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

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Submitted to ***Nuclear Engineering and Design***
Special Issue on HTR-2004
2nd International Topical Meeting on HTR Technology
Beijing, China
September 22-24, 2004

*Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

File Name: NED Sensitivity Paper (NED-final Sens.doc)
Manuscript Date: October 31, 2005

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ABSTRACT: The results of various accident scenario simulations for the two major modular High Temperature Gas-cooled Reactor (HTGR) variants (prismatic and pebble-bed cores) are presented. Sensitivity studies can help to quantify the uncertainty ranges of the predicted outcomes for variations in some of the more crucial system parameters, as well as for occurrences of equipment and/or operator failures or errors. In addition, sensitivity studies can guide further efforts in improving the design and determining where more (or less) R&D is appropriate. Both of the modular HTGR designs studied – the 400-MW(t) Pebble Bed Modular Reactor (PBMR, pebble) and the 600-MW(t) Gas-Turbine Modular Helium Reactor (GT-MHR, prismatic) – show excellent accident prevention and mitigation capabilities because of their inherent passive safety features. The large thermal margins between operating and "potential damage" temperatures, along with the typically very slow accident response times (~days to reach peak temperatures), tend to reduce concerns about uncertainties in the simulation models, the initiating events, and the equipment and operator responses.

KEY WORDS: Nuclear energy, electricity, modular HTGR, Brayton cycle, accident analysis, sensitivity studies

1. INTRODUCTION

The results of various accident scenario simulations for the two major modular HTGR variants (prismatic and pebble-bed cores) are presented, along with representative sensitivity studies that help quantify the uncertainties in the accident outcome predictions. Sensitivity studies can also lead to a better understanding of the important elements of the accident phenomena, and show where more (or less) emphasis should be put on plant design or R&D to improve component or subsystem performance and/or reliability.

The Oak Ridge National Laboratory (ORNL) Graphite Reactor Severe Accident Code (Ball, 1999) was developed primarily to study a wide spectrum of core transient and heatup accident scenarios. Its development, use, and validation exercises began ~30 years ago with several predecessor codes. Current applications of GRSAC primarily involve the simulation of postulated accident scenarios for modular HTGR commercial power reactor designs, as well as for simulation of benchmark transients run at the HTTR (Japan) and HTR-10 (China).

GRSAC employs a detailed (~3000 nodes) 3-D thermal-hydraulics model for the core, plus models for the reactor vessel, shutdown cooling system (SCS), and shield or reactor cavity cooling systems (RCCS). The spectrum of accidents covered range from what are normally classified as design basis accidents (DBAs) to accidents well-beyond DBA with extremely low probabilities. Typically the accident initiator is assumed to be a loss of forced circulation (LOFC), which may or may not be followed by a scram or startup of an SCS. If the primary system maintains pressure, the event is termed P-LOFC (pressurized LOFC). The LOFC may be accompanied by primary system depressurization (D-LOFC). The D-LOFC can include air ingress and graphite oxidation, where air circulation is driven either by via buoyancy (chimney) effects from single breaks or double breaks, or by forced circulation. Since most current modular HTGR designs use the direct gas-turbine (Brayton) cycle for electrical power production, and make a point to keep the primary side helium pressure higher than the water-side pressure in the pre- and inter-coolers and the SCS, the likelihood of water-ingress accidents during operation is greatly reduced.

The 3-D, hexagonal geometry core thermal model allows for detailed investigations of azimuthal temperature asymmetries in addition to axial and radial profiles. Variable core thermal properties are computed as functions of temperature and, for the prismatic cores, may also be dependent on orientation and radiation damage. An annealing model for graphite can account for the increase in thermal conductivity that may occur during heatup accidents.

The primary coolant flow models cover the full ranges expected in both normal operation and accidents, including pressurized and depressurized accidents (and in between), for forced and natural circulation, for upflow and downflow, and for turbulent, laminar, and transition flow regimes. Radial flows (in the pebble bed cores) are not computed. The primary loop pressure calculation can consider variable inventory (due to depressurization actions) and loop temperature changes, and may use a simplified model for balance-of-plant temperatures. The models for the reactor pressure vessel and the shield or RCCS are typically different for each of the various basic reactor models. The models for oxidation of core materials can also include carbon deposits (soot), found in CO_2-cooled reactors, as well as cladding and fuel, where applicable. Fission product release (for metal fuel) and Wigner stored energy release models for graphite in the older-model, low-temperature gas reactors, are also available.

Other GRSAC features of interest are: fast-running (typically ~8000 times real time on a 1.1 GHz PC, for non-ATWS – Anticipated Transient Without Scram - accidents); interactive user interface with on-line and off-line plotting options; a “smart front end” data input checker; and on-line help features and documentation.

Specific design features for a chosen reactor type can be input by the user via design screen selections in the following categories: fuel element, nuclear parameters, core layout design, primary cooling system, vessel design, reactor cavity design (and cooling), fission product release, and core material oxidation parameters. In some cases, such as for the radial and axial power peaking factor inputs and flow coastdown curves, graphical displays and automated consistency check features are included. For user input screens, pop-up HELP windows are available to further describe the inputs, and where appropriate, to suggest fixes for potential problems.

Initial Condition Runs

GRSAC accident sequence analyses require a large set of initial condition values in a RUN file, which can be created automatically via Initial Condition (IC) runs. During an IC run, the user can change operational inputs such as power level, flow, pressure, bypass flow fraction, etc., and observe the resulting detailed temperature and flow distributions attain new steady state conditions. At any point in the IC run, the user can store initial condition values to create a new RUN file.

Interactive and Programmed Inputs, and Run Control Parameters

The interactive input screen for accident simulations allows for user inputs (scram, depressurization, changes in emergency and/or cavity cooling, etc.) at any time during a run. Such inputs can also be pre-programmed, however, via a programmed input screen that is part of the run setup procedure. An input screen also provides for selection of simulation run time and a default computation time step.

Accident Sequence Runs

Long-term LOFC accidents are assumed to begin with a programmed flow coastdown transient. LOFC transients in gas-cooled reactors are generally characterized by slow heatups due to low power densities and large heat capacities associated with the core. They may be simulated in GRSAC both with and without total or partial depressurization of the primary coolant and with or without scram.

Rod withdrawal (slow, but not rod ejection) accidents can be modeled. Optionally, the active or passive shutdown cooling systems can be made to be either unavailable or available only intermittently in fully functional or degraded states.

Fission Product Release and Transport

Release of fission products (FPs) from the fuel occurs when the temperatures are elevated long enough for the TRISO coating barriers to fail (modular HTGR fuel), and are modeled by a simplified algorithm developed by Goodin (Ball, 1991). The many fission products actually involved in typical releases are combined into the same simplified chemical groupings as have been adopted by the U.S. NRC for light-water reactor (LWR) severe accidents (Soffer, 1995). More complex release algorithms for TRISO fuel are planned for subsequent versions of GRSAC.

