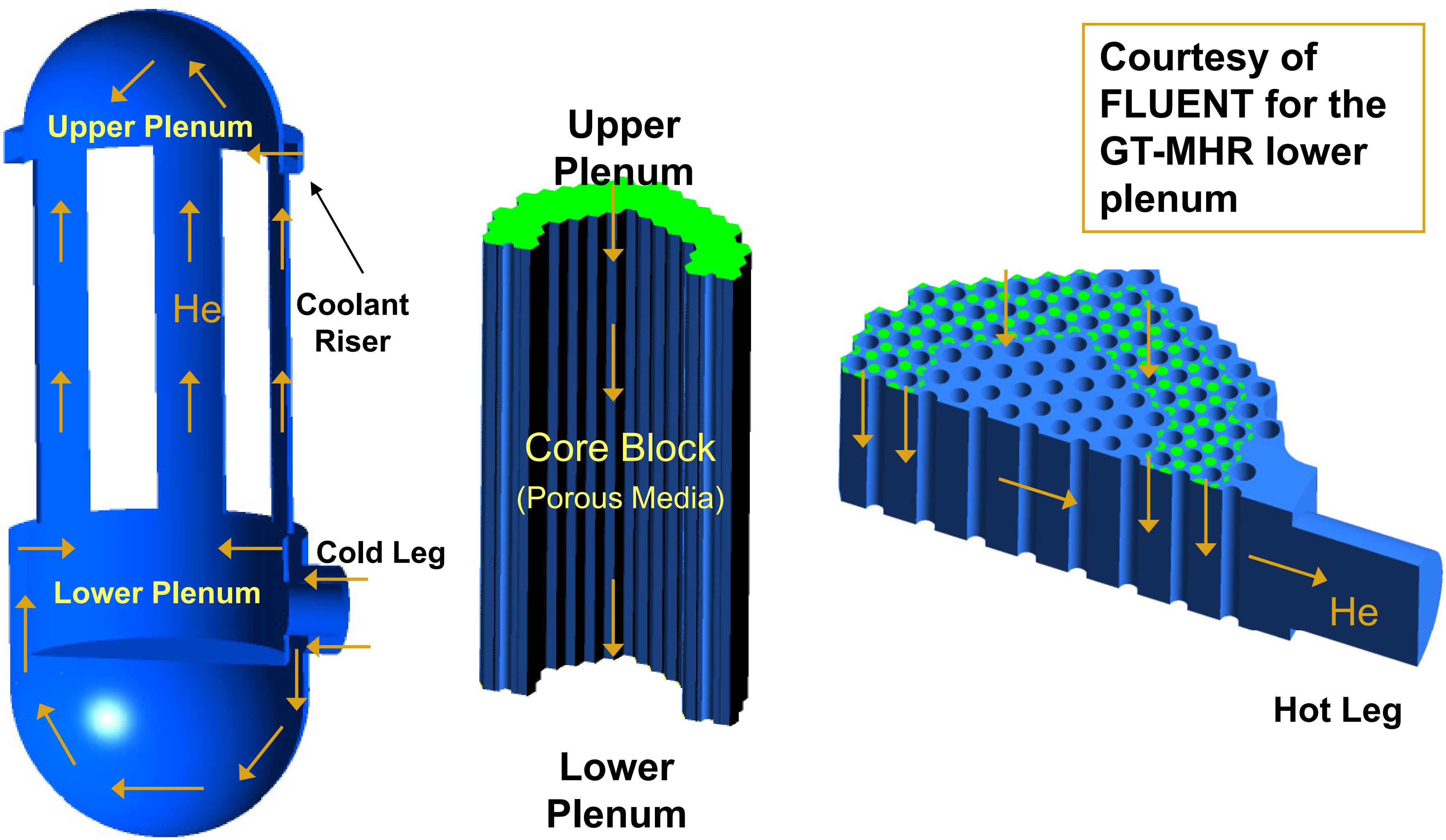


6. CFD Simulations for Air-ingress Accident (Cont.)
- DEGB (3-D Model)





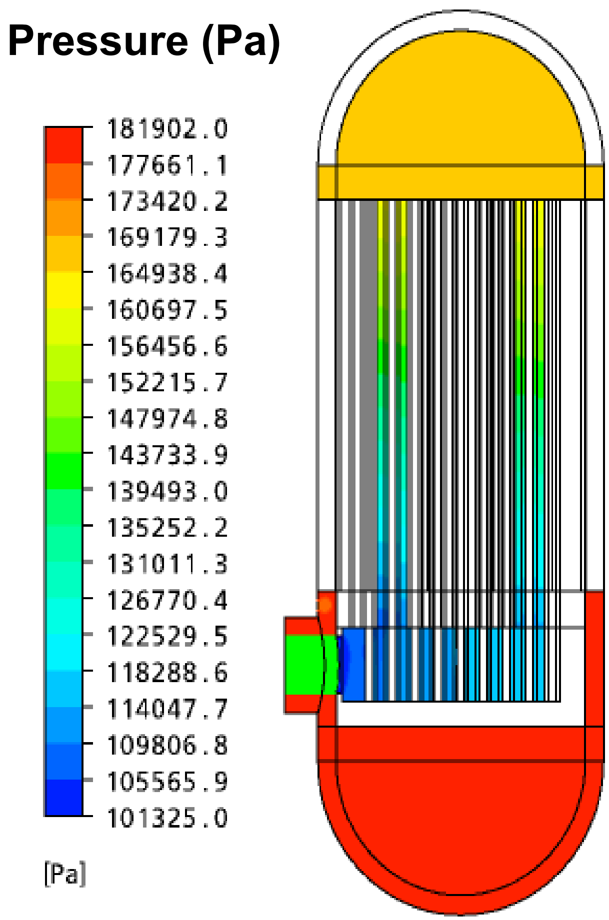
6. CFD Simulations for Air-ingress Accident (Cont.)
- DEGB (3-D Model)



6. CFD Simulations for Air-ingress Accident (Cont.)

- DEGB (3-D Model)

Comparison of core pressure drop to ensure the hydraulic resistance during normal operation: Design vs. CFX Calculation at steady-state conditions



Pressure Drop Results	Conceptual Design Data	CFX Results
In Rx Vessel (CL → HL)	71 kPa	78.8 kPa
Active Core	51 kPa	50.9 kPa

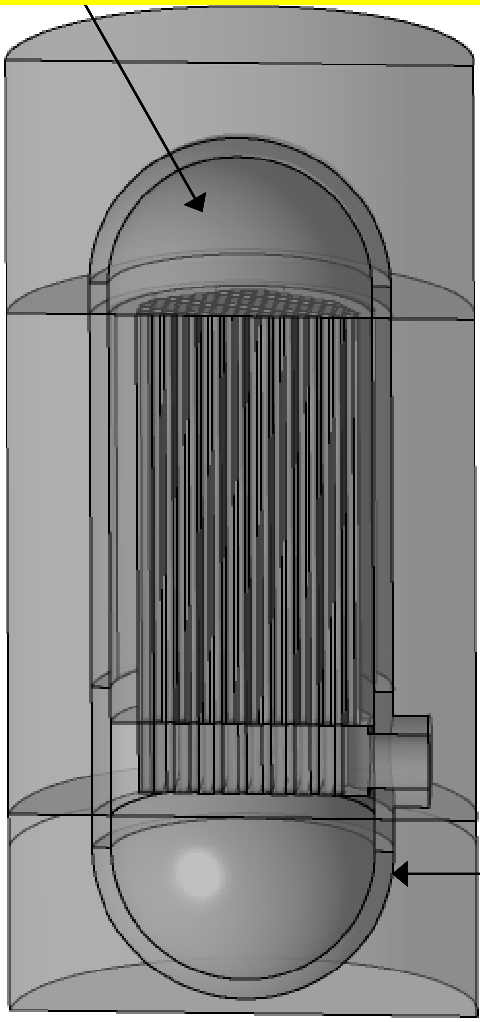
CFD Analysis Conditions

- He mass flow rate : 320 kg/s
- He temp. (inlet/outlet) : 500 / 900°C
- Porous condition in Core
  + Volume porosity : 0.185
  + Permeability : 9.706E-4 m^2
  + Resistance loss coefficient : 1.367 m^{-1}

