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Control of Chemical Attack in the PBMR

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Purpose of Presentation

- To discuss the PBMR safety design approach to control of chemical attack

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Background

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- Severe accidents in nuclear reactors (e.g. Windscale, Chernobyl) have resulted in graphite fires
- Water ingress at the AVR and Ft. St. Vrain HTGRs resulted in lengthy downtimes
- Graphite can corrode at elevated temperatures due to reactions with air or water oxidants
- PBMR safety design approach explicitly focuses on control of chemical attack

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Graphite Fire Severe Accidents

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- Windscale event
  - Caused by buildup of radiation-induced Wigner energy in graphite at low temperature operation.
  - Release of energy caused burning of first metallic fuel and then graphite by air reactor coolant.
  - Fire and radionuclide release aggravated by the open cycle chimney air flow.
- Chernobyl event
  - Caused by severe reactivity excursion that destroyed the reactor core.
  - Metallic fuel and graphite burned ~ 20 hours after the explosion opened the core to air ingress.

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Comparison of Windscale and PBMR Air Ingress Resistance

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	Windscale	PBMR
• Initiating Event	Wigner energy	n/a
• Coolant	air	inert helium
• Fuel	metallic	ceramic
• Air Supply	unlimited (open to atmos by design)	limited

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Comparison of Chernobyl and PBMR Air Ingress Resistance

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	Chernobyl	PBMR
• Initiating Event	positive reactivity	n/a
• Coolant	water	inert helium
• Fuel	metallic	ceramic
• Air Supply	unlimited (open to atmos)	limited

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Comparison of AVR and PBMR Water Ingress Resistance

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	AVR	PBMR
• Water Source	steam generator	direct cycle
• Coolant	inert helium	inert helium
• Fuel	ceramic	ceramic
• Graphite Type	nuclear grade	nuclear grade

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Comparison of FSV and PBMR Water Ingress Resistance

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	Ft St Vrain	PBMR
• Water Source	water bearings	magnetic bearings
• Coolant	inert helium	inert helium
• Fuel	ceramic	ceramic
• Graphite Type	PGX core support	higher grade

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PBMR Safety Design Approach

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- Prevent water corrosion of graphite by limiting pressurized water sources and supply (e.g., no steam generators)
- Prevent air corrosion of graphite by providing reliable reactor isolation and limiting air supply
- Assure core heat removal and control of heat generation
- Retain radionuclides in SiC-coated fuel particles that are highly temperature and corrosion resistant

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PBMR Resistance to Water Ingress

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- During normal operation helium pressure always higher than the water in the secondary heat exchanger
  - Tube leaks result in helium blowdown of water thru secondary relief systems
- During depressurized shutdown events (e.g., maintenance at 1 atm), the Reactor Unit Conditioning System (RUCS) heat exchanger will be at a higher pressure
  - RUCS cools the core to below the graphite oxidation temperature
  - Water-graphite reaction is endothermic
  - A tube break results in water draining to the bottom of the RUCS vessel below the core
  - RUCS water inventory limited—if all hypothetically reacted, negligible core graphite reacts (<.001)

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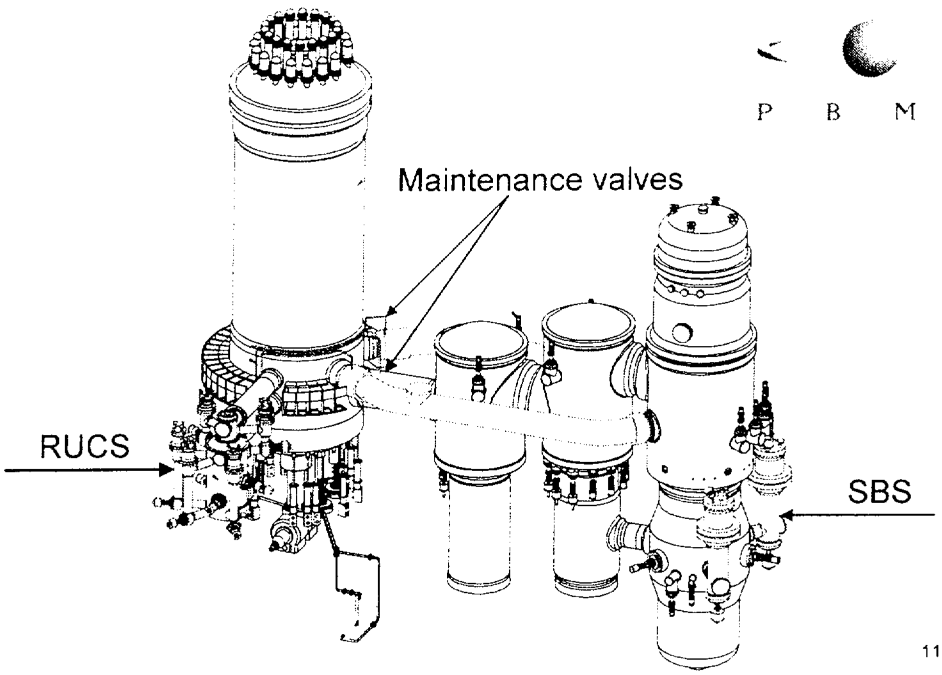

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PBMR Resistance to Air Ingress