For the larger issue of FP release to the atmosphere, many other complex phenomena are involved, including characterization of the release driving functions and pathways, FP trapping (deposition) and release, chemisorption of vaporized FPs, holdup, filtering, and others.

GRSAC has a simplified FP holdup/release calculation option that can be used to obtain rough estimates of holdup and FP discharges to the atmosphere via the primary system and containment/confinement building. Enhancements are expected in later (code) releases. The model takes as input the percent release from fuel vs. time for each of the eight FP groups (via a post-accident-run data file) and calculates releases into and out of the primary system reactor vessel and containment or confinement building. GRSAC then calculates the flow-dependent effective holdup time constants and group-dependent plateout fractions. The resulting data file of release rates to the environment can then be used by ORIGEN-PRO, which converts the data to HPAC (HASCAL-SCIPUFF) input data files, taking into account the radioactive decay and transmutations occurring since the start of the accident, for calculating atmospheric transport, population dose rates, etc.

Pebble Bed (PBMR) Modular HTGR Cores

One modeling consideration for the pebble bed and GT-MHR annular cores is the radial nodalization breakdown for representing the active core vs. the central reflector. The optimum arrangement would have equal volume hexagonal nodes in both the active core and central reflector regions. For the current (400 MWt) PBMR design, this works out to be four (4) rings of hexagonal nodes for the active core, while for the GT-MHR (600 MWt) design, the active core has three (3) actual rings of hexagonal blocks. The selection of number of active core rings is made by the user via inputs to the RPF (radial peaking factor) design data input screen, which is accessed (along with the APF – Axial Peaking Factor screen) from the Nuclear Design inputs section. Comparisons of the active core vs. center reflector node volumes are given by the design input consistency check program ("smart front end").

The model for the pebble bed core accommodates some of the core's unique features, such as its variable packing density and the variability of the reactivity (or Peaking Factor – PF) in each core node. Random variations in PF are due to the random loading of new (fresh) or recycled fuel balls in various stages of burnup. From the fuel design input screen, the user can input a bed void mean value and a sigma (or plus-minus limit) value for the void uncertainty range. Another flag is used to select between options for characterizing the skew of the distribution. Pebble bed core designs with either solid or graphite pebble (or no) central reflector are accommodated.

The user can also choose whether or not the void variation affects the individual nodes' PFs (in addition to coolant flow resistance).

A related user input in the core design screen is the "boundary void multiplier." Typically the effective pebble bed localized void fraction next to a solid boundary (reflector) is higher than average. The multiplier is applied to all nodes adjacent to the side (and central – if applicable) reflector.

Currently only the German consensus (KFA and others) variation of the Ergun correlation (Cleveland, 1986) for pebble bed pressure drop vs. flow is available, while three correlations are available for effective core thermal conductivity k_c. (Note that for pebble bed cores, k_c is very different from solid graphite conductivity.) The k_c is generally considered to be mainly a function of temperature. Due to the typically wide variations in pebble irradiations in any given node, nominal core k_c values independent of irradiation are assumed. Of the k_c correlations currently included in GRSAC, the combination Zehner-Schlunder and Robold correlation (Hsu, 1994) appears to be the most widely-used. Other options include the correlation derived from SANA tests at KFA (IAEA, 2001), and the default function used in the THERMIX code (Cleveland, 1986). Note that the uncertainty ranges in k_c can be accommodated by the k_c multipliers (for both radial and axial conductivities). Radial and axial differences in graphite conductivity are due to grain orientation, and thus do not apply to pebble bed core conductivity.

2. REFERENCE CASE MODELS

The reference models used for both the GT-MHR and PBMR are based on recent versions of the two designs; however, they do not purport to be entirely representative, since some features are still under development. Hence the results of these simulations should ***NOT*** be viewed as definitive (with either alarm or relief); but rather as starting points for the sensitivity studies, and general indicators of the nature (potential severity, time responses, etc.) for each type of accident.

2.1 Gas Turbine Modular Helium Reactor (GT-MHR)

The GT-MHR-Pu design is currently under development in a program jointly sponsored by the U.S. Department of Energy (DOE/NNSA) and the Russian ROSATOM for burning excess weapons-grade plutonium. Approximate nominal full-power operating parameters for the reference design are given in Table 1 as being “typical” for the commercial LEU-fueled GT-MHR (but not for the higher-temperature Generation-IV version).

Adaptations of the GT-MHR-Pu design for commercial use (with uranium fuel) would likely involve changes in both the TRISO fuel design and confinement/containment requirements, which may affect the RCCS design. The core and vessel arrangement for the GT-MHR is shown in Fig. 1.

2.2 Pebble Bed Modular Reactor (PBMR)

The current South African PBMR design (Fig. 2) has a tall, relatively thin annular core design with fuel pebbles in an annulus surrounding a solid graphite central reflector. Major design parameters and features with nominal full-power operating conditions for the reference case, which do not include mid-2004 changes in the power conversion unit (PCU), are shown in Table 2. On-line refueling allows for recirculation of the pebble fuel (6 to 10 times) until the desired burnups are attained. Fresh fuel is added to maintain the excess reactivity as needed for power maneuvering.

3. GT-MHR ACCIDENTS

3.1 P-LOFC

The reference case P-LOFC for the GT-MHR assumes a flow coastdown and scram at time t=zero, with the passive RCCS operational for the duration. The natural circulation of the pressurized helium coolant within the core tends to make core temperatures more uniform, therefore lowering the peak temperatures, than would be the case for a depressurized core, where the buoyancy forces would not establish significant recirculation flows. The chimney effect in P-LOFC events also tends to make the core (and vessel) temperatures higher near the top. Maximum vessel head temperatures are typically limited by judiciously-placed insulation. High-temperature alloys such as Alloy 800H may be used for the core barrel to allow for head room in that area. For this "reference case" event (Fig. 3), the peak fuel temperature of 1290°C occurs at 24 hr, with the maximum vessel temperature of 509°C at 72 hr. In P-LOFCs, the peak fuel temperature is not a concern (with the typical nominal "limit" for low-burnup TRISO fuel being ~1600°C); the usual concern is more likely to be the maximum vessel temperature and the shift in peak heat load to near the top of the reactor cavity (Fig. 4, top frame), resulting in the axial distribution of maximum fuel temperature peaking towards the inlet (left, or top of the core). Depending on the high-temperature capabilities of the vessel steel, some variations in vessel insulation strategies may be needed.

The parameter most likely to affect the "success" of P-LOFC outcomes, assuming that the RCCS is functioning properly, is the emissivity controlling the radiation heat transfer between the vessel and RCCS (assumed to be 0.8 over the full range of normal-to-accident temperatures). For an assumed (unlikely) 25% decrease in both vessel and RCCS surface effective emissivities, the peak vessel temperature is 37°C higher. The difference in peak fuel temperatures is small (7°C), which is indicative of the decoupling between the peak fuel and vessel temperatures in LOFC events.