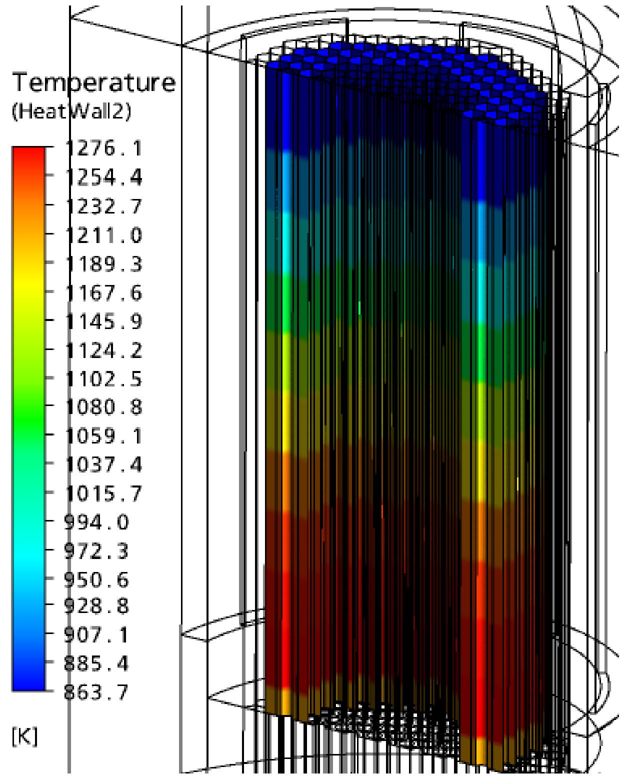
6. CFD Simulations for Air-ingress Accident (Cont.)

- CFX Version 12

Symmetry Condition (180º Plane)

