Sensitivity Studies of Modular High-Temperature Gas-Cooled Reactor (MHTGR) Postulated Accidents

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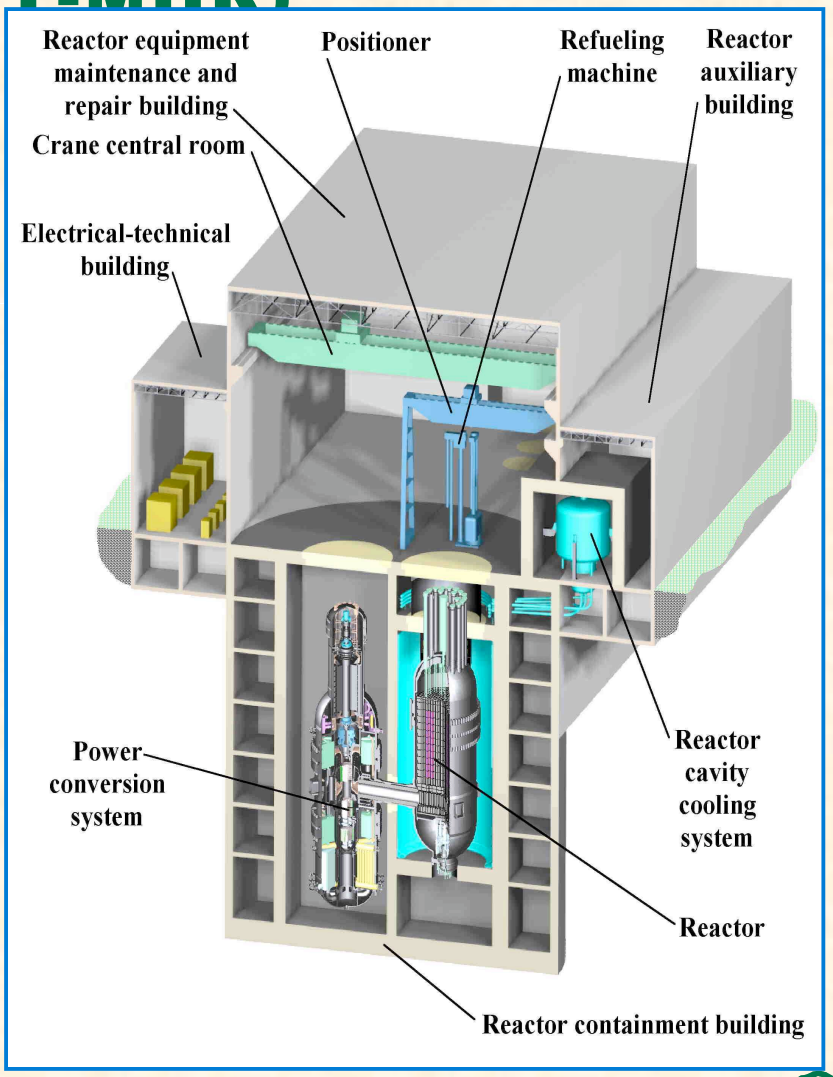
HTR-2004 - INET Beijing, PRC
September 22-24, 2004

Objectives

- Sensitivity studies of accident scenarios (early in the design) can:
  - 1) provide estimates of the uncertainties in the predictions;
  - 2) guide further efforts in improving the design as well as the accuracy of the predictions;
  - 3) determine where more (or less) R&D is appropriate

The Gas-Turbine Modular Helium Reactor (GT-MHR)

- Electrical output 286 MW(e) [illegible]
- Each module includes:
  - Power Conversion System
  - Reactor System 600MW(t)
- Annular core - 102 columns;
- Hexagonal prismatic blocks similar to FSV
- Power Conversion System includes:
  - Generator, turbine, &
  - compressors on single shaft – surrounded by recuperator, pre-cooler and inter-cooler