3.2 D-LOFC

The D-LOFC reference case assumes a rapid depressurization along with a flow coastdown and scram at time = zero, with the passive RCCS operational. It also assumes that the depressurized coolant is helium (no air ingress). This event is also known as a "conduction-heatup" (or "-cooldown") accident, since the core effective conductivity is the dominant mechanism for the transfer of afterheat from the fuel to the vessel. In the reference case, the maximum fuel temperature peaks at 1494°C 53 hr into the transient, and the maximum vessel temperature (555°C) occurs at time = 81 hr (Fig. 5). Note that in this case, the peak fuel (and vessel) temperatures occur near the core beltline, or mid-plane (Fig. 4, bottom frame), rather than near the top as in the P-LOFC, since the convection effects for atmospheric pressure helium are insignificant.

There are several parameter variations of interest for this accident, which is generally considered to be the defining accident for determining the "reference case accident peak fuel temperature." These variations are: effective core graphite conductivity (which is a function of irradiation history, temperature, orientation, and annealing effects), afterheat power vs. time after shutdown; and power peaking factor distribution in the core after shutdown. If maximum vessel temperatures are of concern, emissivity effects should be considered.

For variations from this "reference case" event, the sensitivity of peak fuel temperature for the various assumed parameter changes are as follows:

1) 20% decrease in core conductivity (with annealing): a 124°C increase in peak fuel temperature.
2) 15% increase in afterheat: a 120°C increase in peak fuel temperature.
3) 20% increase in maximum radial peaking factor: a 30°C increase in peak fuel temperature.

The emissivities figure in most prominently in the estimation of the maximum vessel temperatures. An assumed 25% decrease in vessel and RCCS opposing surface emissivities resulted in an increase in maximum vessel temperature of 54°C, while the increase in peak fuel temperature was only 14°C.

3.3 D-LOFC with Air Ingress

These accidents assume the D-LOFC is followed by ingress of ambient air into the primary system, either just after the depressurization is complete (to ambient pressure), or at some later time. The oxidation of core graphite that follows generates heat, in addition to the afterheat, and the air (gas) flows subsequently provide for convective cooling (or heating) of the core.

Key factors are the net air flow rate into the reactor vessel and core, and ultimately the "availability" of fresh air over the course of the accident. The net air flow through the core is strongly dependent on the buoyancy forces due to differential temperatures and the flow resistances in the core and at the break(s).

For a single "break" or opening in the primary system, calculations and experiments have shown that it may take days before a sustained, significant net air inflow is established. This process would involve the diffusion of air into the helium-filled top region of the reactor vessel. For a much less likely case of a double break in the vessel allowing access to both the top and bottom of the core, a chimney-like configuration could promote a higher net air flow more quickly. Since the reactor cavity is typically below ground and to some extent sealed-off, even for a confinement (vs. "leak-tight" containment), at some point early in the accident there would not be oxygen-rich air available to sustain significant graphite oxidation rates. Air (oxygen) availability limitation models are currently not incorporated in GRSAC.

When a net air ingress flow is established, oxidation begins in the lower part of the core, in the bottom reflector area. However, the oxygen is typically depleted before the "air" reaches the active core area. Later in the transient, however, oxidation may occur in the lower part of the active core if the lower reflector has cooled sufficiently and no longer oxidizes. For typical GT-MHR single-break transients, power generated from the oxidation is comparable to the afterheat power; however, since it is deposited in the lower part of the core, the peak fuel temperature is about the same as for D-LOFC cases without air ingress. Depending on break assumptions and other factors, the oxidation rates can be quite high. Up to 2% of the core graphite per day may be consumed if unlimited fresh air is available.

Oxidation rate estimates do not account for core geometry changes, and are progressively less realistic as the percent of total core graphite oxidized increases. Variation in the time at which a net air ingress flow occurs (within the first week) has little effect on peak fuel temperature, and the total graphite oxidized is roughly proportional to the air-flow exposure time. With no mitigation assumed, the air flow and oxidation rates would eventually decrease due to limitations in available oxygen and the decreased buoyancy forces as the core cools, but they could either increase or decrease due to geometry changes.

Variations of the oxidation rate multiplier coefficients over factors of ~2 or more in the oxidation rate equations (described in detail in Wichner, 1999) made negligible differences in the accident outcomes (in terms of peak fuel or vessel temperatures). However, the rate equations do affect the location in the core where the oxidation is predicted to occur.

For the case of a double vessel break that forms a chimney, the air ingress flow is assumed to begin immediately following depressurization. A higher flow (~double that of the single-break case where core flow resistance is limiting) produces a higher oxidation rate, and the oxidation also penetrates further up the core, into the fueled region. If the available oxygen is limited, the total damage done would be about the same as in the single-break case, but it would happen faster. Figure 6 shows axial profiles of peak fuel temperature (top frame) and oxidation rate (bottom frame) for an example case with break flow restrictions (air flow rates ~ 0.3 kg/s) and oxygen penetration into the fuel region, about one week after the start of an accident. All these analyses clearly show that if such extremely unlikely accidents are considered, some mitigating actions to eventually limit fresh air availability must be incorporated.

3.4 P-LOFC with ATWS

Although all modular HTGR designs have several diverse safety-grade scram or other reactivity shutdown systems, ATWS accidents are considered. The early part of the transient (Fig. 7) is very similar to the P-LOFC with scram since the negative temperature-reactivity feedback coefficient is quite strong and reduces the power quickly as the nuclear average temperature increases and the

Xenon poison builds up. Recriticality occurs here at about 32 hr and, with no further action, peak fuel temperature exceeds the 1600ºC "limit" after ~2 days. The oscillations in power (Fig. 8) upon recriticality are characteristic of these transients, and are (probably) not due to numerical instabilities in the calculation. The maximum vessel temperatures are also well beyond acceptable values for this case. Since a significant fraction of the core reaches temperatures beyond 1600°C, GRSAC's (simplified time at temperature) fuel performance model predicts significant fuel failure occurring after the first two days.

Variations in the accident consequences are naturally sensitive to the assumed values of fuel and moderator temperature-reactivity feedback coefficients (functions), which are temperature and burnup dependent. Another factor of interest is the temperature-reactivity feedback effects of the central and side reflectors.

An interesting variation on this case is one in which, after recriticality occurs, the operator valiantly succeeds in restarting the SCS with still no scram. This added cooling reduces the core nuclear average temperature and thus increases the power level. However, in the hotter (higher peaking factor) channels, the convection cooling flows are lower (higher gas temperature leads to increased viscosity, which leads to higher friction factor, which leads to lower flow). We call this effect "selective undercooling." In a special case where a SCS flow restart at reduced capacity (~5 kg/s) is assumed to occur ~4 hr after recriticality, there is a sharp increase in peak fuel temperature over the period of extra "emergency" cooling which adds to, rather than mitigates, fuel failure problems.