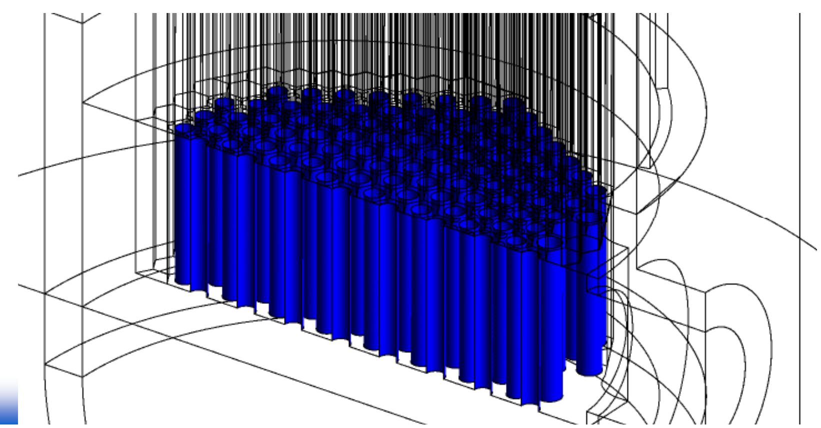


Wall Temp. of Rx Vessel Surface = 763 K

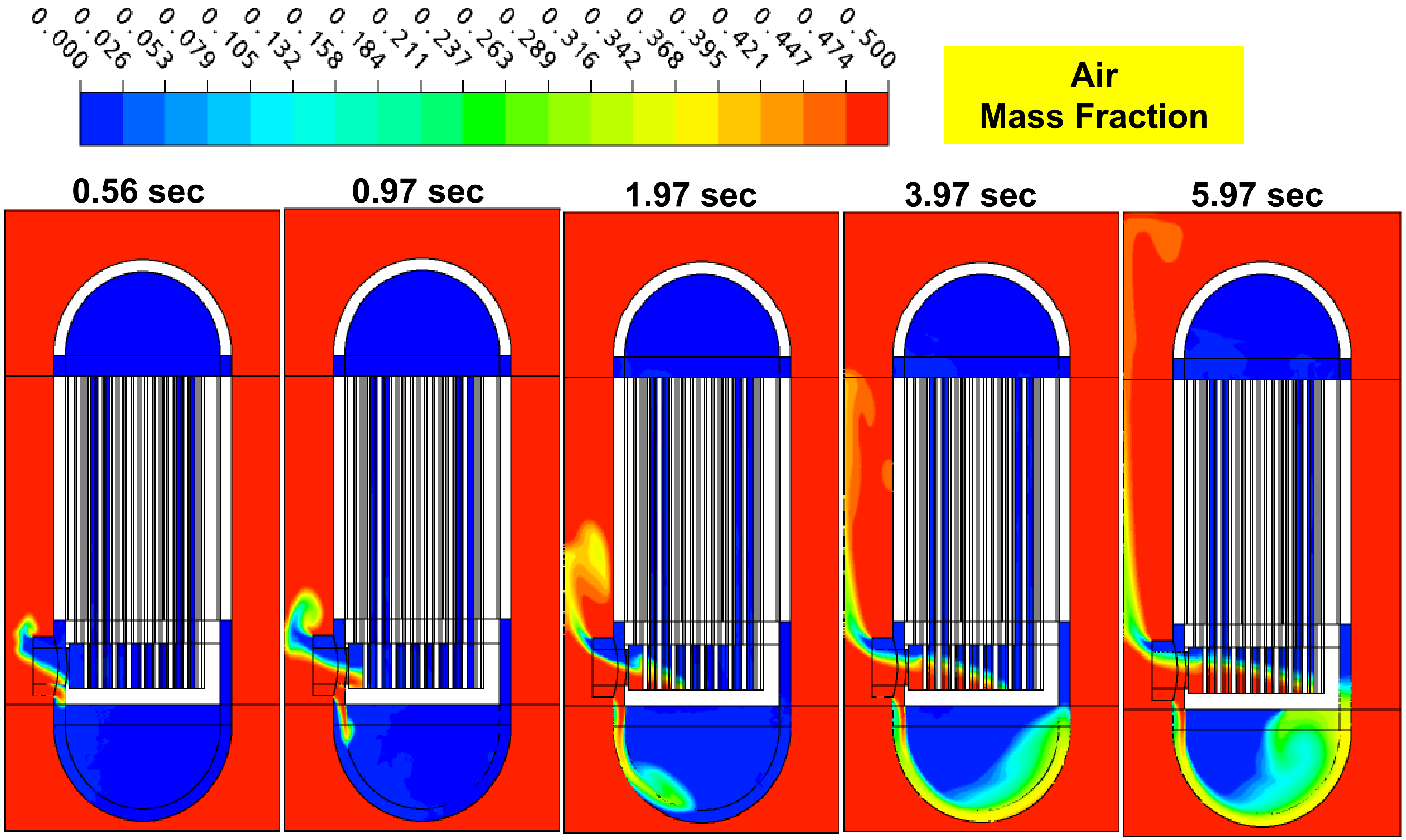


Wall Temp. of Core Block Surface = 863 ~ 1276 K

Wall Temp. of Support Block Surface = 900 K

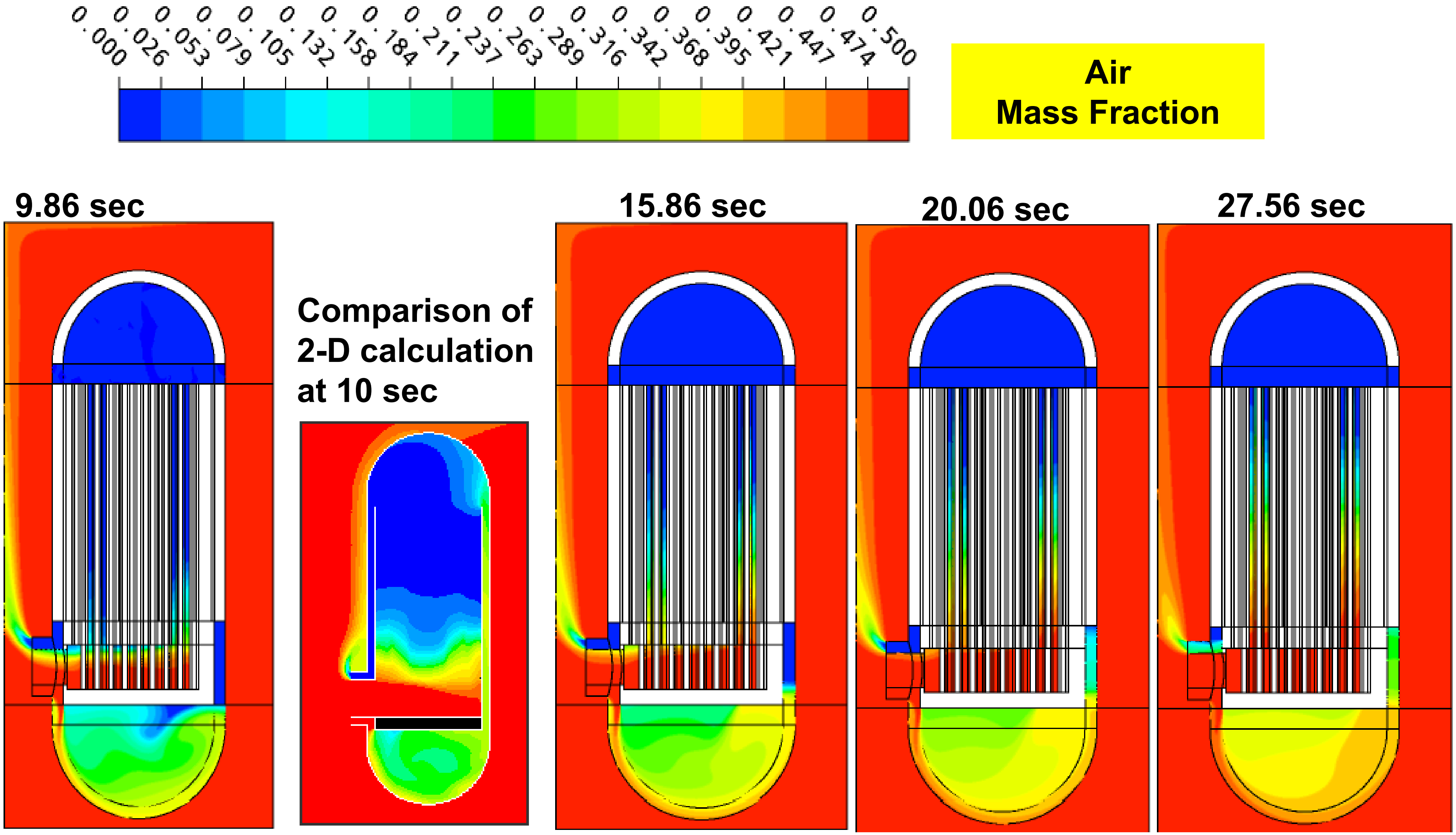


Air Ingress Accident – Results of Air Mass Fraction Calculations following Depressurization



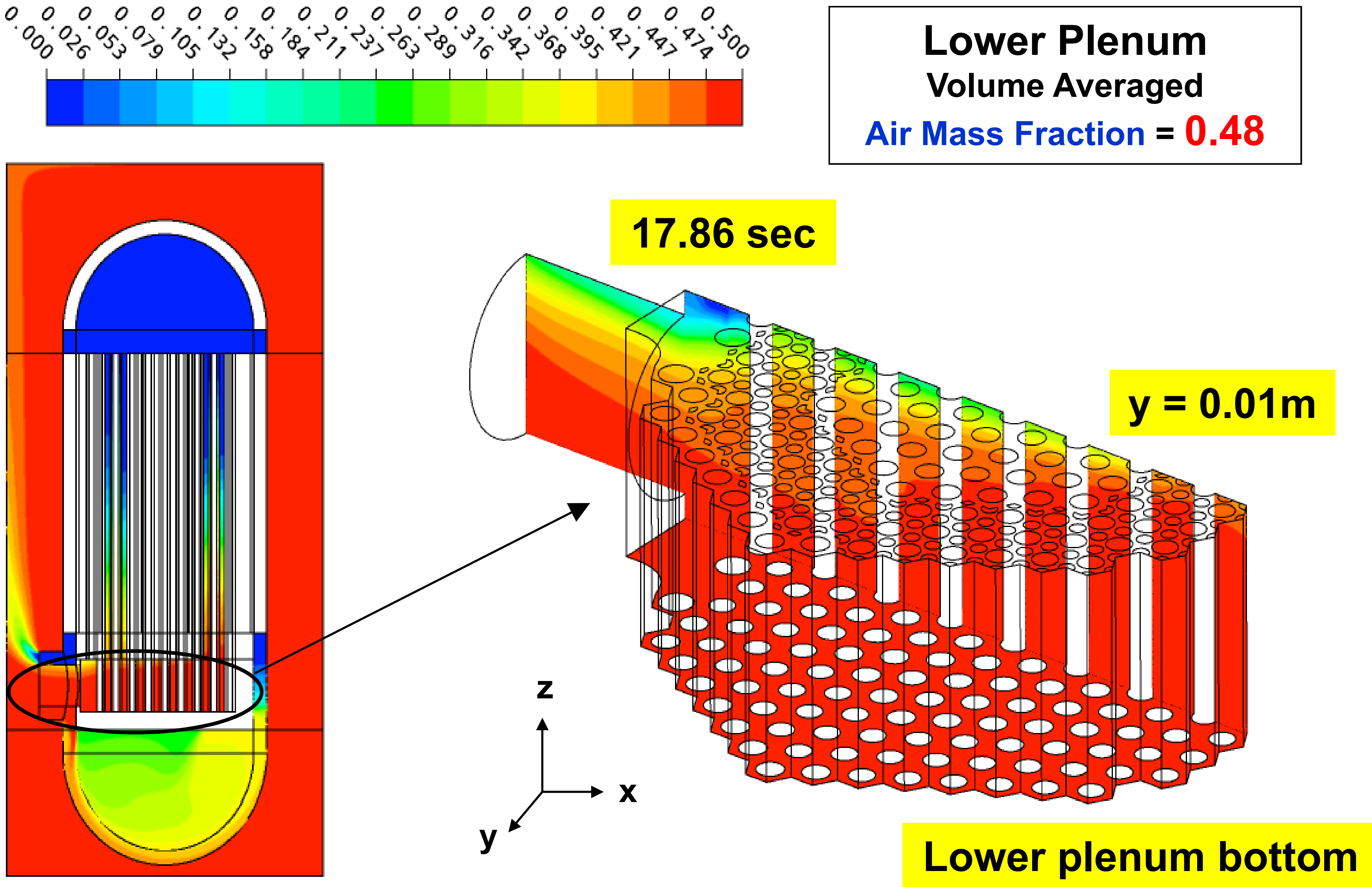
(*Contour on y = 0.01 m)

