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

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

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**Abstract:** The results of various accident scenario simulations for the two major Modular High Temperature Gas-cooled Reactor (MHTGR) variants (prismatic and pebble-bed cores) are presented. Sensitivity studies attempt to account for uncertainty ranges in some of the more crucial system parameters as well as for occurrences of equipment and/or operator failures or errors. Both of the MHTGR designs studied – the 400-MW(t) Pebble Bed Modular Reactor (pebble) and the 600-MW(t) Gas-Turbine Modular Helium Reactor (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 peak), significantly reduce concerns about uncertainties in the models, the initiating events, and the equipment and operator responses.

**Key words:** Nuclear energy, electricity, Modular HTGR, Brayton cycle, accident analysis

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## 1. INTRODUCTION

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

The Graphite Reactor Severe Accident Code (GRSAC) development, use, and validation exercises began over 25 years ago with several predecessor codes (Ref. 1). Current interest in GRSAC involves the simulation of accident scenarios for MHTGR designs, and simulation of benchmark transients run on 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). There are options to include Anticipated Transients Without Scram (ATWS) accidents and to model air ingress accidents, simulating the oxidation of graphite (and other) core materials.

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 MHTGR designs use the 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, the likelihood of water-ingress accidents is virtually eliminated.

## 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 jjointly sponsored by the U.S. Department of Energy (DOE/NNSA) and the Russian MINATOM 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 Gen-IV version).

**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 |
| **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 |

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. Core, vessel, power conversion unit (PCU) and RCCS arrangements for the GT-MHR are 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 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 as needed to maintain the desired excess reactivity as required for power maneuvering.

- Electrical output 286 MW(e) per module
- Each module includes Reactor System and Power Conversion System
- Reactor System 600 MW(t), 102 column, annular core, hexagonal prismatic blocks similar to FSV
- Power Conversion System includes generator, turbine, compressors on single shaft, surrounded by recuperator, pre-cooler and inter-cooler