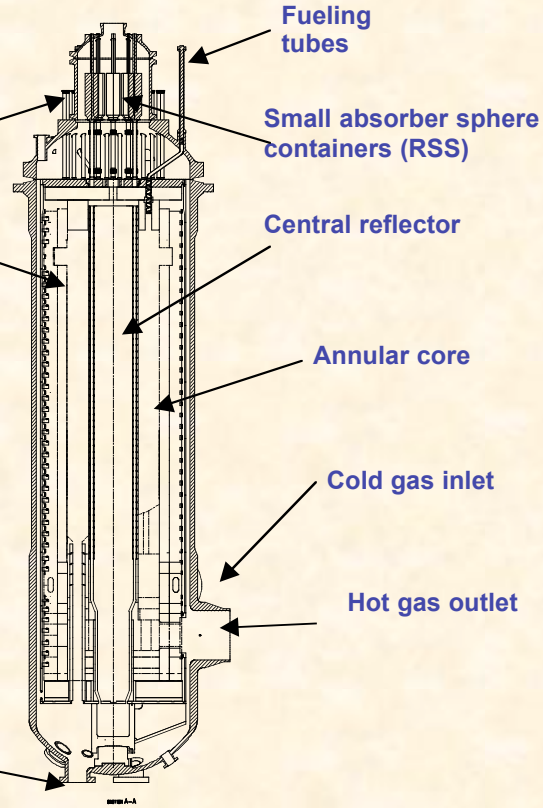


GT-MHR-Pu Module
Nominal Full-Power Operating Conditions

Reactor power, MW(t)	600
Reactor inlet/outlet temperatures, ^{o}C	490/850
Core inlet pressure, MPa	7.07
Helium mass flow rate, kg/s	320
Turbine inlet/outlet pressures, MPa	7.01/264
Recuperator hot side inlet/outlet temps, ^{o}C	510/125
Net electrical output, MW(e)	286
Net plant efficiency, %	47
Active core inside/outside diameters, m	2.95/4.83
Active core height, m	7.96
Outer reflector outside diameter, m	5.64
Other operating parameters (GRSAC simulation):	
RCCS heat removal, MW	2.7
Active core coolant outlet temperature, ^{o}C	915
Maximum vessel temperature, ^{o}C	400
Maximum fuel temperature, ^{o}C	1060
Coolant bypass fractions for side/central reflectors	0.08/0.05
Core pressure drop, MPa	0.044

Pebble Bed Modular Reactor (PBMR) – South African Design

P B M R



SPECIFICATION	
Total height RPV	30 m
Inside dia. RPV	6.2 m
Coolant	Helium
Max. helium pressure	9 MPa
Normal Ops. temp. of RPV	300°C
RPV vessel material	SA 508 Forgings
RPV mass assembled	~1700 t
RPV vessel mass	1000 t (lid included)

PBMR Nominal Full-Power Operating Conditions

Reactor power, MW(t)	400
Reactor inlet/outlet Temperatures, ^{o}C	500/900
Core inlet pressure, MPa	9.0
Helium mass flow rate, kg/s	193
Net electrical output, MW(e)	165
Net plant efficiency, %	41
Active core inside/outside diameters, m	2.0/3.7
Active core height, m	11
Outer reflector outside diameter, m	5.5
Other operating parameters (GRSAC simulation):	
RCCS heat removal, MW	3.1
Core inlet/outlet mean temperatures, ^{o}C	495/890
Active core coolant outlet temperature, ^{o}C	980
Maximum vessel temperature, ^{o}C	410
Maximum fuel temperature, ^{o}C	1080
Pebble bed mean void fraction	0.383
Coolant bypass fractions for side/central reflectors	0.13/0.05
Core pressure drop, MPa	0.31