Air Ingress Accident – *Results of Air Mass Fraction*



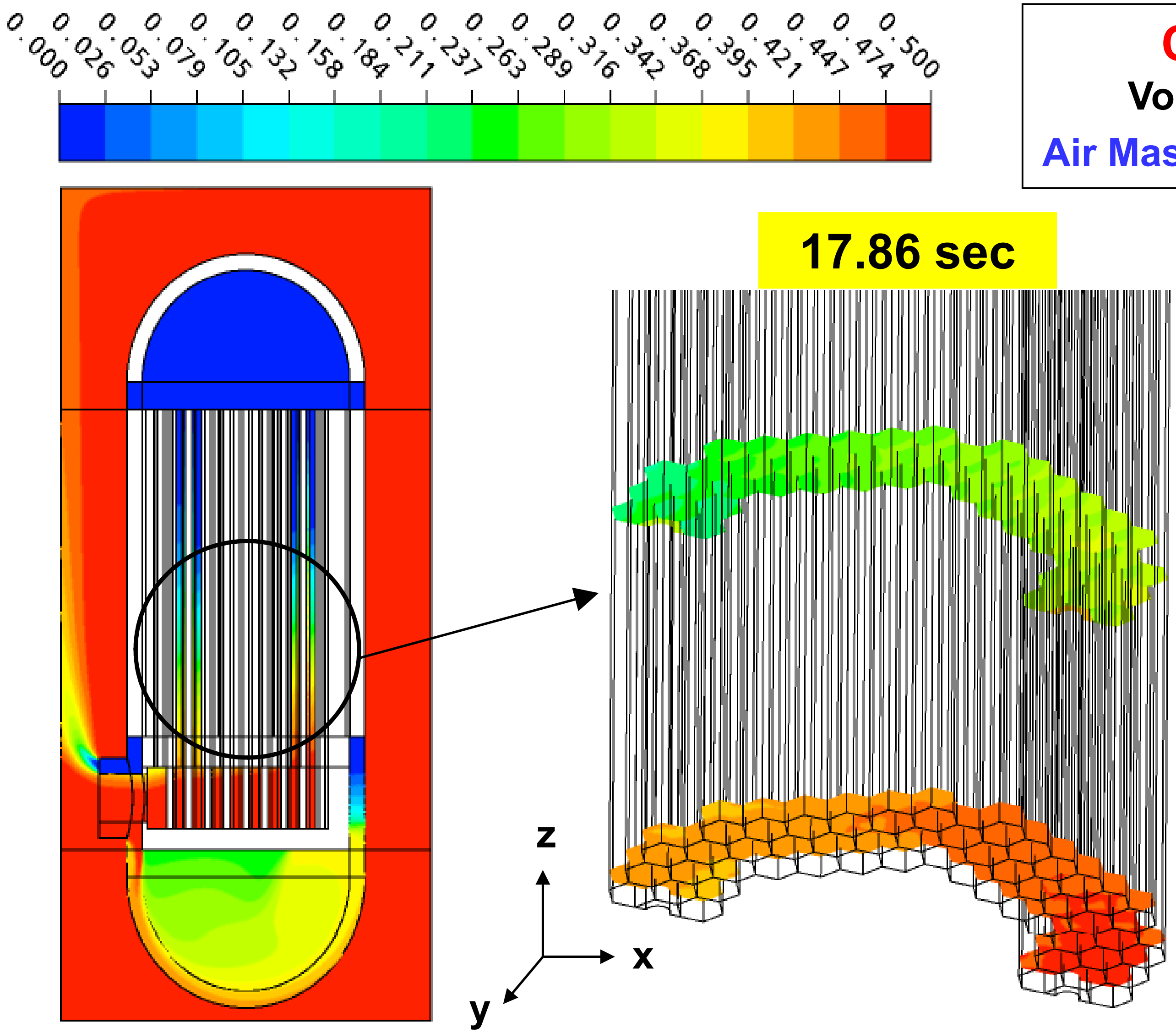
(*Contour on y = 0.01 m)

Air Ingress Accident – Results of Air Mass Fraction



Air Ingress Accident – *Results of Air Mass Fraction*

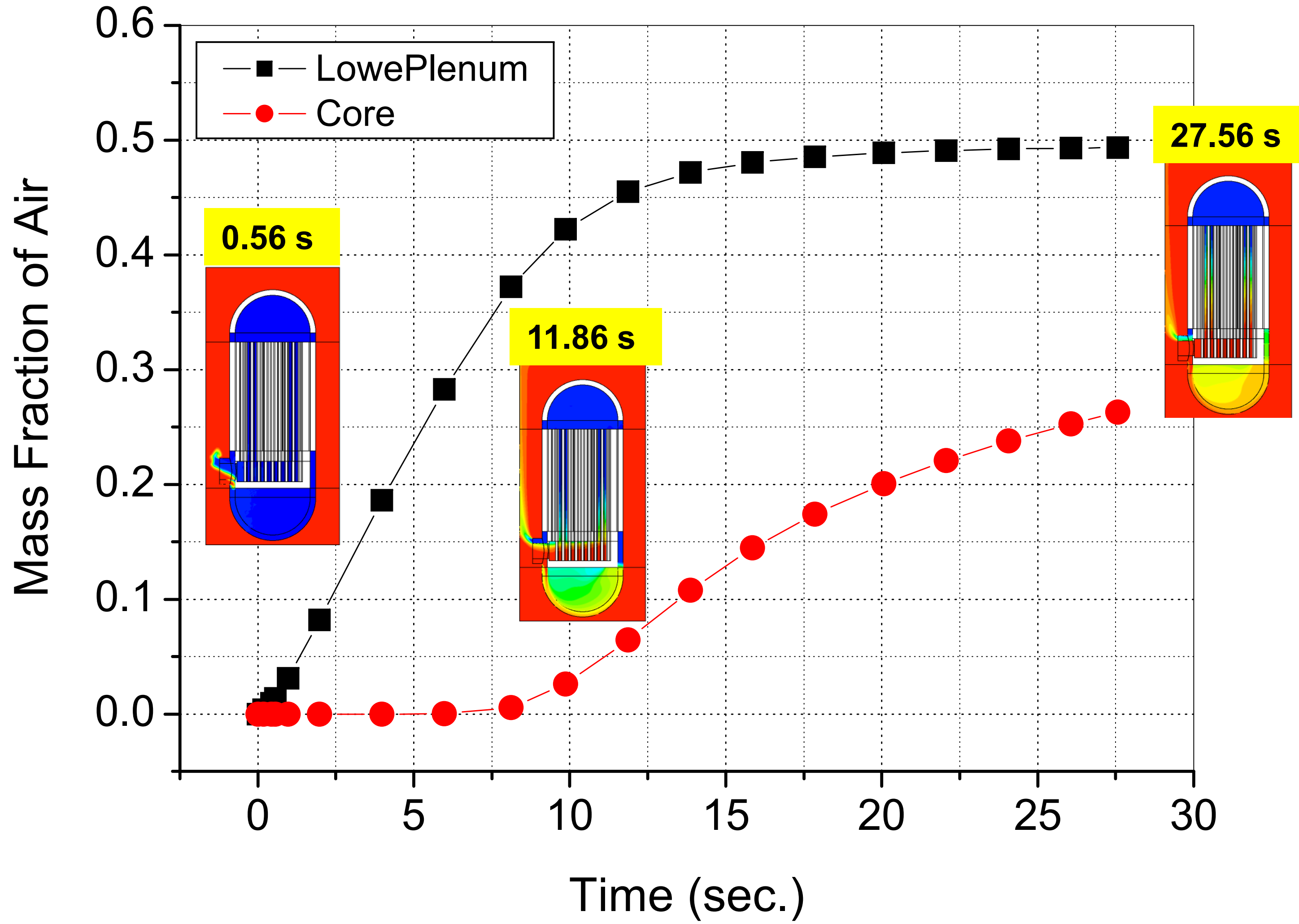
Core Block
Volume Averaged
Air Mass Fraction = 0.174