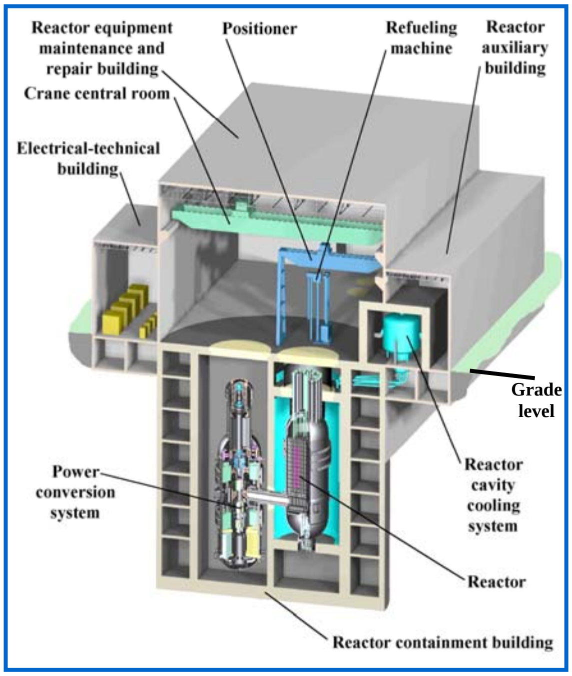

FIG. 1. *GT-MHR Module Layout*

| 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) |

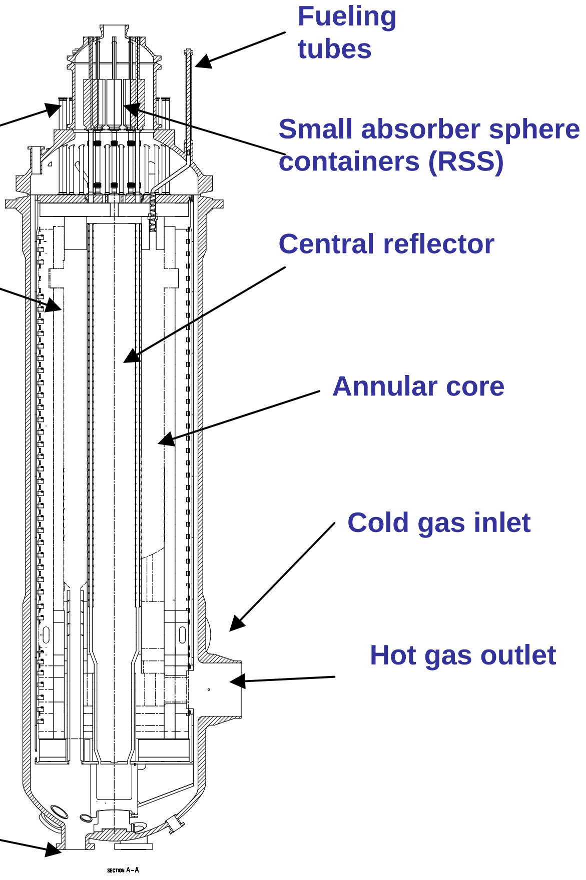

FIG. 2. *PBMR Reactor Unit – Vessel Assembly*

**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 |

## 3. GT-MHR ACCIDENTS

3.1 P-LOFC: The reference case P-LOFC assumes a flow coastdown and scram at time = 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, and the use of Alloy 800H for the core barrel allows for head room in that area. For this “reference case” event (Fig. 3), the peak fuel temperature of 1290°C occurred at 24 hr, and the maximum vessel temperature was 509°C at 72 hr. In P-LOFCs, the peak fuel temperature is not a concern (with the typical nominal “limit” for low-burnup 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.

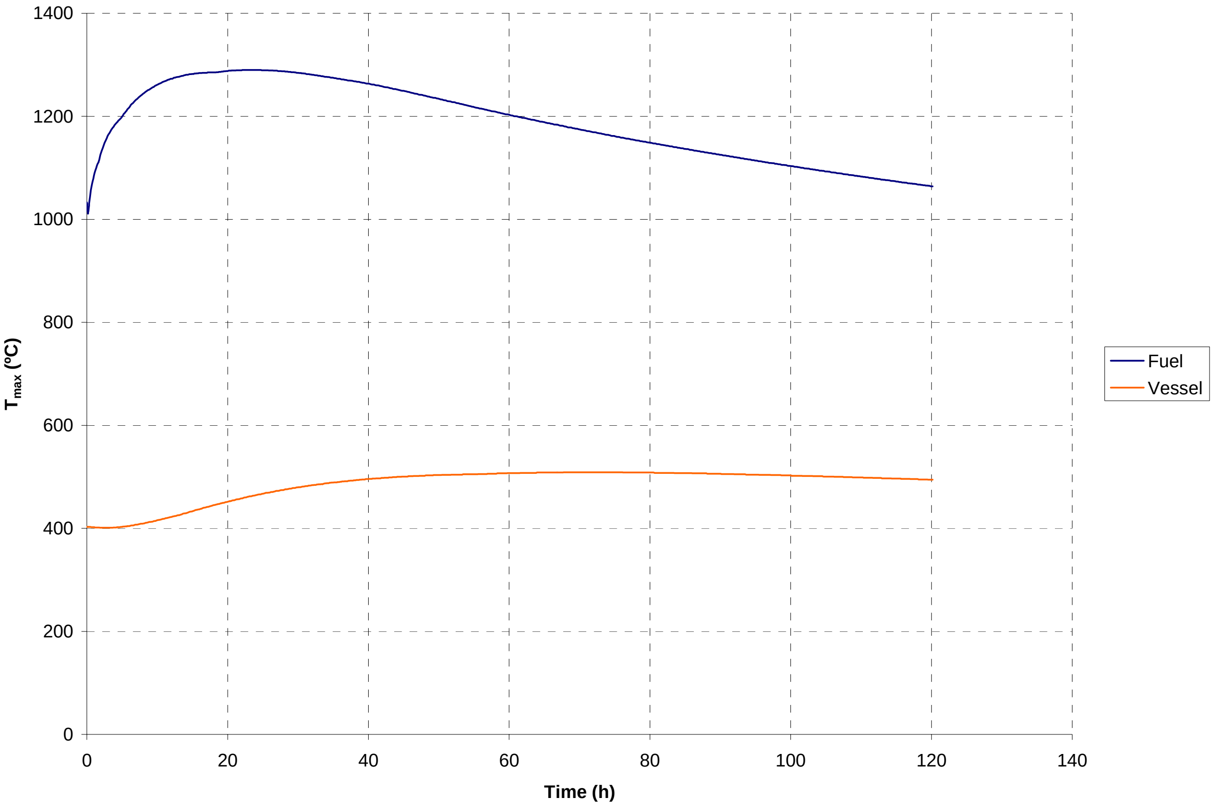

FIG. 3. *GT-MHR P-LOFC reference case – maximum fuel and vessel temperatures*

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 typical 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" 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 center (Fig. 4, bottom frame), rather than near the top as in the P-LOFC, since the convection effects for atmospheric pressure helium are nil.