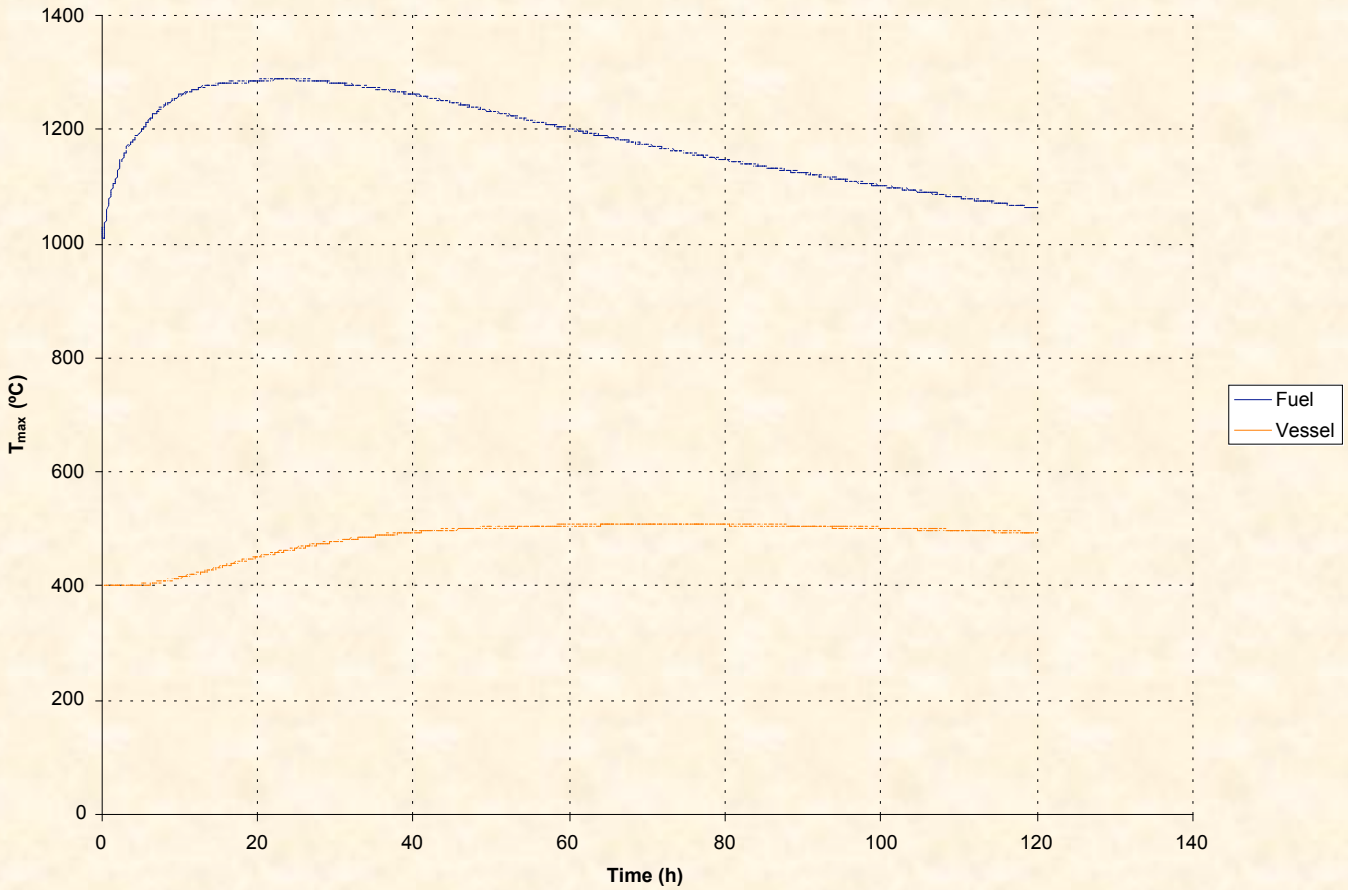
Accident Types Considered:

- P-LOFC – Pressurized Loss-of-Forced Circulation (long term)
- D-LOFC – Depressurized LOFC
- Both LOFCs without scram (ATWS)
- D-LOFC with air ingress
- NOT considered here:
  - water ingress;
  - rod ejections;
  - loss of Reactor Cavity Cooling System (RCCS)