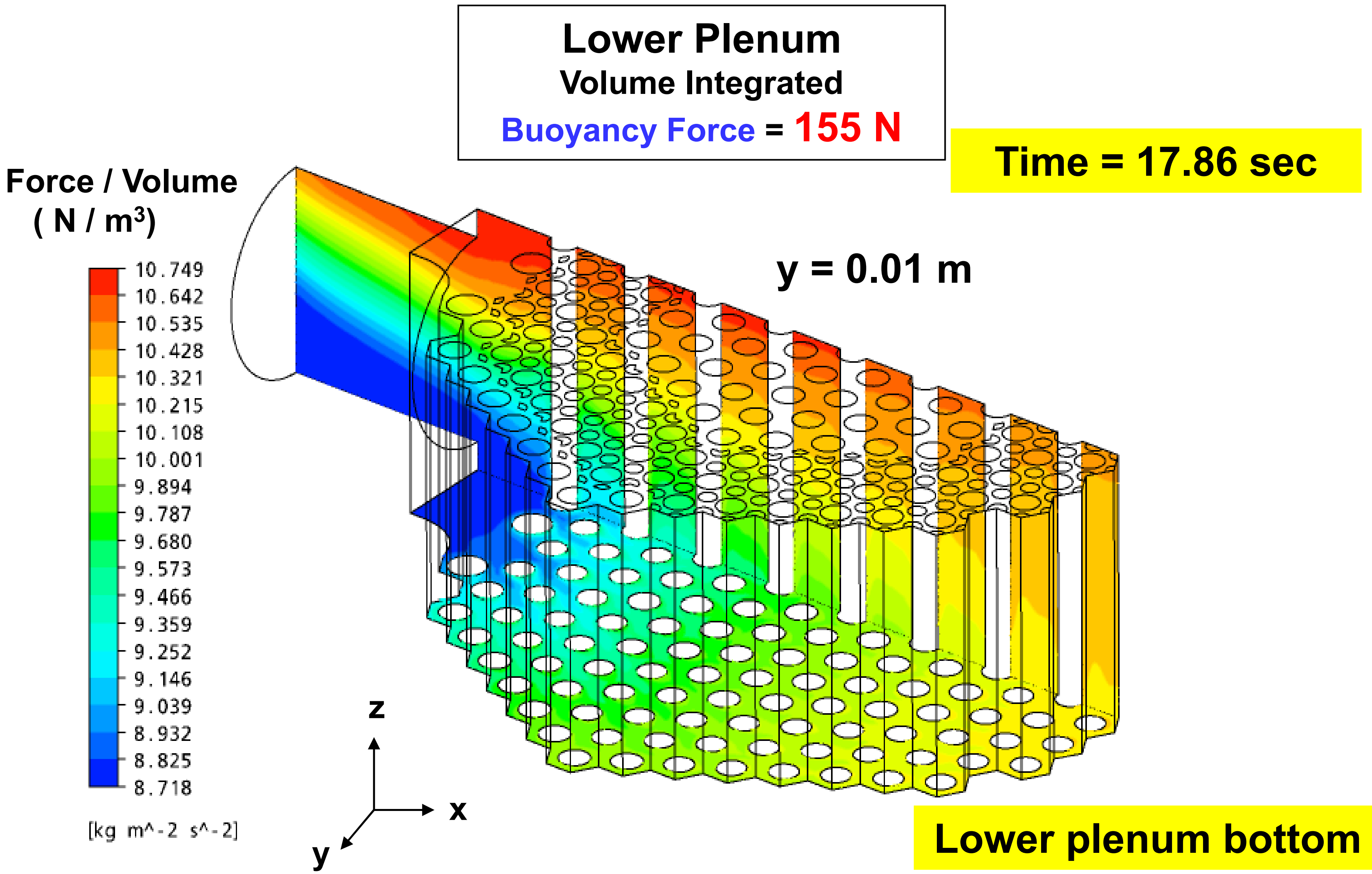
Z = 3.4 m from the core bottom
MF_{air} = 0.27

Z = 0.3 m
(Core Bottom : 0 m)

Air Ingress Accident – *Voulme averaged air mass fraction*

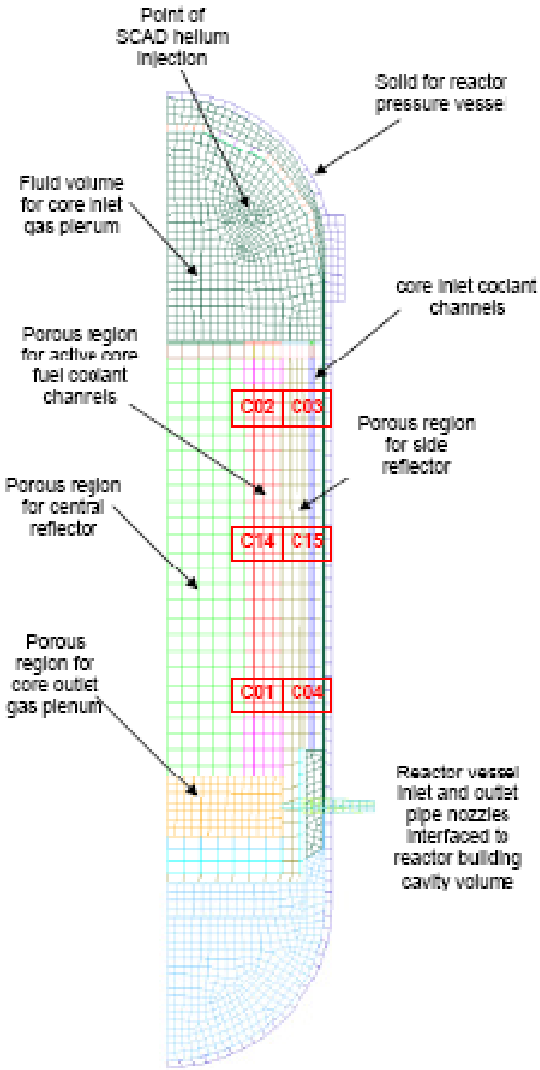


Air Ingress Accident – Buoyancy Force



Air Ingress Accident – Force of helium injection at the top of GTHTR 300

Xing L. Yan et al, "A Study of Air Ingress and Its Prevention in HTGR", *Nuclear Technology*, Vol.163, Sep. 2008