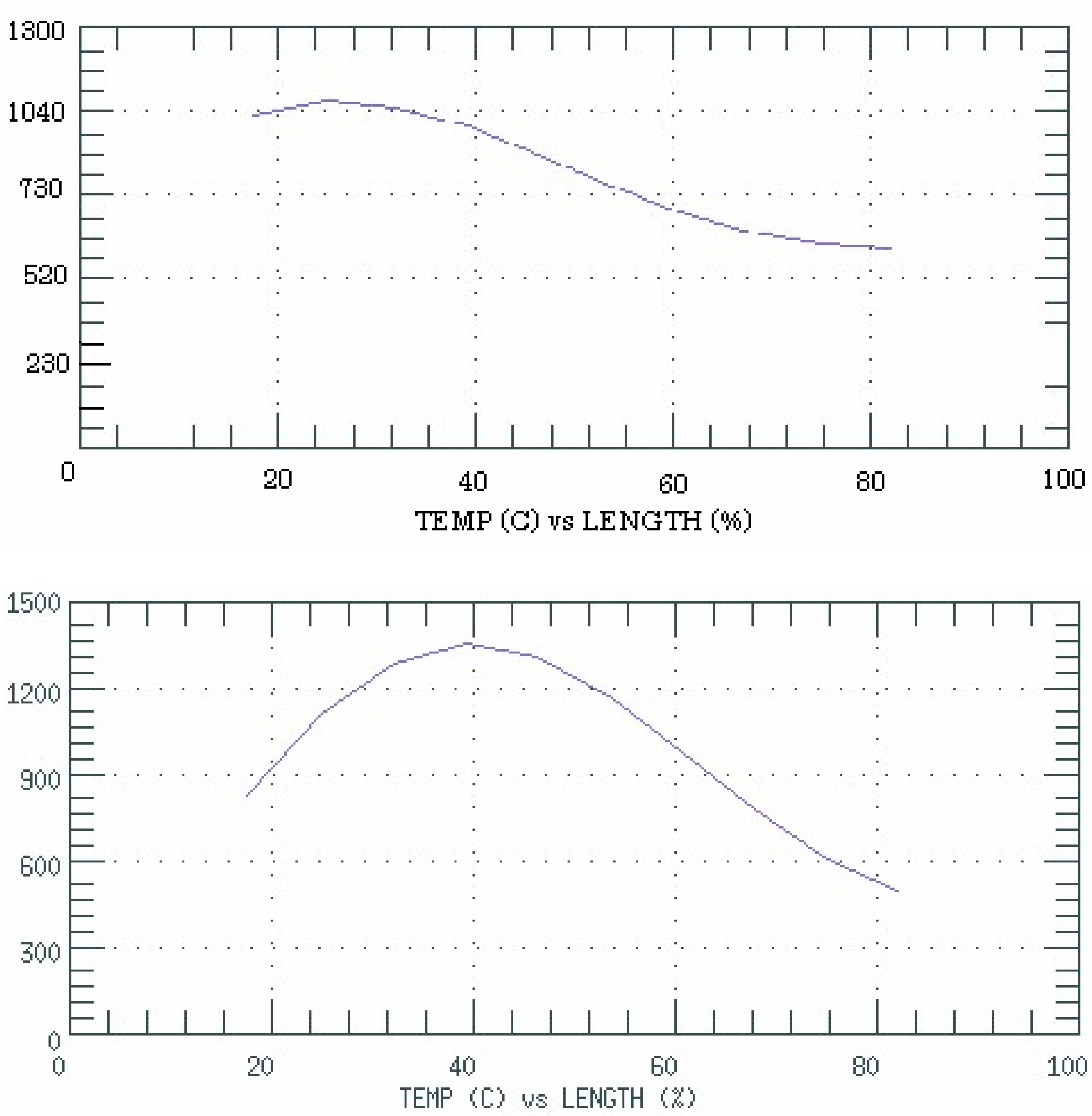

FIG.4. *Maximum fuel temperature axial profiles for P-LOFC (top frame) and D-LOFC (bottom)*