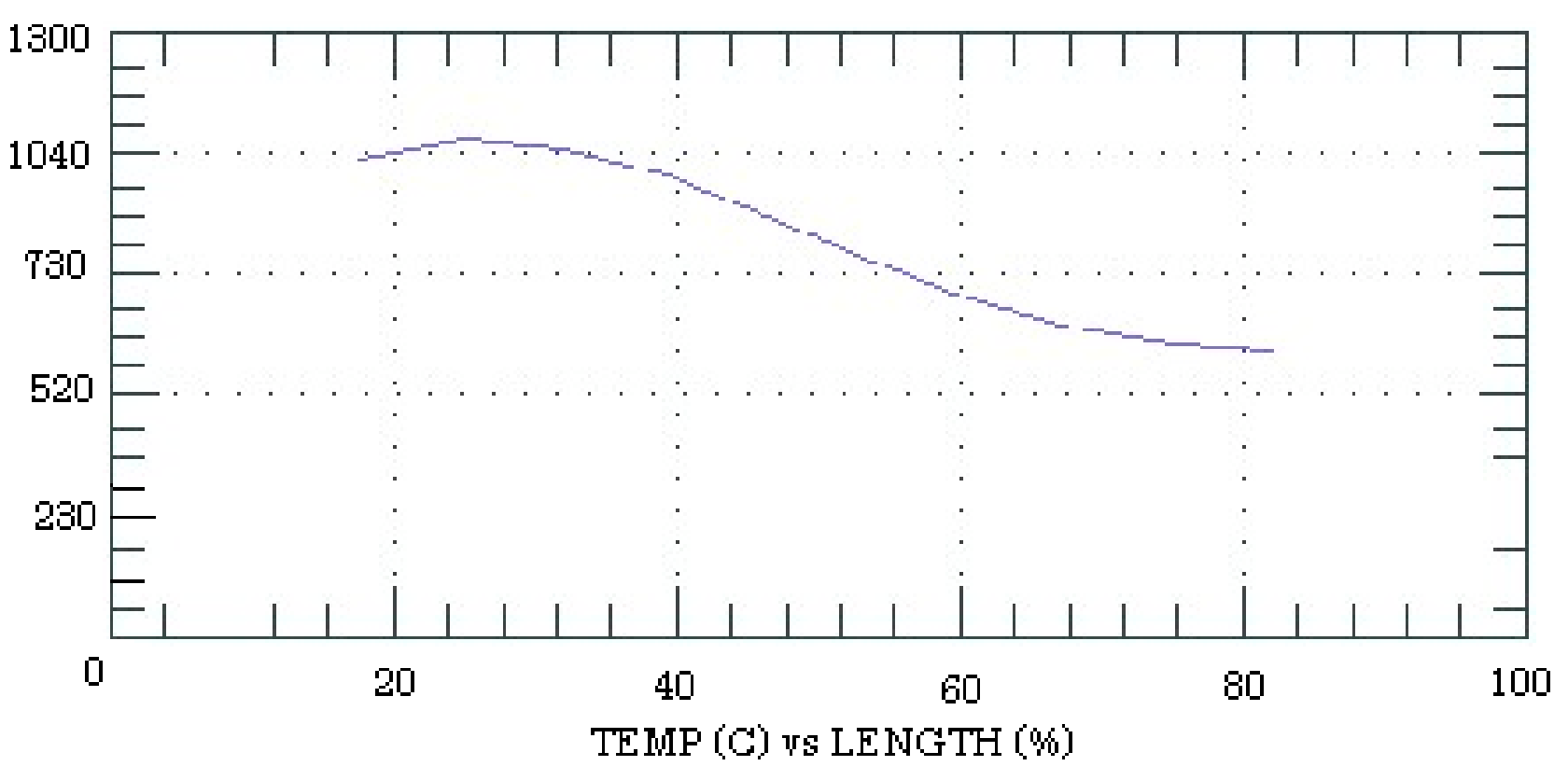
Graphite Reactor Severe Accident Code (GRSAC)

- GRSAC based on ~30 years of accident code development, V&V at ORNL for gas reactors
  - Sponsored by NRC/DOE (ORECA/MORECA codes)
- Detailed accident modeling for gas-cooled reactor systems
  - 3-D core thermal hydraulics, ~3000 nodes
  - Optional neutronics (point kinetics) for ATWS accidents
  - Graphite oxidation model options
  - Recent adaptations to GT-MHR & PBMR (for NRC)
  - PC version runs ~ 8000 X faster than real time (non-ATWS)