3.5 D-LOFC with ATWS

As in the case of the P-LOFC with ATWS, there is very little effect of the ATWS seen vs. the non-ATWS D-LOFC until recriticality occurs (at ~38 hr). The oscillation in power level is not as extensive as in the P-LOFC case. As in the P-LOFC ATWS case, maximum fuel temperatures exceed 1600°C after ~2 days.

4. PBMR ACCIDENTS

4.1 P-LOFC

The reference case P-LOFC for the PBMR is similar to the corresponding GT-MHR accident, with a peak fuel temperature of 1266°C occurring at ~37 hours, and with a maximum reactor vessel temperature of 501°C at 77 hr. Sensitivities to variations in the emissivities of the vessel and RCCS are nearly identical to those for the GT-MHR.

4.2 D-LOFC

In the D-LOFC reference case "conduction-heatup" accident, peak fuel temperature peaks at 1517°C at ~77 hr into the accident, and for this configuration, maximum temperatures for the reactor vessel (SA 508) and core barrel (316 SS) are not of concern.

The PBMR's on-line refueling results in a random mixing of pebbles in the core with various burnups and irradiation histories. Also, since the effective core conductivity is usually considered to be primarily due to radiant heat transfer between pebbles, it is modeled as a function of temperature. The reference conductivity correlation is derived from the Zehner-Schlunder and Robold correlations.

Variations on this "reference case" show the sensitivity of peak fuel temperature for changes as follows:

1) 25% decrease in core conductivity: 165°C increase in peak fuel temperature.

2) Use of the THERMIX code default core conductivity correlation: 64°C increase in peak fuel temperature.
3) Use of the core conductivity correlation derived from the SANA tests by H. F. Niessen (see Fig. 4-109 in IAEA, 2001): 103°C decrease in peak fuel temperature.
4) 15% increase in afterheat: 121°C increase in peak fuel temperature.
5) 20% increase in maximum radial peaking factor: 17°C increase in peak fuel temperature.

4.3 D-LOFC with Air Ingress

As with the GT-MHR, the key factors are the net air flow rate into the reactor vessel and core and the availability of fresh air. Because of the higher flow resistance of the pebble bed core, the net air flow rates are lower for core-resistance-limited air ingress cases. Typically, power generated from the oxidation is up to half that of the afterheat power; but again, since it is deposited in the lower part of the core, the peak fuel temperatures are about the same as in D-LOFC cases with no air ingress. The total oxidation rates can still be quite high, however, consuming up to 1% of the core graphite per day if unlimited fresh air is available. Likewise, for unlikely "chimney" cases (double vessel breaks allowing air access to both the bottom and top of the core), oxidation would penetrate further up the core into the pebble fuel region. Since the pebble shells (coatings) are not "reactor grade graphite," oxidation rates are higher than those for the GT-MHR fuel blocks. As in the case of GT-MHR air ingress scenarios, mitigating actions to limit the availability of fresh air are necessary.

4.4 P-LOFC with ATWS

In this PBMR design, recriticality occurs at about 28 hours, and peak fuel temperature reaches the 1600°C "limit" at ~36 hr. Maximum vessel temperatures also go higher, eventually, to unacceptably high values. Without corrective action, fuel failure after 7 days would be significant. Variations in this accident are sensitive to fuel and moderator temperature-reactivity feedback coefficients. As with the GT-MHR, if after recriticality the SCS is started (with still no scram), peak fuel temperatures would exceed limits even more due to the selective undercooling effect.

4.5 D-LOFC with ATWS

Recriticality occurs at ~31 hr. In this case, peak fuel temperature exceeds the "limiting value" of 1600°C at ~38 hr, and the maximum vessel temperature also, after a week, reaches ~500°C and is still rising gradually. Without mitigation, fuel failure at the end of a week would be significant and unacceptable.

5. CONCLUSIONS

Both modular HTGR designs show excellent accident prevention and mitigation capabilities even for well-beyond design-basis accidents due to their inherent passive safety features. The 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, since their finalized design features have not been factored into the simulations. Other aspects of the predictions, such as assumed irradiated core thermal conductivities, temperature-reactivity feedback functions, and heat-sink related emissivities, are also dependent on many factors that should be considered in detail for specific design features and operating conditions.

The value of sensitivity studies at this point (i.e., relatively early) in a design and analysis phase is to provide estimates of the uncertainties in the predictions, and to guide further efforts in improving the design as well as the accuracy of the predictions. The results for both concepts have shown the importance of effective core thermal conductivity and afterheat functions in the predictions of peak fuel temperature.

It was also shown, for the accidents postulated, that wide variations in the graphite oxidation rate function multipliers do not significantly affect peak fuel temperatures, since the oxygen in the incoming air for postulated buoyancy-driven air ingress accidents is typically oxygen-depleted before reaching the active core, except for higher-flow, prolonged accident cases. 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. It is clear, however, that for long-term air ingress accidents, the actual availability of "fresh" air needs to be considered, and limited. Often overlooked is the fact that vessel-break accidents that could lead to such large-scale oxidation events are extremely unlikely. For the GT-MHR reactor vessel design, for example, coincident vessel breaks in both the top and the bottom sections would probably result in both breaks being in the coolant inlet path, and even then would not provide a ready "chimney" for enhanced natural circulation. For single-break accidents, novel "passive" means have been proposed which inhibit initiation of significant air ingress flows (Takeda, 2004).

For the long-term ATWS cases, for both concepts, these preliminary results show that there is a concern for peak fuel temperatures much higher than 1600°C following recriticality. Results do indicate, however, that no fuel failures would be expected for about the first two days, leaving ample time to insert negative reactivity. A day-long requirement to ensure negative reactivity insertion should neither be too large a challenge for a designer nor too great a concern for a regulator. SCS restarts during an ATWS are shown to be counterproductive due to "selective undercooling" effects.

Water (steam) ingress accidents are not considered here. The Brayton cycle gas-turbine design, compared to the steam cycle, greatly reduces the chance of water ingress since the primary to secondary pressure differences are maintained for the gas to exit rather than the water to enter the primary system. Steam ingress into a hot, critical core could add positive reactivity and cause significant corrosion, perhaps inducing fuel failures as well. However unlikely, some cases may be postulated that could turn the flow around, and such eventualities should be considered and avoided by design.