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 whether or not annealing is accounted for), 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 again 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 (including annealing effects): a 124°C increase in T(fuel)-max.
2) 15% increase in afterheat: a 120°C increase in T(fuel)-max.
3) 20% increase in maximum radial peaking factor: a 30°C increase in T(fuel)-max.

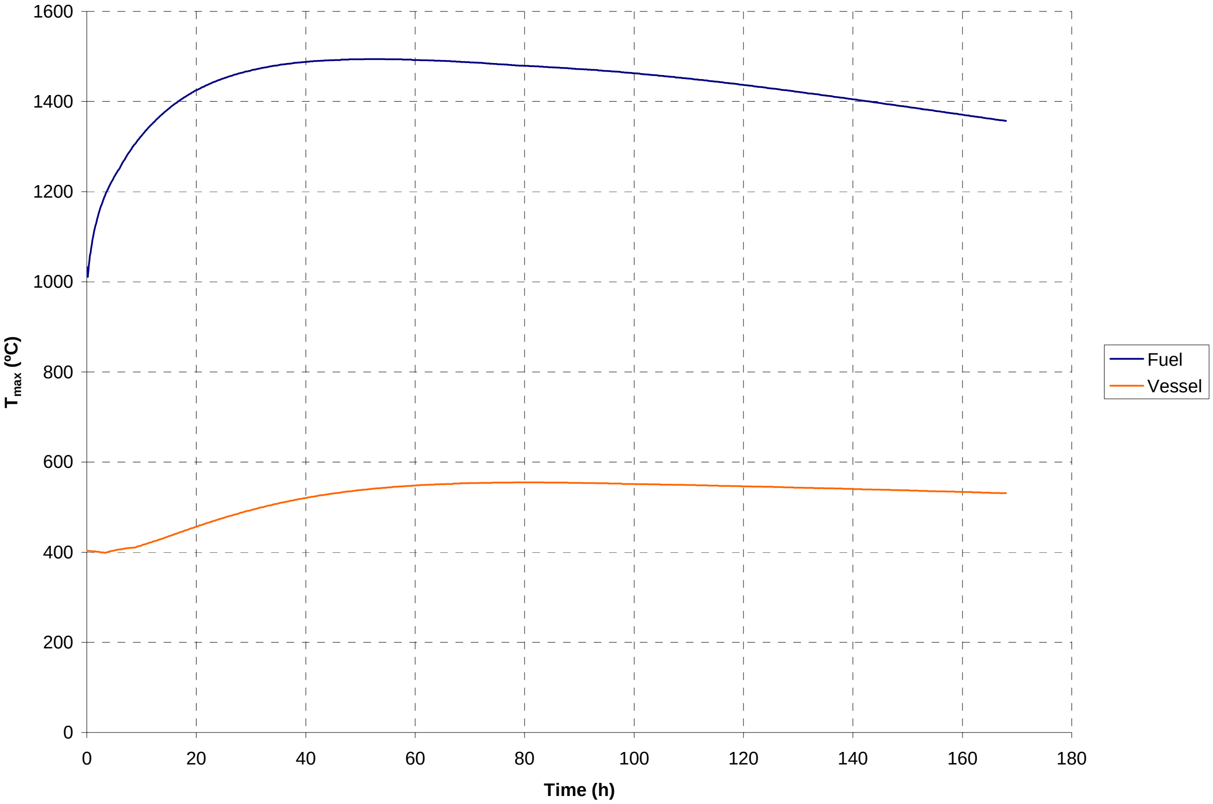

FIG. 5. *GT-MHR D-LOFC reference case – maximum fuel and vessel temperatures*

For the maximum vessel temperatures, again the emissivities figure in most prominently. 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 T(fuel)-max was only 14°C.

3.2 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 mainly dependent on the buoyancy forces due to differential temperatures and the flow resistances in the core.