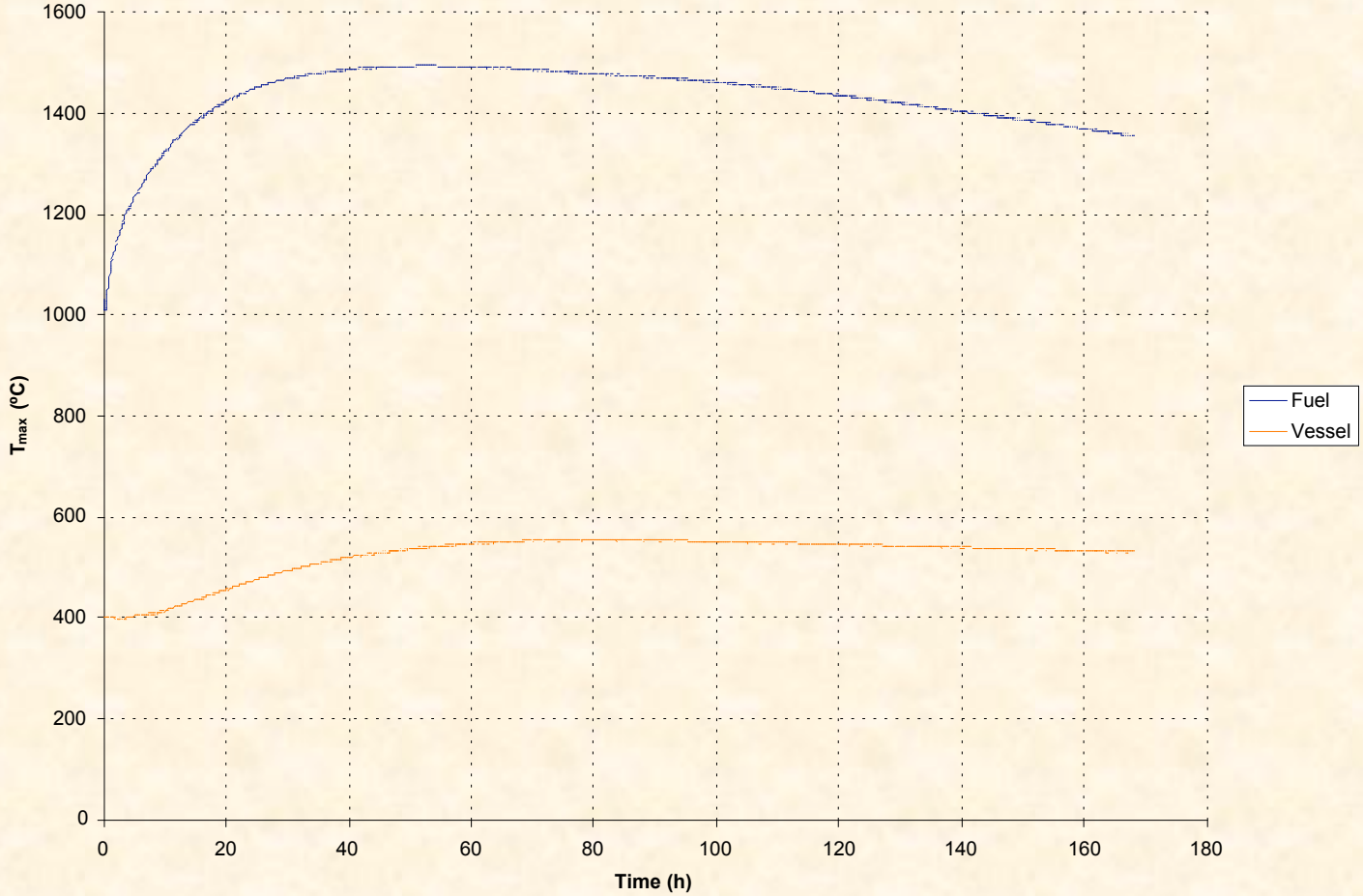
GT-MHR: Response to P-LOFC Reference case



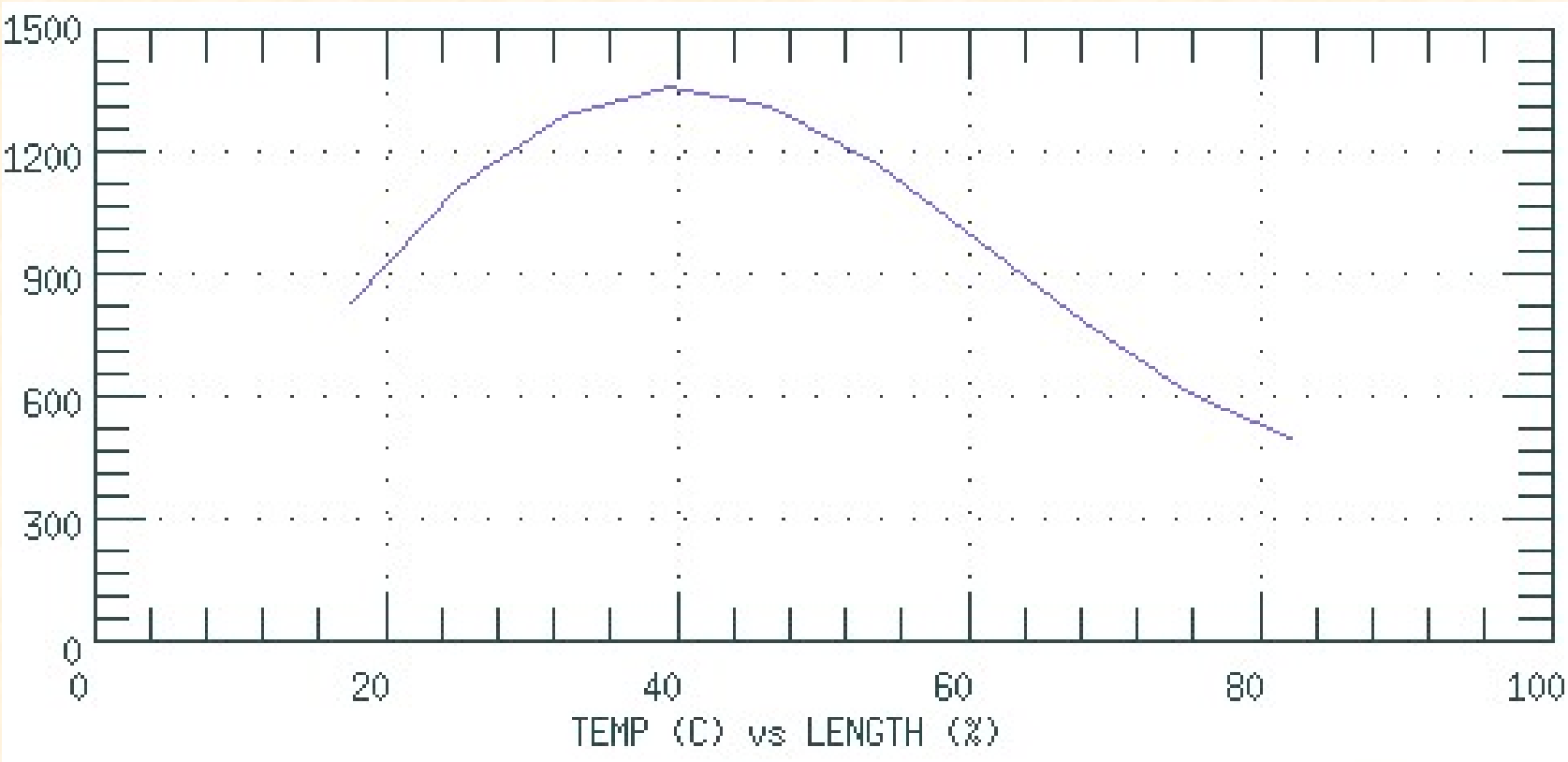
GT-MHR P-LOFC: Max Fuel Temp Axial Profile – peaks near inlet (top)