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Table 1. GT-MHR-Pu module design and full power operating parameters

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	7.01/2.64
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
<u>Other operating parameters (GRSAC simulation)</u>:	
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

Table 2. PBMR module design and full power operating parameters

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

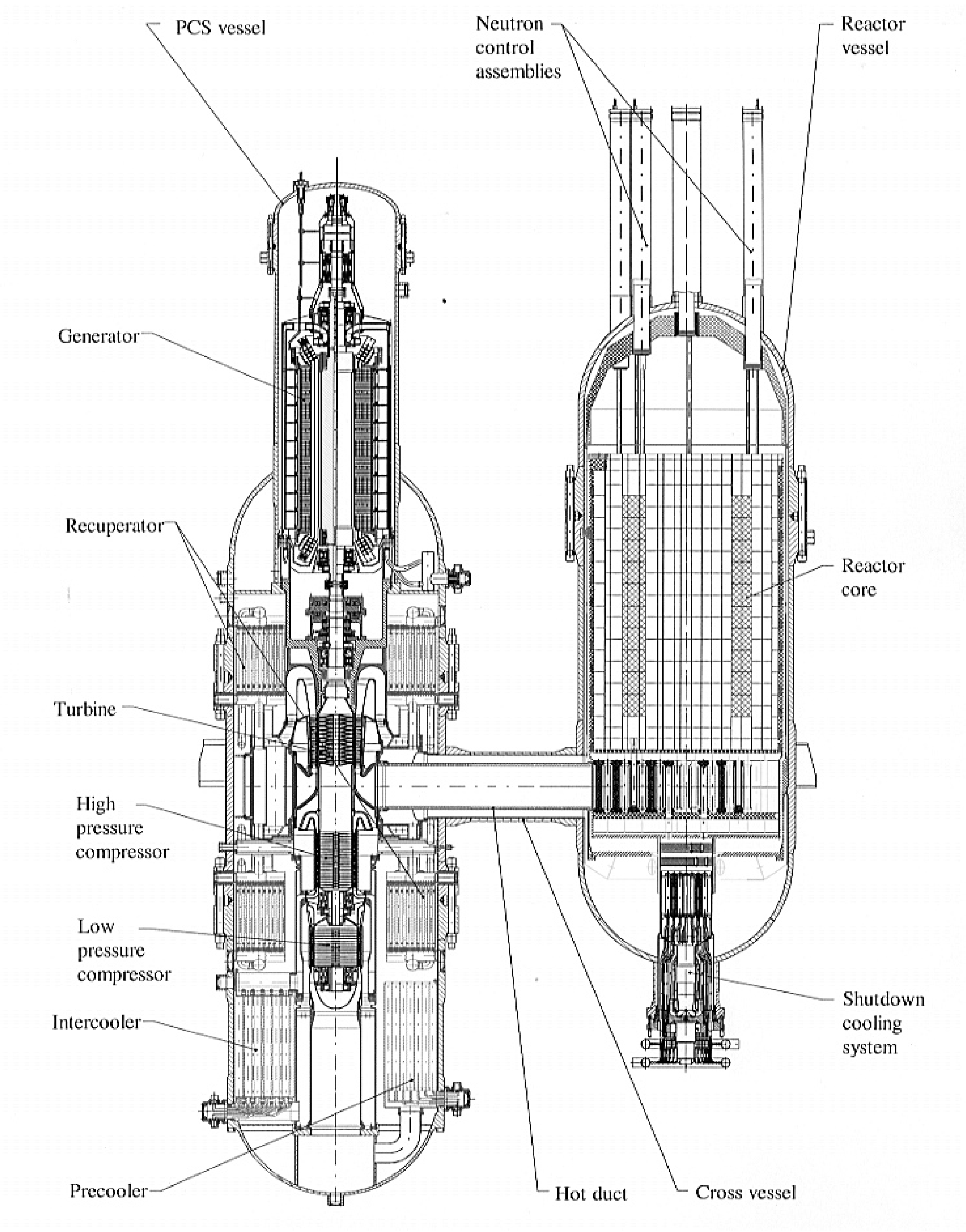