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

In the first case it is assumed that a single break occurs and it takes 2 days to establish the net air ingress flow. At that time, oxidation occurs in the lower part of the core, in the bottom reflector, but the oxygen is depleted before the "air" reaches the active core area. Later in the transient, however, oxidation occurs in the lower part of the active core, since the lower reflector has cooled sufficiently and no longer oxidizes. For this case, the maximum (initial) oxidation power is ~350 kW, and T(fuel)-max is about the same as in the D-LOFC case with no air ingress.

Assuming unlimited fresh air availability at the break, after 7 days, ~1.5 % of the total of the core graphite is oxidized. These estimates do not account for core geometry changes, and are progressively less realistic as the percent of total core graphite oxidized increases. Variations in the time at which a net air ingress flow begins had little effect on T(fuel)-max, but affected the total graphite oxidized within the one-week period roughly proportional to the air 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.

Variations in the oxidation rate equations (described in detail in Ref. 2) made negligible differences in the accident outcomes (in terms of peak fuel or vessel temperatures), varying the oxidation rate multiplier coefficients over factors of 2 or more. However, the rate equations do affect the location in the core where the oxidation takes place (i.e., the lower reflector, support system, and lower part of the active core).

For the case of a double vessel break that forms a chimney, and assuming a 2-meter high chimney is somehow established above the vessel, the air ingress flow is assumed to begin immediately following depressurization. The higher flow (~double that of the single-break case) produces a higher oxidation rate, and the oxidation also penetrates further up the core. Figure 6 shows the axial profiles of the peak fuel temperature (top frame) and the oxidation rate (bottom frame) one week into the accident. T(fuel)-max is somewhat less than in the reference case due to the cooling effect of the higher air coolant flow rate. Assuming unlimited fresh air availability, after 7 days ~5% of the total core graphite is oxidized. This clearly shows that if such extremely unlikely accidents are to be considered, some mitigating actions (to eventually limit fresh air availability) need to be incorporated.

3.3 P-LOFC with ATWS: Although MHTGR 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 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, T(fuel)-max reaches 1724°C at 108 hr. 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 effect is driven by a combination of time lags in the heating-cooling process and spatially-dependent flow oscillations. The maximum vessel temperatures are also well beyond acceptable values for this case, reaching 659°C at 138 hr. A significant fraction of the core reaches temperatures beyond 1600°C, and a simplified (time at temperature) fuel performance model predicts ~15% fuel failure.