Force : 0.062 Newton

- Mass Flow Rate : 0.2 kg/hr
  - Yan [2008] used this flow rate.
- Orifice Flow Area : 0.011 mm^2
  - Diameter : 0.12 mm
- Calculated Mass Flow Rate

$$\dot{m} = A \cdot P_o \cdot \sqrt{k \cdot \frac{1}{R \cdot T} \cdot \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

= 0.23 kg/hr

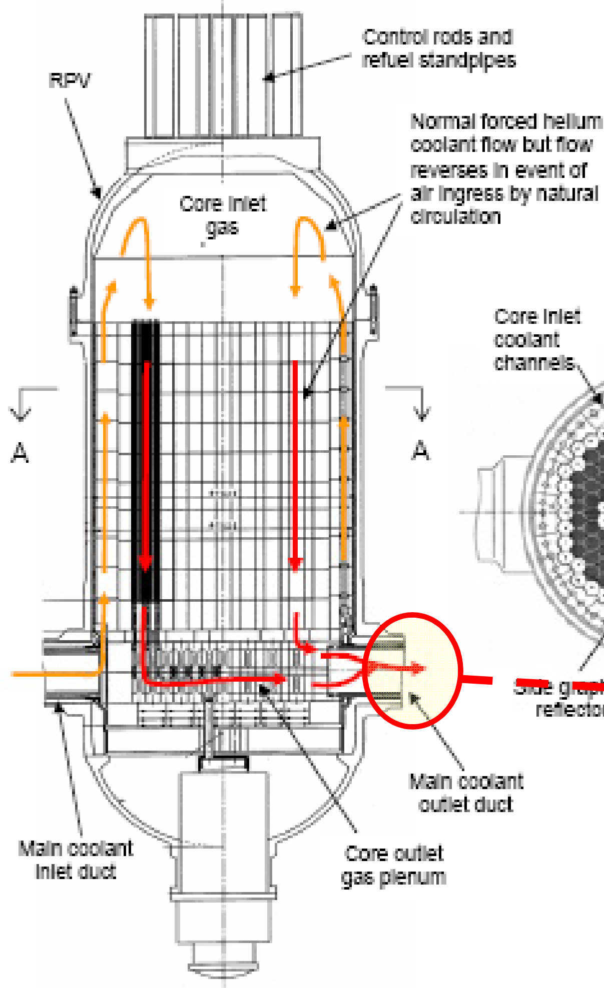
- Momentum : $\dot{m}\,V = 0.062\ Newton$