GT-MHR D-LOFC: Max Fuel Temp peaks after ~ 2 days



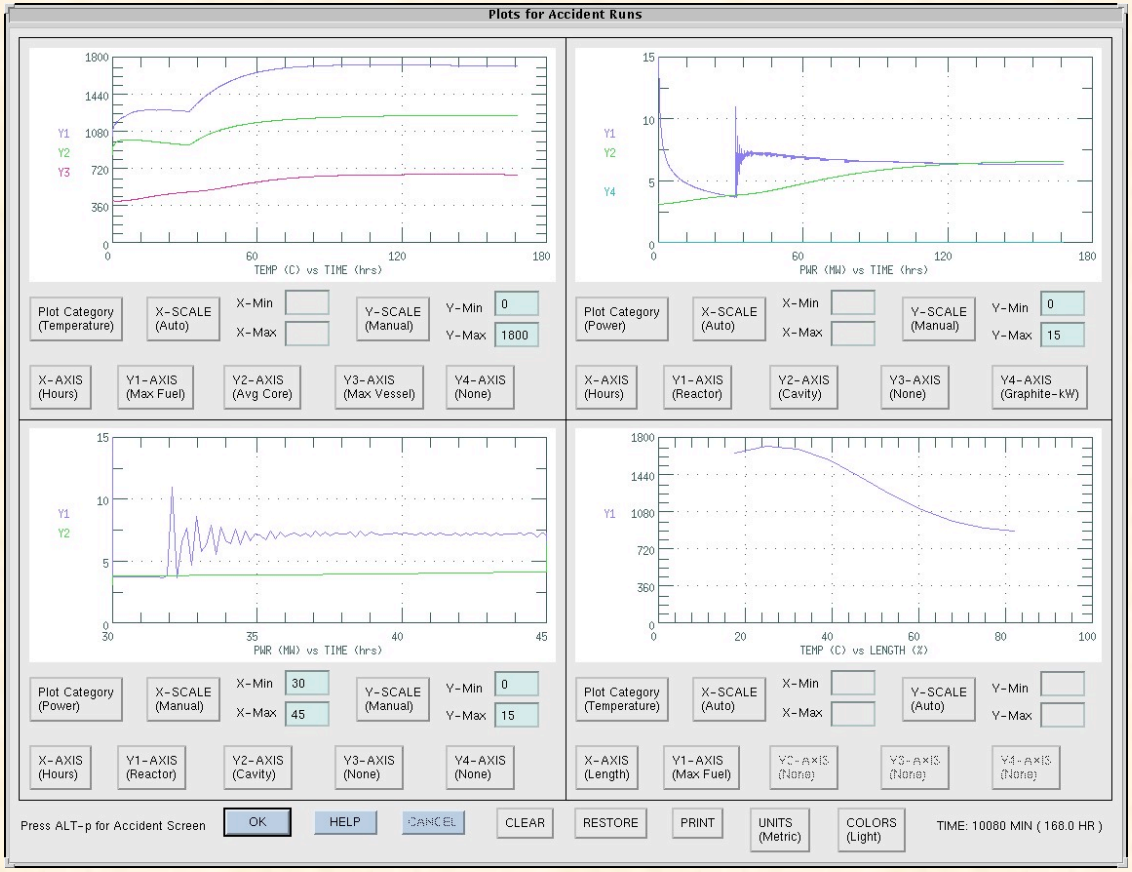
GT-MHR D-LOFC: Max Fuel Temp Axial Profile – peaks near vessel beltline