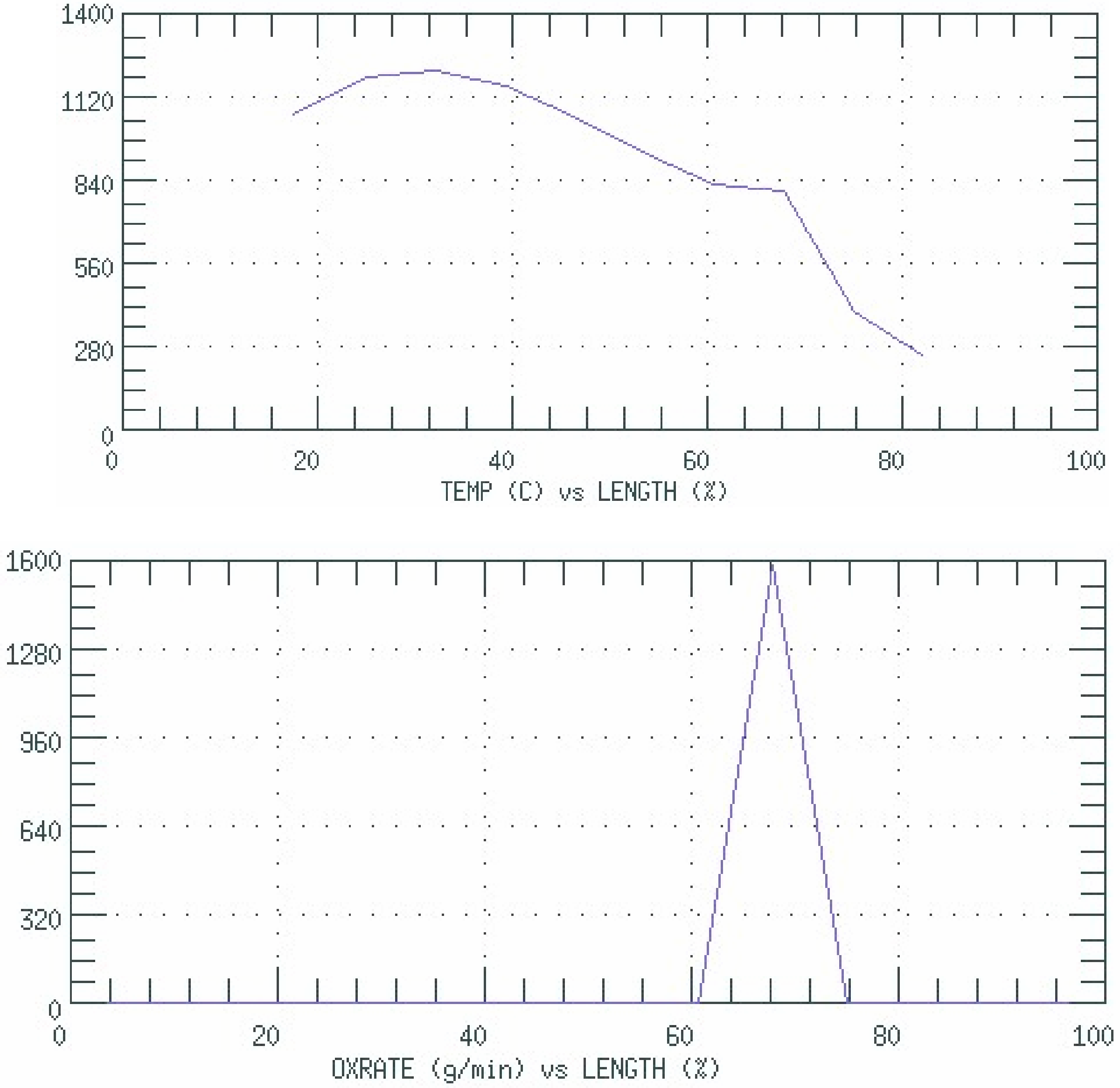

FIG. 6. *GT-MHR double-break air ingress axial profiles: maximum fuel temperature (top frame) and graphite oxidation rate (bottom)*

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 → increased viscosity → higher friction factor → lower flow). We call this effect selective undercooling. In a case where the SCS flow restart (at reduced capacity, ~5 kg/s) occurred ~4 hr after recriticality, there was a sharp increase in T(fuel)-max over the period of extra "emergency" cooling which added to, rather than mitigated, fuel failure problems.