- GTHTR 300 design and modeling

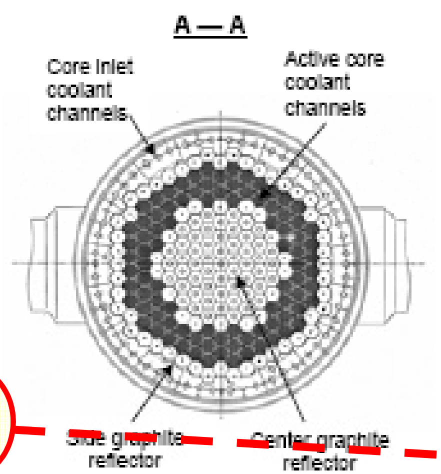
Yan Xing, 2008

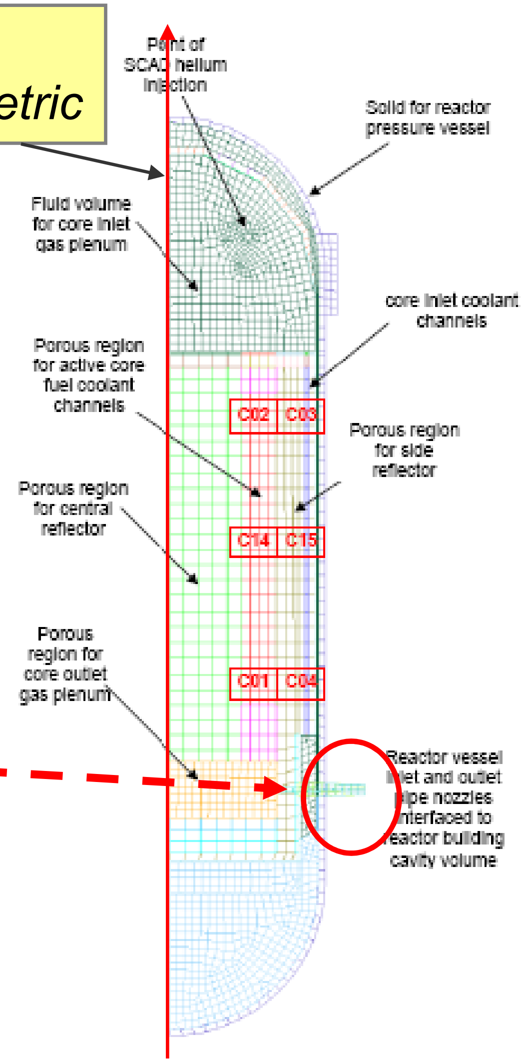
Assumed to be axi-symmetric

Modified for matching surface area



GT-HTR 300

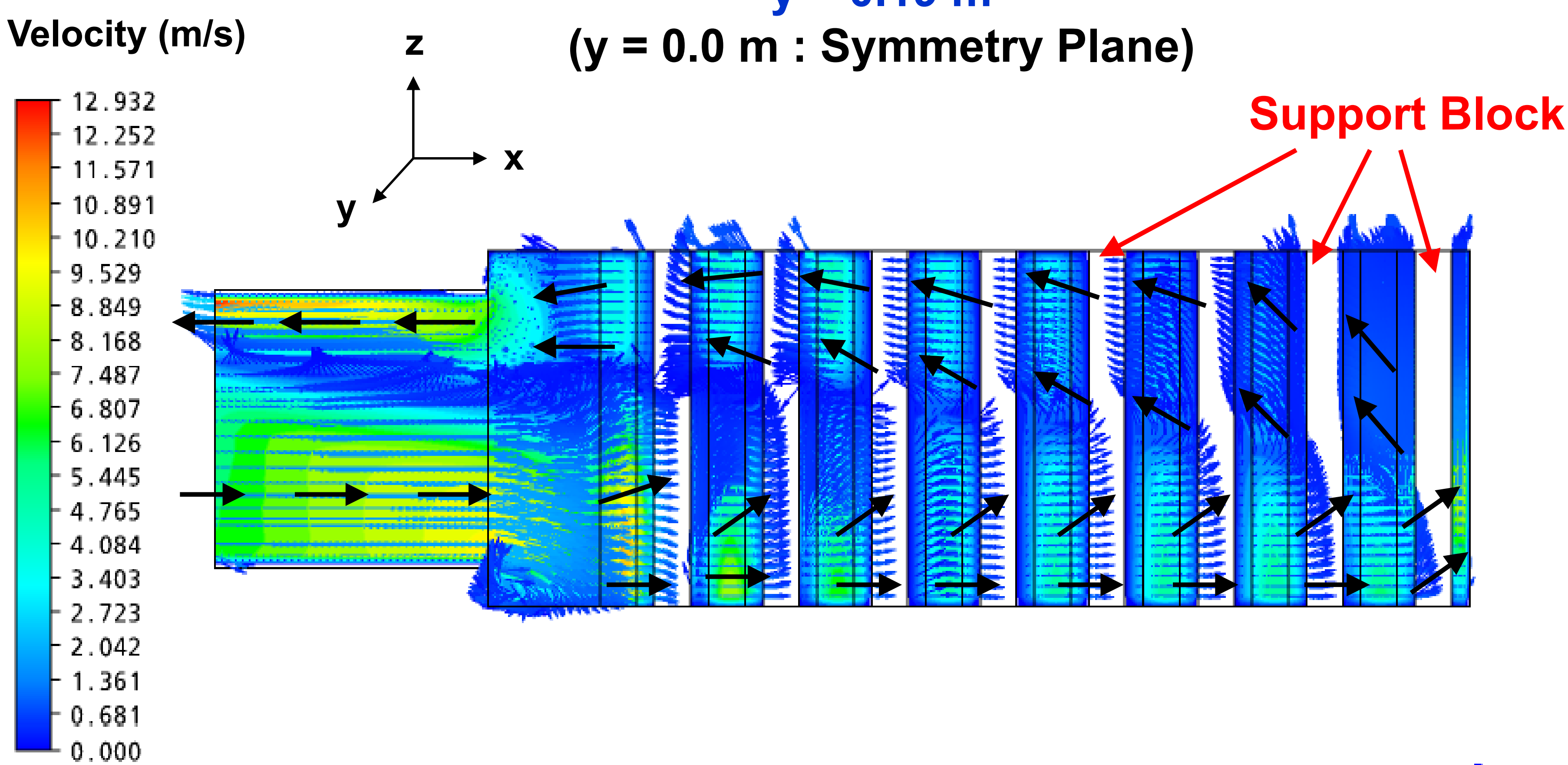




CFD Modeling

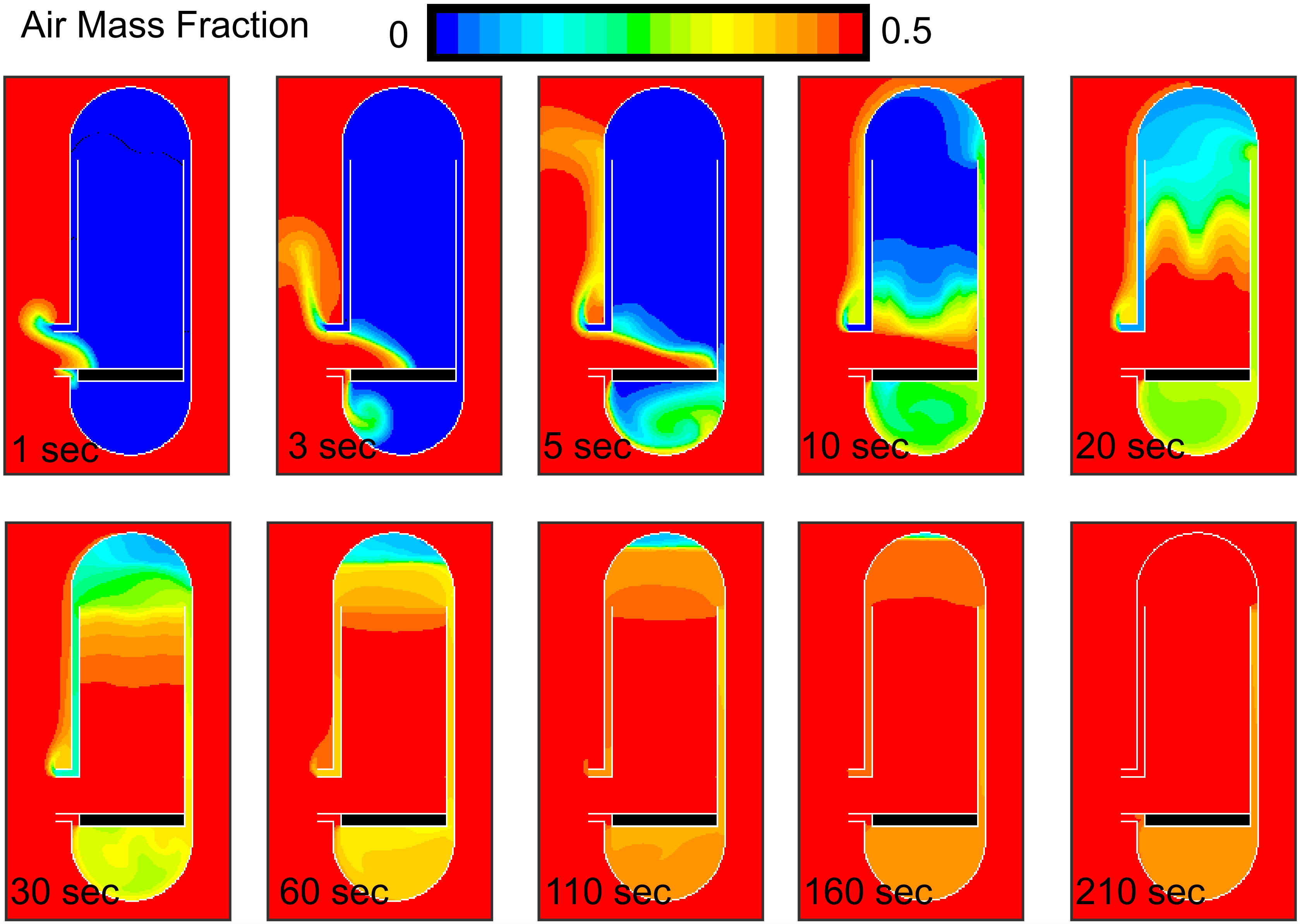
Air Ingress Accident – Velocity Vector

Time = 5.97 sec



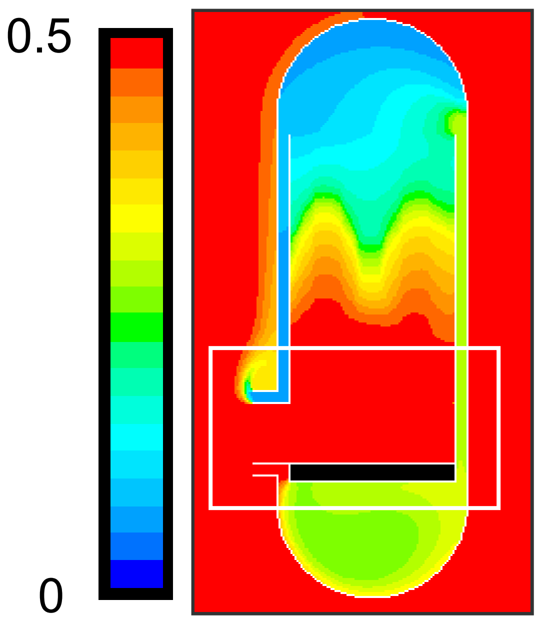
6. CFD Simulations for Air-ingress Accident (Cont.)