Observations on LOFC Accidents

- For the Pressurized Loss-of-Forced-Cooling (P-LOFC) accident, peak fuel temperatures are not a concern; vessel temperatures ~maybe
- The Depressurized LOFC typically “limits” the design via predicted peak fuel temperature
- The major factors contributing to peak fuel temperatures are effective core conductivity and afterheat curve assumptions.

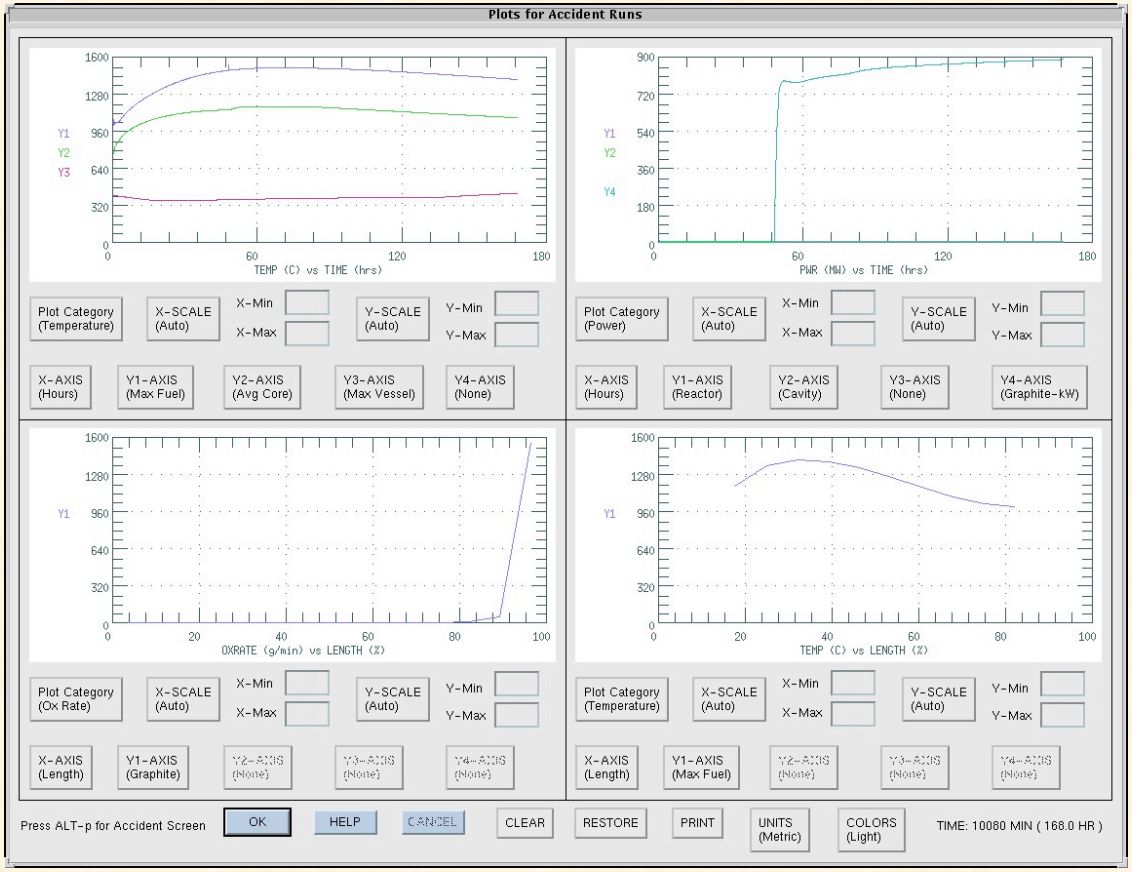
GT-MHR P-LOFC + ATWS; Recriticality after ~1.5 days (=> fuel failure later)