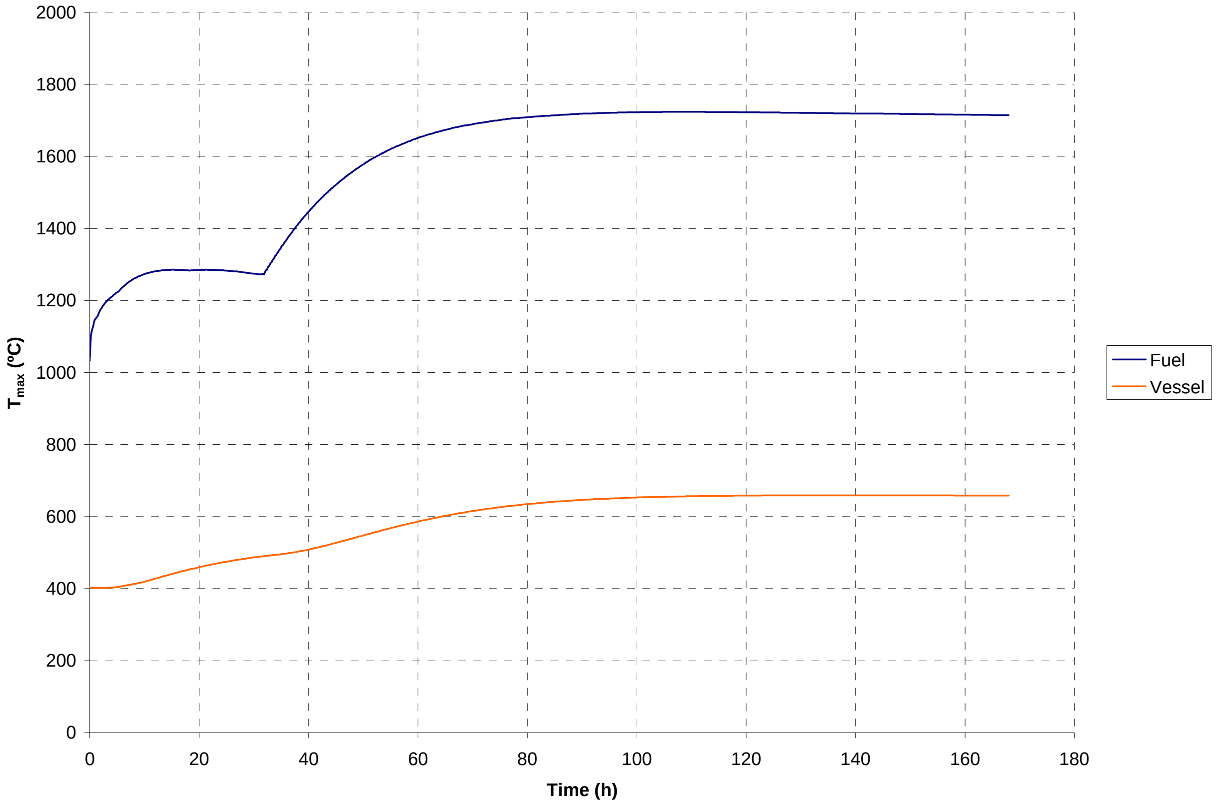

FIG. 7. *GT-MHR P-LOFC with ATWS – maximum fuel and vessel temperatures*

3.3 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, perhaps because the buoyancy-driven flows are nil. As in the P-LOFC ATWS case, maximum fuel temperatures exceeded 1600°C.

## 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, 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, T(fuel)-max peaks at 1517°C 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.