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- Air ingress events are infrequent---not expected in plant lifetime
- Helium pressure boundary (HPB) designed to ASME standards
- Citadel provides protection from external events
- Nuclear grade graphite blocks undergo limited air oxidation relative to other graphite and carbon forms
  - Reduced impurities limit catalytic and other oxidation enhancing effects
  - Electrode blocks of higher impurity which are more susceptible to oxidation at 500-600°C are routinely cooled in air during manufacturing
- Air supply limited by citadel volume

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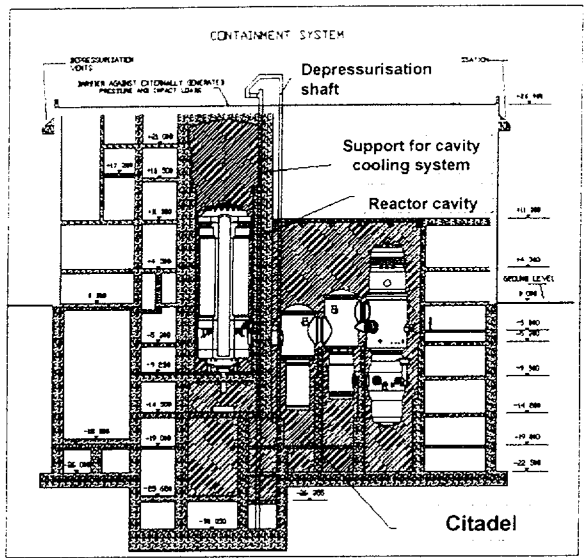

PBMR Citadel Provides External Protection and Limits Air Supply

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Air Ingress Design Basis

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- Helium Pressure Boundary(HPB) breaks in design basis-- not expected within lifetime of fleet of plants
  - Instrument lines (<10mm)
  - Fuel Handling and Storage System (FHSS) lines (<65mm)
  - Helium Inventory and Control System (HICS) lines (<65mm)
- Isolation of HPB possible depending on break location
  - Automatic or remote manual, if within FHSS or HICS
  - Remote manual, if within Power Conversion Unit HPB
- Reactor Pressure Vessel (RPV) designed with no piping above core support, ASME pressure vessel closures --- lighter helium prevents air ingress to core

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Air Ingress Design Basis (cont.)

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- Breaks <10mm (78 mm^2) designed to vent slowly (hrs) through HVAC filters to environment
- For breaks <10mm, negligible air ingress and graphite oxidation
  - Opening too small (flow resistance)
  - Helium egress prevents air ingress
  - SBS and RUCS if available designed to cool core to below corrosion temperatures
  - If no action taken and entire RPV filled with air (80% is inactive nitrogen), <.00005 of reactor graphite oxidized

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Air Ingress Design Basis (cont.)

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- Breaks <65mm (3318 mm^2) designed to vent quickly (minutes) to environment thru containment system rupture disc with damper reclosure
- For breaks <65mm in RPV, insignificant graphite oxidation
  - Helium depressurization and core heatup cause outward expansion of helium for several days
  - Reaction is exothermic, but small contributor relative to decay heat
  - If no action is taken, as conduction cooldown to RCCS progresses, contraction of helium within HPB will result in air ingress to reactor
  - However, air ingress is limited by two moles (CO_2 or CO) forming for every mole of air reacting
  - Heated air slows down flow due to increased flow resistance
  - If entire citadel air supply hypothetically entered, <.002 of reactor graphite oxidized

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PBMR Resistance to Large Air Ingress

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- Beyond the design basis---not expected within the lifetimes of a fleet of plants
- Breaks of between 65 and 170 mm (area 1330 – 23000 mm^2) designed to vent thru blow out panels in top of citadel
  - Depending on location of break, two way flow through large breaks is conceivable
  - Depending on location of break, air transport to and through reactor core is possible
  - If no mitigative measures taken (e.g., blocking blowout panels in top of citadel) and entire reactor building supply of air entered, <.01 of reactor graphite oxidized, .07 of spheres or .12 of fuel free graphite in spheres
- Even with large amounts of local core oxidation, radionuclide retention is expected to be maintained within the ceramic fuel particles

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Air Ingress Research

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- International air oxidation tests have been performed (e.g., Veluna, Nacok), but provide limited insights
  - Non-representative core geometry, mass flow resistance, and reactor temperature distributions
  - Require top-bottom multiple openings or idealized failures to intentionally optimize natural convection
- Better strategy is to balance prevention measures within the design basis with a range of potential mitigative measures given the large times available for external actions

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Mitigation Strategies

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- Given building is filled with helium-air-radionuclide mixture, conditions provide possibility of manned but contamination protected entrance
  - External dose rates (after 12 hrs) < 100 μSv/hr
- Alternatively, remote external actions may also be possible
- Objectives are to to block leak with simple means and to slowly add inert gas to building, citadel, and/or core

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SUMMARY

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- Limited water ingress potential leading to insignificant damage of graphite components
- Negligible air ingress through openings <10mm
- Air circulation through openings <65mm only after the core cools down with negligible public health impact
- Large HPB breaks beyond the design basis have acceptable risk
  - Extremely unlikely due to the design and choice of materials
  - Time available to take mitigating action before significant corrosion
  - Temperatures do not rise above the level that coated fuel particles are unable to retain radionuclides

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