Fig. 1. GT-MHR primary system

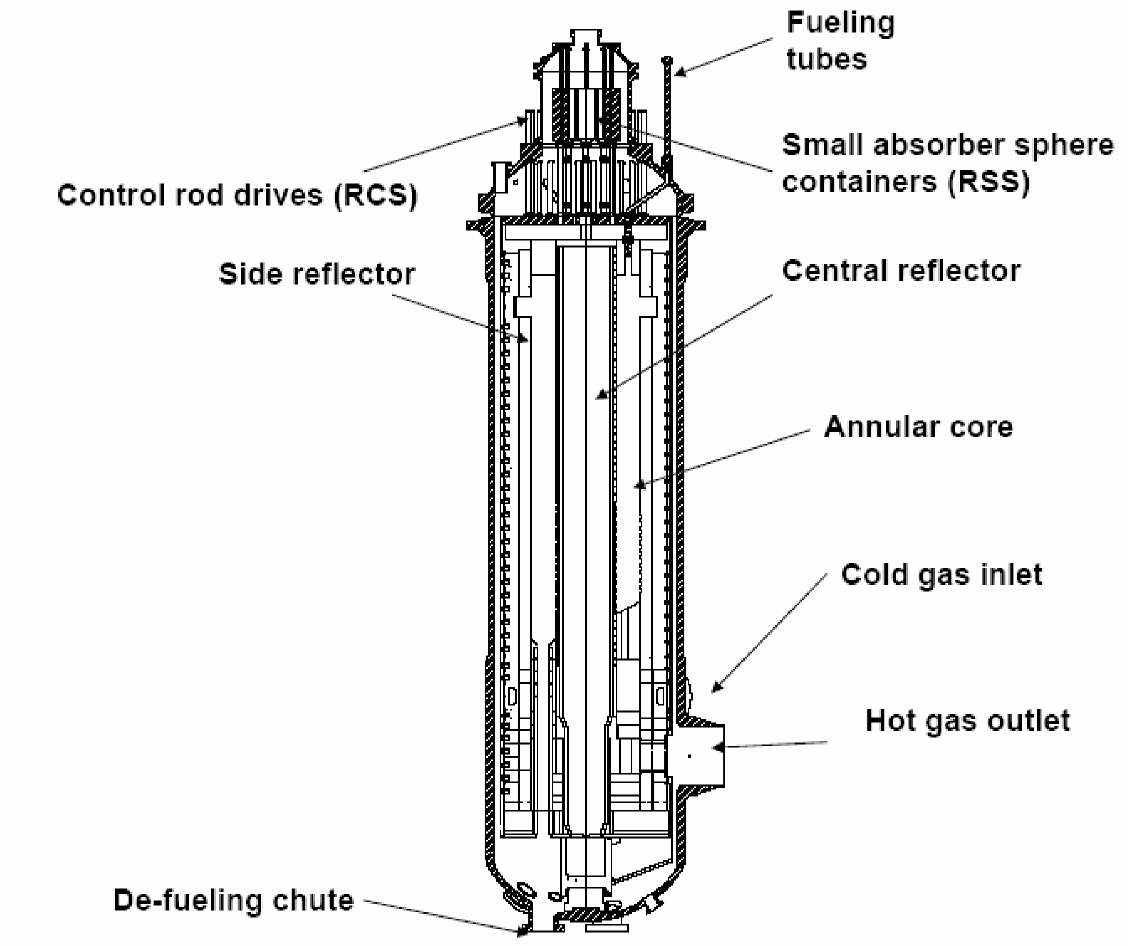

Fig. 2. PBMR reactor unit – vessel assembly

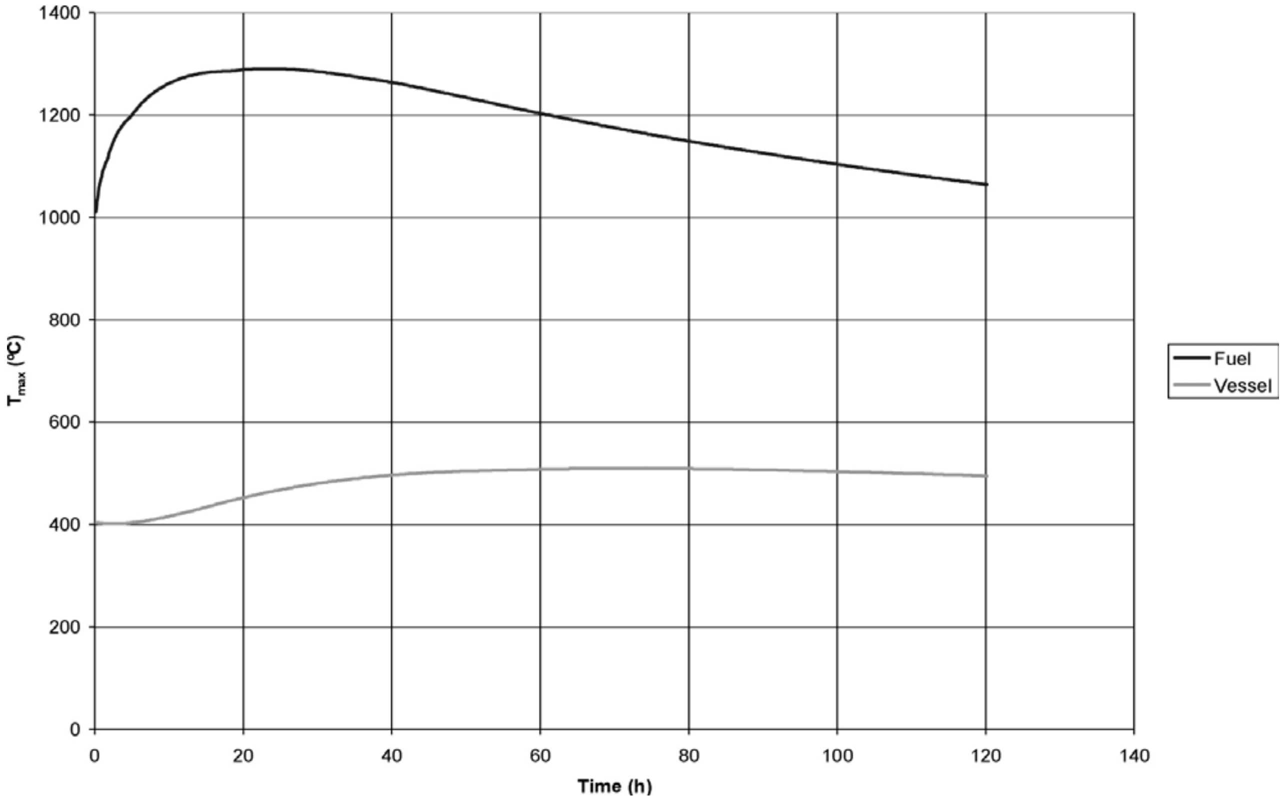

Fig. 3. GT-MHR P-LOFC Reference case – maximum fuel and vessel temperatures vs. time

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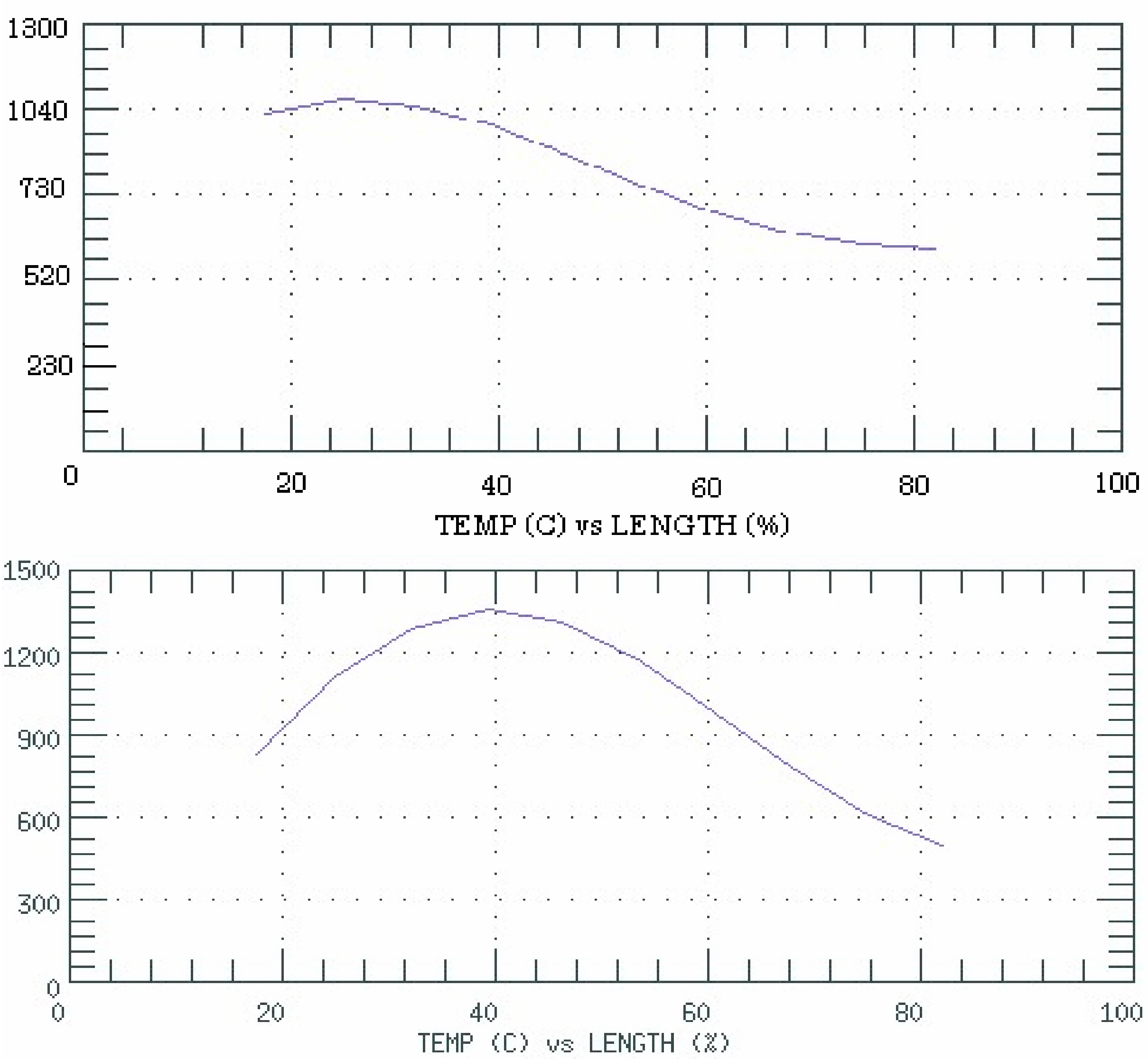

Fig. 4. Example GT-MHR maximum fuel temperature axial profiles during LOFCs: pressurized (top frame) and depressurized (bottom frame). Left to right = top to bottom of core.