ATWS Conclusions

- Long-term ATWS cases: much-higher-than 1600°C peak fuel temperatures occur following recriticality
  - However, no fuel failures expected for ~2 days
  - Ample time to insert negative reactivity.
- SCS restarts during an ATWS:
  - counterproductive due to “selective undercooling” effects.
- Rapid reactivity insertions: “no mechanisms” (design)

PBMR Air Ingress (single break) has delay in start of sustained air flow



German experiment (KFA) shows most oxidation occurs in lower core

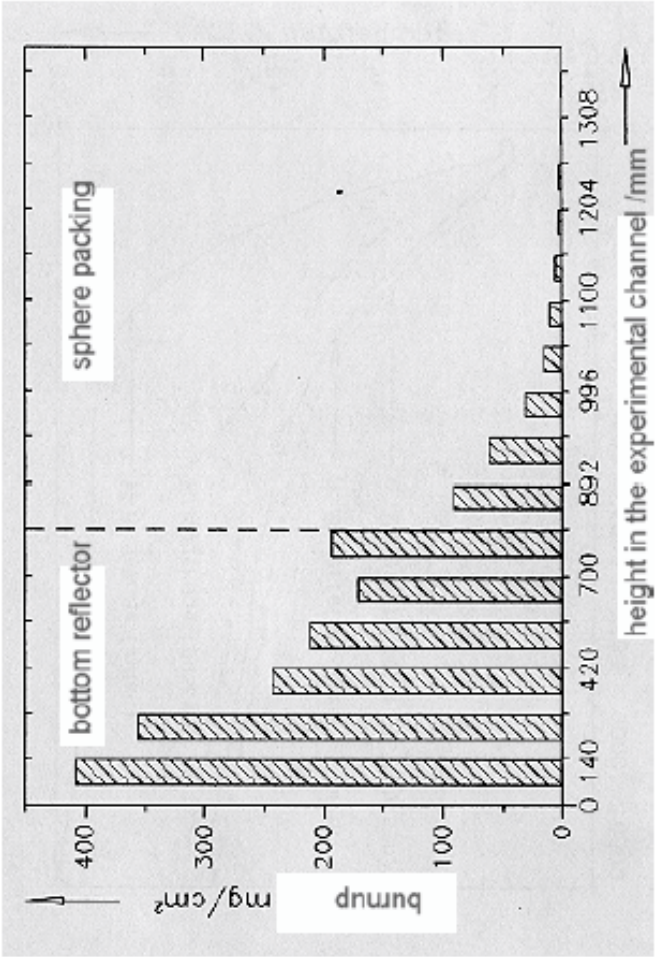


Fig. 4.6.22 Burnup measured in the bottom reflector and in the sphere packing after 3 hrs of corrosion

Air Ingress Conclusions

- Early on (~2 days), oxygen in the entering (fresh) air flow typically depleted before reaching the active core. Flow limited by high core resistance.
- Other considerations, however, such as predicting damage to hot structures that do encounter the oxygen, may require additional refinement of the data and further analysis.
- Limiting assumed fresh air supply to initial cavity air is likely to prevent any serious core damage.
- Typically, coincident vessel breaks in both the top and the bottom sections would result in both breaks being in the coolant inlet path, not providing a ready “chimney” for enhanced natural circulation.
- Often overlooked is the fact that vessel-break accidents that could lead to large-scale oxidation events are extremely unlikely.

Conclusions

- Both MHTGR designs: excellent accident prevention & mitigation capabilities, even for well-beyond DBAs
- "Disclaimers":
  - Differences in the predicted absolute values of peak temperatures (for both fuel and vessel) for the two concepts for given accident scenarios should not be taken as definitive
  - Finalized design features (e.g. vessel insulation strategies) influence peak temperatures and have not been factored into the simulations.
  - Operation-dependent factors (irradiated core thermal conductivities, temperature-reactivity feedback functions, heat-sink emissivities,…) must also be considered.

Conclusions , (cont'd)

- The design-defining D-LOFC accident results are very sensitive to core conductivity and afterheat assumptions
- ATWS cases and air ingress (for D-LOFC) are very-low-probability variations that can eventually lead to core damage
- Unlikely air ingress accidents are likely to run out of oxygen before significant core damage occurs