- Double Ended Guillotine Break (2-D Modeling) Using FLUENT

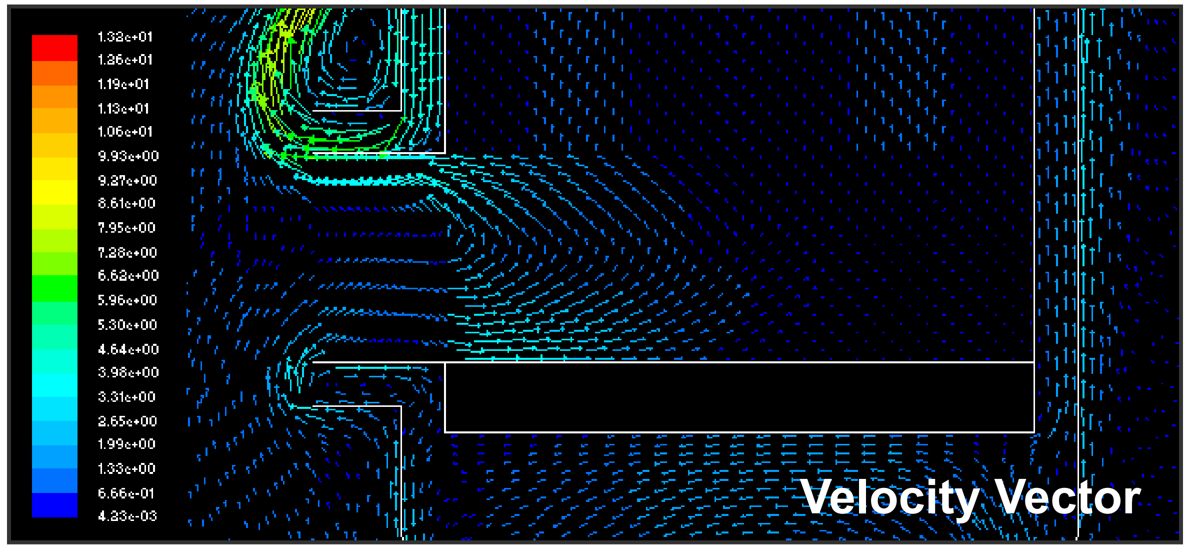


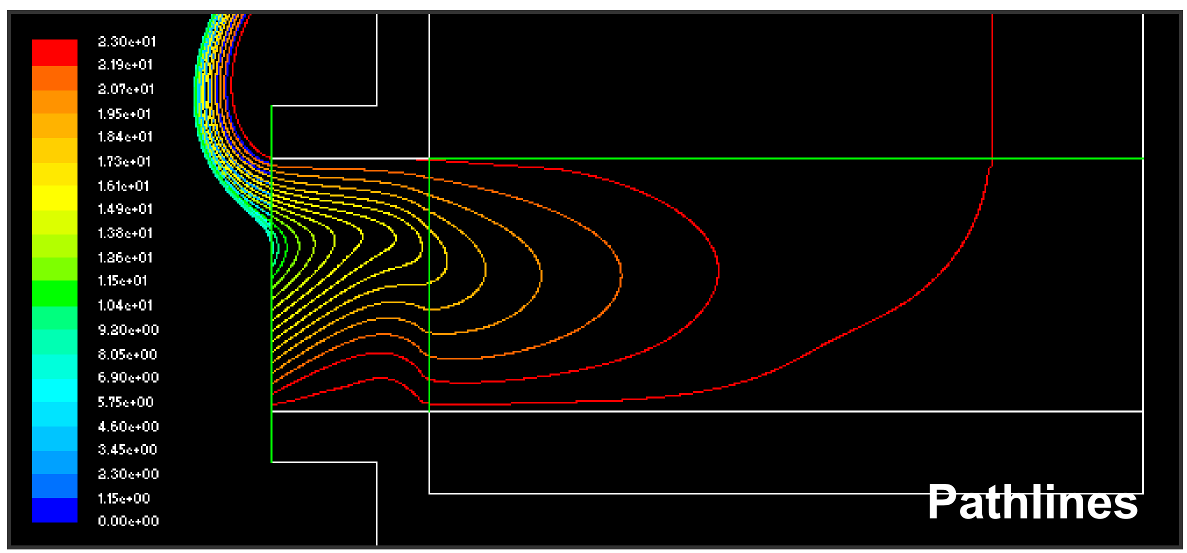
6. CFD Simulations for Air-ingress Accident (Cont.)

- Double Ended Guillotine Break (2-D Modeling)

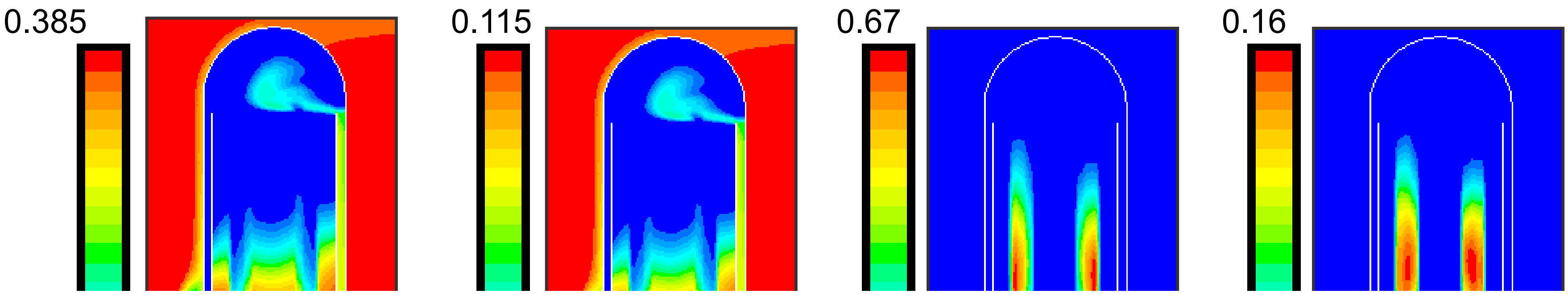


Air Mass Fraction (20 sec)





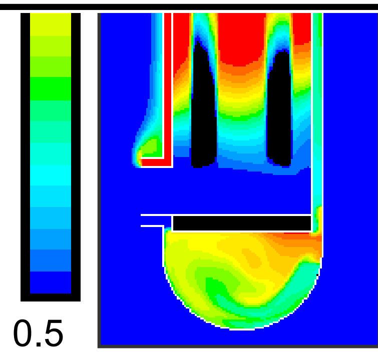
6. CFD Simulations for Air-ingress Accident (Cont.)
- Double Ended Guillotine Break (Chemical Reaction)



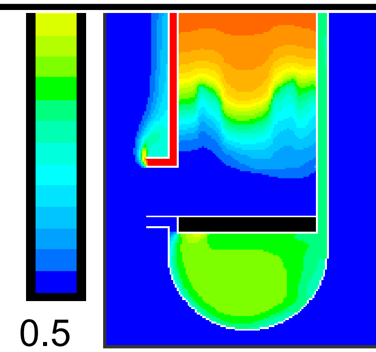
Buoyancy parameter of various fluids at 20 oC and 1 atm in earth gravity

Fluid	$g\beta/\nu^2$, K^{-1} m^{-3}
Helium	2.4e6
Air	1.5e8
Carbon Dioxide	5.3e8
Water	2.0e9

He mass fraction (with reaction)



He mass fraction (without reaction)



Summary

1. ***Density-Gradient Driven Stratified Flow is the Dominant Air Ingress Mechanism for Large Breaks and Some Small Leaks***

2. ***Air Ingress is Location, Size, and Orientation Dependent***

3. ***Density-Gradient Driven Stratified Flow moves Air into the Reactor Vessel much Faster than Molecular Diffusion***

4. ***Natural Convection occurs shortly after Air moves into the Lower Plenum***

5. ***Air Ingress Experiments are needed for Code Validation and for Additional Phenomena Clarification***

Recommendations

- ***Air ingress experiments***
- ***Develop air ingress mitigation methods using the validated CFD code (inert gas injection from the lower plenum)***
- ***Detailed stress analyses and experiments (silicone carbide coating) on the lower plenum graphite***

Questions & Answers