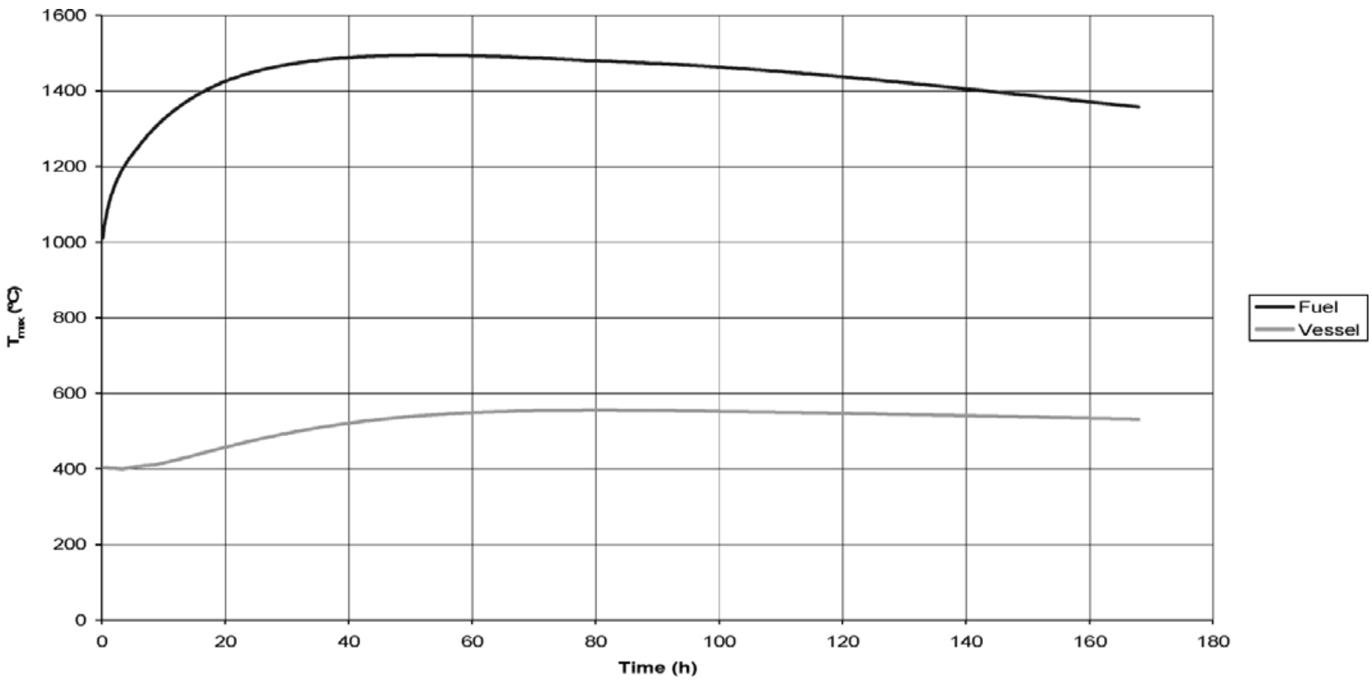

Fig. 5. GT-MHR D-LOFC Reference case – maximum fuel and vessel temperatures vs. time