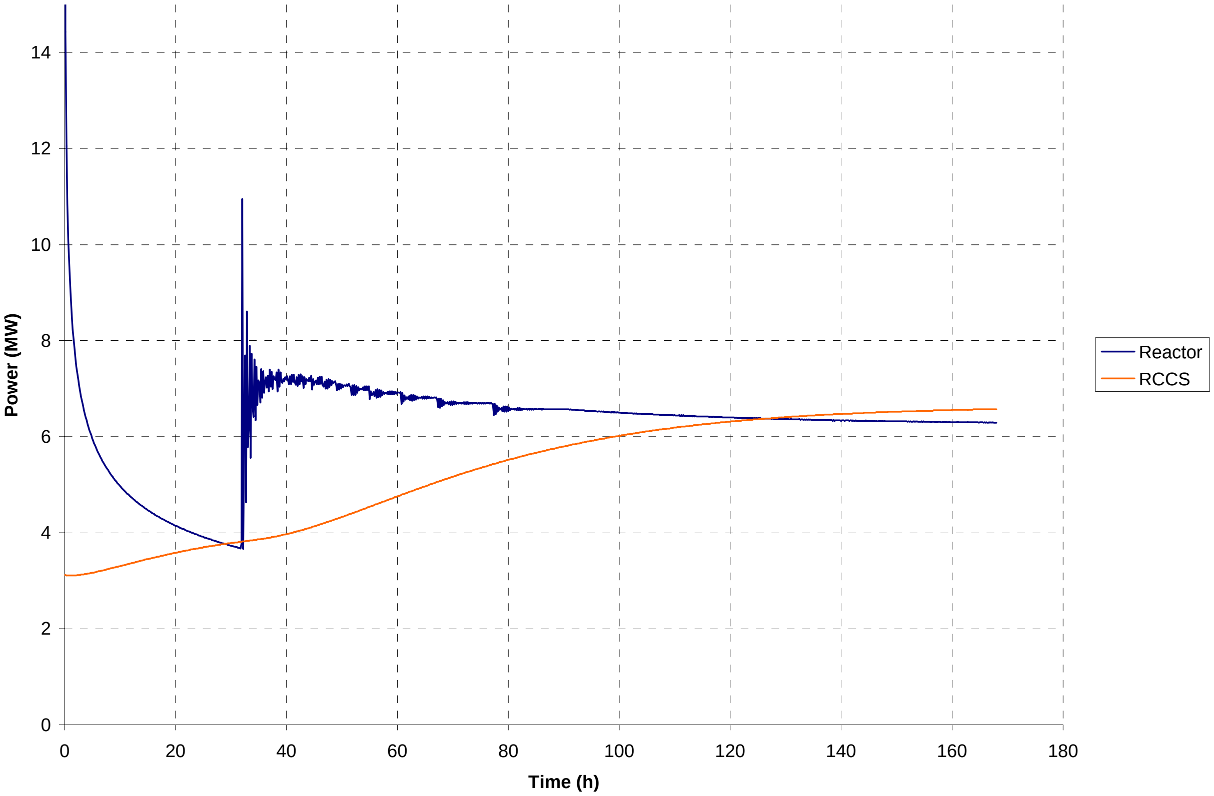

FIG. 8. *GT-MHR P-LOFC with ATWS – reactor and RCCS power*

Because the PBMR on-line refueling results in a mixing of pebbles with various burnups and irradiation histories, and the effective core conductivity is usually considered to be primarily due to radiant heat transfer between pebbles, and so is only a function of temperature. The reference conductivity correlation is derived from a combination of the Zehner-Schlunder and Robold correlations (Ref. 3).

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 T(fuel)-max.
2) Use of the Thermix code default core conductivity correlation (Ref. 4): 64°C increase in T(fuel)-max.
3) Use of the core conductivity correlation derived from SANA tests at KFA by H. F. Niessen (see Fig. 4-109 in Ref. 5): 103°C decrease in T(fuel)-max.
4) 15% increase in afterheat: 121°C increase in T(fuel)-max.
5) 20% increase in maximum radial peaking factor: 17°C increase in T(fuel)-max.

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. For a single vessel break with two days to establish the net air ingress flow, and assuming unlimited fresh air availability at the break, after 7 days ~5 % of the total core graphite is oxidized, and T(fuel)-max is about the same as with no air ingress. For the "chimney" case (double vessel break that allows air access to both the bottom and top of the core), and assuming a 2-meter high chimney "appears" above the vessel, air ingress flow is assumed to begin upon depressurization. The higher oxidation rate than in the previous case eventually, after ~4 days, penetrates further up the core as the lower reflector and support structure are cooled to the point that little oxidation occurs there. T(fuel)-max is lower than in the reference – no air ingress – case, but the maximum vessel temperature is higher 453°C at 168 hr. With unlimited fresh air available, after 7 days ~10 % of the core graphite is oxidized. Some mitigating actions (to limit the air supply) are necessary.

4.4 P-LOFC with ATWS: In this PBMR design, recriticality occurs at about 28 hours, and T(fuel)-max reaches 2127°C at 103 hr. Maximum vessel temperatures are also higher, 711°C at 145 hr. Fuel failure after 7 days was 57%. 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.

4.5 D-LOFC with ATWS: Recriticality occurs at 31 hr. In this case, T(fuel)-max is 2166°C at 137 hr, and the maximum vessel temperature (496°C at time = 168 hr) was still rising slowly after a week. Fuel failure at the end of the week was 59%.

## 5.0 CONCLUSIONS

Both MHTGR 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, such as vessel insulation strategies, 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 and operating conditions.

The value of sensitivity studies at this point (i.e., early) in the design and analysis 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. Clearly, the results for both concepts have shown the importance of effective core thermal conductivity functions and afterheat in the predictions of T(fuel)-max.

It was also shown, for the accidents postulated, that wide variations in the graphite oxidation rate function multipliers did not significantly affect peak fuel temperatures, since the oxygen in the incoming air for the postulated buoyancy-driven air ingress accidents is typically depleted before it reaches 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 very clear, however, that for long-term air ingress accidents, the 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 the long-term ATWS cases, for both concepts, these preliminary results show that there is a concern for much-higher-than 1600°C peak fuel temperatures 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. SCS restarts during an ATWS are seen to be counterproductive due to "selective undercooling" effects.

Also note that water (steam) ingress accidents are not considered here. The Brayton cycle gas-turbine design (vs. a steam cycle) greatly reduces the chance of water ingress since the pressure differences, primary to secondary, are maintained for the gas to exit rather than the water to enter. 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 to turn the flow around, and such eventualities should be considered and avoided.

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