CHAPTER 2

AFTERHEAT REMOVAL IN MODULAR GAS-COOLED REACTORS

The primary emphasis of the Coordinated Research Project was on afterheat removal under accident conditions. However, it is also important to consider other aspects of incorporation of the passive heat removal systems into the design. Both considerations are discussed below.

2.1. AFTERHEAT REMOVAL UNDER ACCIDENT CONDITIONS

The reactor cavity cooling systems (RCCS) for GCRs are typically safety grade systems, either with passive or with highly-reliable, redundant forced-convection cooling systems, designed to remove all of the core afterheat in the unlikely case of failure or unavailability of the main and all other shutdown cooling systems. The objective of most RCCS designs is to serve as an ultimate heat sink, ensuring the thermal integrity of the fuel, core, vessel, and critical equipment within the reactor cavity for the entire spectrum of postulated accident sequences. The requirements for RCCS performance and reliability may vary considerably depending on the particular reactor design features, power level, materials, containment type, and investment protection or licensing considerations. In some cases, these requirements could be extremely stringent if afterheat removal is the critical factor in determining maximum design power level and the need (or not) for a sealed containment structure.

A common solution to the problem of ensuring adequate heat removal is to over design (the capacity of) the system. This would not normally be acceptable for the RCCS, however, because during normal operation, and in some cases for normal shutdowns, excessive parasitic heat losses are undesirable. On the other hand, since the RCCS is necessarily a large, distributed structure in the reactor cavity not easily amenable to inspection and cleaning, allowances would usually be necessary for the inevitable fouling and degradation occurring over the reactor lifetime.

Another challenging aspect of RCCS design is the fact that the heat load distribution during long-term loss of forced convection (LOFC) accidents can vary considerably with the accident characteristics. For example, in a pressurized LOFC, natural circulation within the vessel causes the peak vessel temperatures to occur near the top, while for depressurized LOFC accidents, the peak temperatures appear near the vessel belt-line. Furthermore, for rapid-depressurization accidents, the RCCS may be required to withstand a simultaneous hot jet of coolant gas impinging on the structure and an over pressurization of the cavity. For steam cycle HTRs, pressurization of the cavity from steam line leaks may also be a design consideration.

Because of the wide variety of requirements for RCCS performance and reliability, analysis methods and (validated) codes for predicting detailed RCCS and vessel temperature profiles must be used in conjunction with whole-system accident simulators to determine the adequacy of the design. This means that, in fact, two types of analytical tools are needed for confirmation of a safe shutdown: one, a very detailed finite-element or finite-difference model (typically with >10,000 nodes) for steady-state thermal analysis, and the another a simpler dynamic model (>100 nodes) that can be used in the overall accident analysis.

This emphasis on performance and reliability of passive cooling systems for the reactor vessel is unique to the MHR concept because of its potential for surviving the remotely possible accidents that could result in both loss of coolant and total loss of all active cooling systems. Current reactor designs (LWRs) have achieved satisfactory levels of safety by using combinations of diverse (and expensive) safety-grade active systems. The intent of the RCCS is to provide an ultimate heat sink for the "thermally stable" GCR, which can withstand a loss of both coolant and forced cooling without fuel failure or fission product release.

Because of the complexities and subtleties of the GCR afterheat removal problem, it is especially useful and helpful for researchers with a wide variety of backgrounds and experience, such as the Chief Scientific Investigators of this Coordinated Research Project, to work together on its resolution.

2.2. OTHER ASPECTS OF AFTERHEAT REMOVAL

While much of the focus of RCCS design is on performance during accident conditions, it must be kept in mind that these extreme conditions are not likely to exist during the life of a modular GCR plant. Thus the effect of the RCCS on normal operation of the plant, both at power and during shutdowns must be addressed along with other considerations as discussed below.