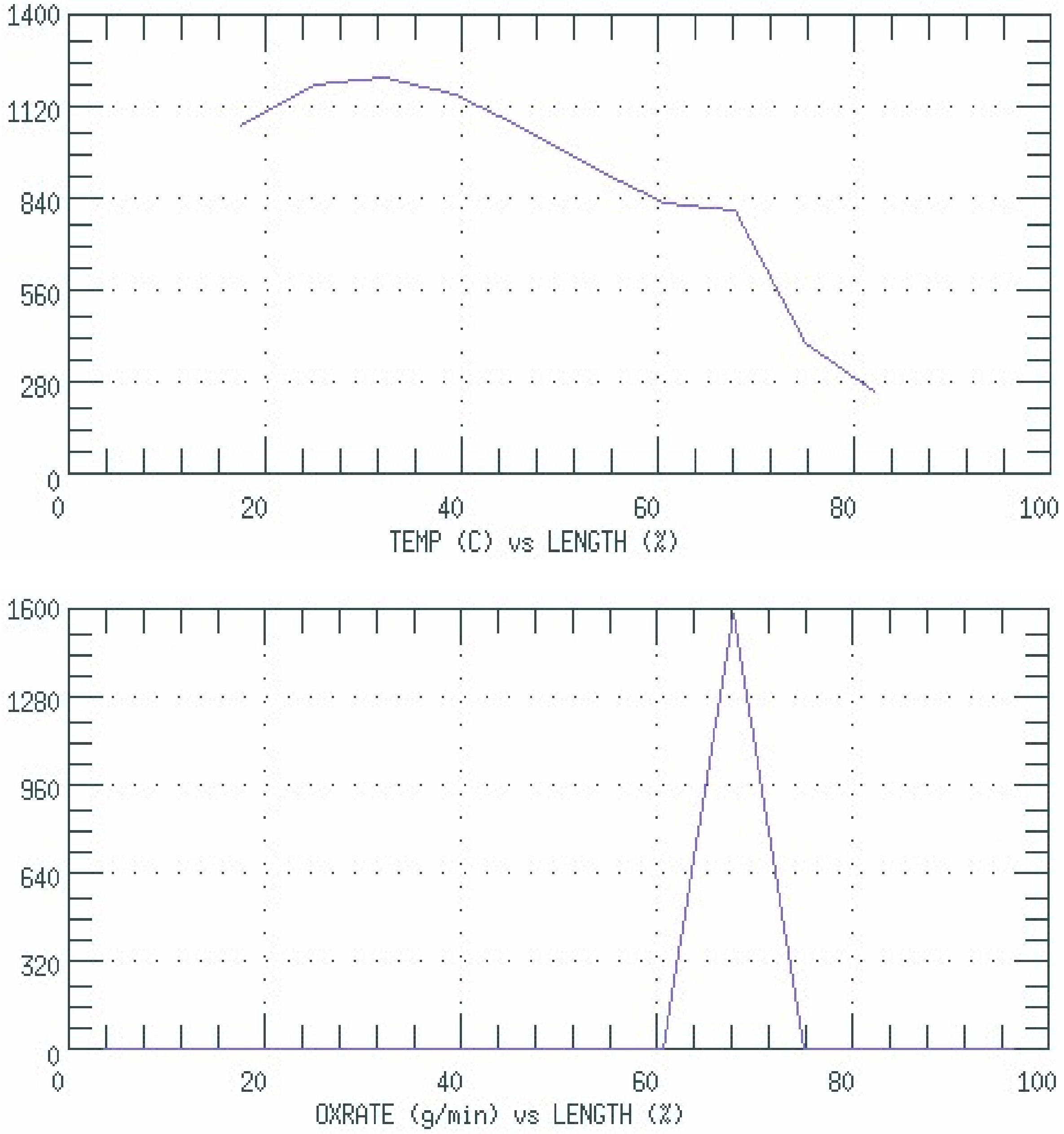

Fig. 6. Example GT-MHR double-break air ingress axial profiles: maximum fuel temperature (top frame) and graphite oxidation rate (bottom frame). Left to right = top to bottom of core.

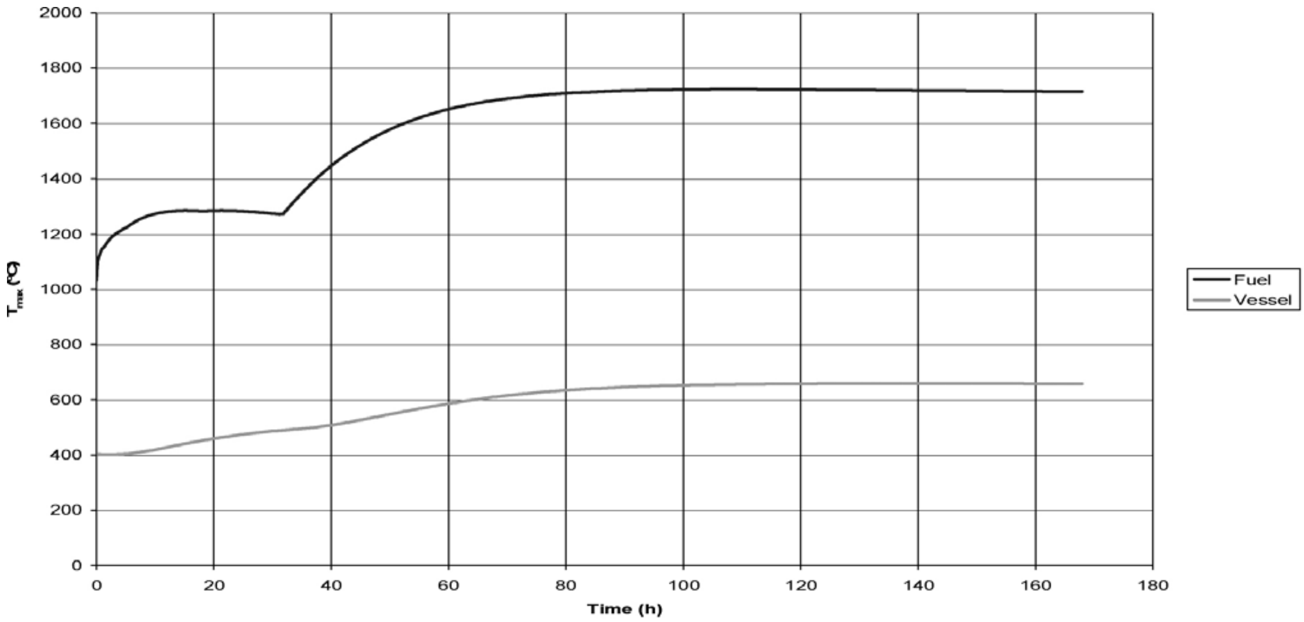

Fig. 7. GT-MHR P-LOFC with ATWS – maximum fuel and vessel temperature vs. time

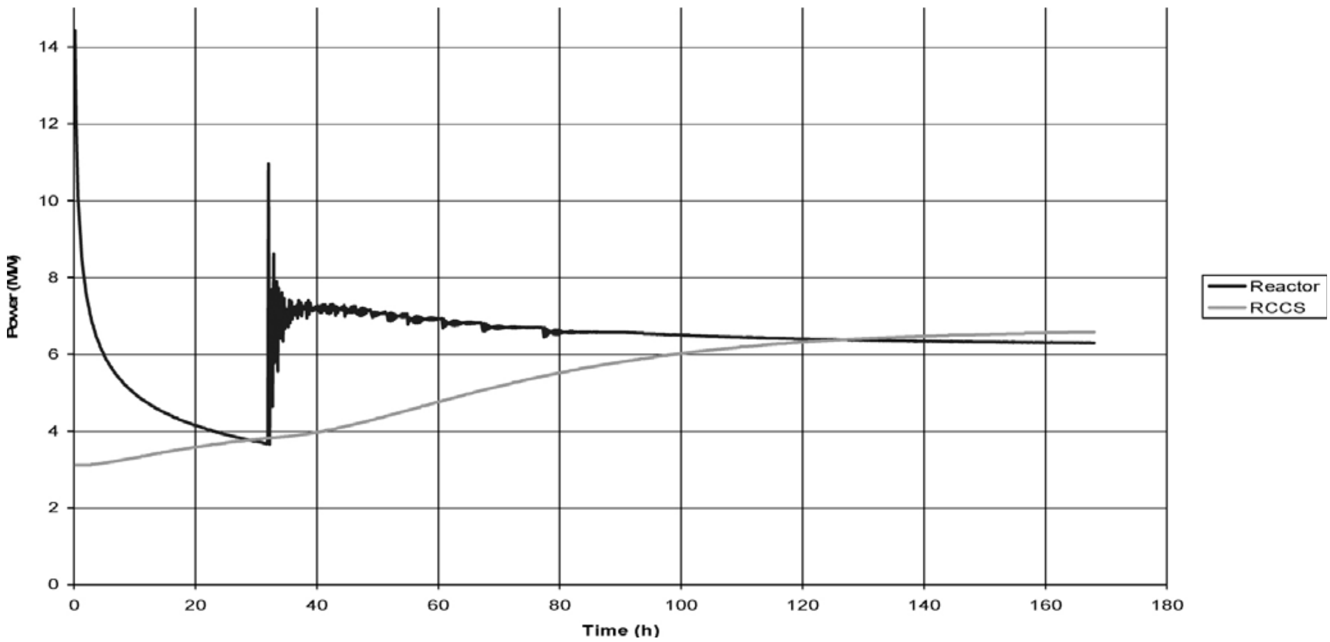

Fig. 8. GT-MHR P-LOFC with ATWS – reactor and RCCS power vs. time