2.2.1 Afterheat Removal Systems Performance During Normal Operation and Shutdown

Since the heat removed from the reactor vessel during normal operation is a parasitic heat loss, it would be desirable for this to be minimized. However, in passive systems, engineered means for reducing heat removal except during accident conditions are normally not advisable, since the probability of failure of the control mechanism might make the overall RCCS predicted failure rate excessive.

Another concern with some RCCS designs is the potential for severely overcooling the vessel and cavity if the reactor is shutdown (e.g., for refuelling or extended maintenance) during very cold weather shutdowns. There is also a concern regarding freezing of the coolant fluid in liquid-cooled RCCS designs.

2.2.2 System Failure and Recovery

The main focus of the Coordinated Research Project is on performance of afterheat removal systems that function "as designed" during postulated accident sequences. However, the designers, operators, and regulators need to be cognizant of the variations in heat removal capabilities of the systems over the full range of accident conditions due to possible modes of RCCS degradation and failure. Such considerations should include:

– Failure modes for various RCCS design options - passive systems: air-cooled, water-cooled, CO_2 critical-temperature-cooled (TIPACS); or active systems. Redundancy requirements. Effects of selected RCCS design option on containment design (none, filtered, or sealed),

– Failure modes and effects analysis (FMEA) of internal (e.g., vessel depressurization, fouling, leakages, ...) and external (e.g., earthquakes, floods, very hard freezes, ...) events,

– Stresses and deformations in the RCCS (and the vessel) due to localized/uneven heating (or cooling). Analyses may need to consider both steady state and transient cases; and

– Performance monitoring (on-line diagnostics), in-service inspection (ISI), remote maintenance, and ad hoc repair methods during accident scenarios. In allowing credit for ad hoc repair of damaged afterheat removal systems during an accident, GCRs will typically have an advantage over most other concepts due to the very long time responses in accident progression sequences.

The use of passive afterheat removal systems in GCRs also presents unique challenges in quantifying reliability, which means that the regulators, who may have limited experience in licensing passive heat removal systems, may tend to be overly conservative about allowing extremely small unavailability or failure rates. On the other hand, validation of claims of extremely small failure probability rates (e.g., 10^{-6}/yr) is very difficult.

In some cases, the design may even need to account for extremely low probability "complete" failures of the RCCS, and in the case of below-ground silo reactor designs, account for conduction to the surrounding earth. For this it is desirable to have minimal insulation within the RCCS cooling panels.

2.2.3. System Design and Licensing

Some of the aspects of design and licensing an RCCS would be conventional; thus many of the standard structural design codes (ASME Codes, for example) could be applied to construction and inspection requirements, and some of the licensing requirements for emergency core cooling systems for conventional LWRs would also apply directly. On the other hand, certain unique characteristics of the GCR with a (passive) RCCS make direct application of LWR licensing standards inappropriate.

The adequacy of the RCCS design for plant licensing will depend on the RCCS' capability in maintaining acceptable vessel and core component temperatures during postulated accident sequences. This in turn will depend on thermal and nuclear responses of the reactor that may be beyond the common interests of the Coordinated Research Project participants. The RCCS heat removal capabilities under accident conditions, however, involve parameters of universal concern, and some were noted in the benchmark problem solutions as being crucial, and therefore of licensing concern:

– Reactor vessel and panel emissivities: Since thermal radiation accounts for a major fraction of the heat transfer from the vessel to the RCCS, emissivities would play a major role in the licensability of the RCCS. The design and periodic monitoring of the surfaces is crucial,

– Water vapor in the cavity (or other materials that could affect the radiant heat transport) may need to be accounted for,

– Redundancies in coolant flow paths to offset effects of blockages or breaks may be needed,

– Means of monitoring performance under normal conditions to detect potential problems with heat removal capacity under accident conditions,

– Assessments of repair and recovery capabilities, including ad hoc measures that could be taken during accident sequences, could affect licensability.

Some relief for the advanced concepts from perhaps overly conservative licensing restrictions in these matters was signaled recently by a change in German Atomic Law (1994) which now requires that ".... also events, whose occurrence is practically excluded....would not require incisive counter measures...."