#40

Reprint from

"CURRENT
NUCLEAR POWER PLANT
SAFETY ISSUES"

VOL. II

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1981

D-9

PROPOSED SAFETY CRITERIA FOR HIGH-TEMPERATURE GAS-COOLED REACTORS

K. HOFMANN
TÜV-Arbeitsgemeinschaft Kerntechnik West,
Essen

J.B. FECHNER
Federal Ministry of the Interior,
Bonn,
Federal Republic of Germany

Abstract

PROPOSED SAFETY CRITERIA FOR HIGH-TEMPERATURE GAS-COOLED REACTORS.

Several countries have carried out programmes for the development of the High-Temperature Gas-Cooled Reactor (HTGR). However, until now little work has been done in developing criteria and guides for HTGRs. In the Federal Republic of Germany (FRG), nuclear power plants have to meet the "Safety Criteria for Nuclear Power Plants". They were mainly established for Light-Water Reactors (LWRs). They also have to be applied to other reactor types, indirectly however when plant specific systems are considered. For developing safety criteria for HTGRs in the FRG the German safety criteria have been taken as a basis while considering proposed foreign regulations for HTGRs. The safety criteria have been divided into three different groups, each of which has been treated in a different way: the safety criteria which refer to inspections and testability, shutdown systems, reactor coolant boundary, residual-heat-removal systems and containment design have been essentially revised because of the properties and inherent safety characteristics of an HTGR power system; another group would have been applicable to LWRs and HTGRs without modifications but was improved and completed following experience with nuclear power plants and work in establishing standards; the third group was found to be independent of the reactor system and it is proposed without modifications for HTGRs. This group is formed of criteria referring to basic plant safety principles, radiation exposure of the environment, external influences, fire and explosions, plant security, escape routes and communications, decommissioning and ventilation systems. At present a draft of safety criteria for HTGRs is being discussed with the different groups participating in the licensing process. Because of its general character the IAEA standard "Design for Safety of Nuclear Power Plants, A Code of Practice" is applicable to HTGRs without the need for much interpretation; in the case of "Emergency Core Cooling" analogous requirements in the HTGR design are to be met.

1. INTRODUCTION

Several countries have carried out programmes for the development of High-Temperature Gas-Cooled Reactors (HTGRs). In the USA and the Federal

Republic of Germany two experimental power stations with HTGRs have been operated successfully: Peach Bottom No. 1 with an electric output of 40 MW and the reactor of the Arbeitsgemeinschaft Versuchsreaktor (AVR-Reactor) with 15 MW. In the USA, the Fort St. Vrain (FSV) power plant with prismatic fuel elements and an electric output of 330 MW is already in operation, and in the FRG the Thorium-High-Temperature-Reactor THTR-300 with 300 MW and a pebble bed reactor core is still under construction. More units are in the design phase.

Until now, little work has been done in developing safety criteria and guides for HTGRs. In the FRG, nuclear power plants have to meet the "Safety Criteria for Nuclear Power Plants" [1]. Although they were established for Light-Water Reactors (LWRs) in the first place, they also apply to other reactor types. Such guides may be applied indirectly when considering plant-specific systems of the other reactor types. In order to avoid interpretations of Ref. [1] in further HTGR projects which will not always lead to solutions tailored to the HTGR, the Federal Ministry of the Interior suggested that separate safety criteria defining design principles for HTGRs be developed [2]. These will facilitate the safety assessment of these plants during the licensing procedure and serve as a planning objective for the vendor.

2. STARTING POINT FOR DEVELOPING HTGR SAFETY CRITERIA

A search for safety criteria and guides specific to HTGR power plants shows the following results: most activities in developing criteria and guides have been undertaken in the USA. The following are the most important ones:

> A draft of "Nuclear Safety Criteria for the Design of Stationary Gas-Cooled Reactor Plants" with supplements prepared by the American Nuclear Society [3]
>
> An analysis showing whether the Regulatory Guides are applicable to HTGRs
>
> Revision of the "General Design Criteria for Nuclear Power Plants" presented in Appendix A of Part 50, Title 10, Code of Federal Regulations, for the application to HTGRs (draft) [4].

In the FRG, within the standards of the Kerntechnischer Ausschuß (KTA) the KTA 3102 [5] "Core Design of HTGRs" is being developed.

The Safety Criteria for Nuclear Power Plants [1] issued by the Federal Ministry of the Interior of the FRG have been taken as a basis for establishing Safety Criteria for High-Temperature Gas-Cooled Reactors [2].

The intentions were:

to retain as close as possible the basic concept of the safety criteria [1],

to revise the safety criteria [1] with consideration of inherent HTGR safety characteristics, experience gained during the THTR-300 licensing process, experience from HTGR plant operation and safety criteria already proposed,

to revise plant non-specific safety criteria with respect to the need of modifications due to experience with LWR-plant operation and standards,

to keep the safety criteria for HTGRs so general that they can be applied to different HTGR concepts such as pebble bed or prismatic core or process heat application.

According to these principles, the safety criteria [1] have been divided into three different groups:

criteria which have to be revised for an application to the HTGR because of being too LWR-specific,

plant non-specific criteria which could be improved or completed because of licensing or operating experience,

plant non-specific criteria not needing any modification because of their general applicability.

These groups will be treated subsequently.

3. CRITERIA WITH HTGR-SPECIFIC MODIFICATIONS

The first group comprises the following proposals for HTGR safety criteria:

No. 2.2[1]	Testability
No. 3.1	Reactor core design
No. 3.2	Coupling characteristics of the reactor core
No. 3.3	Internals of the pressure-bearing vessel
No. 3.4	Systems for control and shutdown of the reactor

[1] The numbers refer to Ref. [2].

No. 4.1	Reactor coolant boundary
No. 4.2	Design basis of the reactor coolant boundary
No. 4.3	Pressure-bearing vessel
No. 5.1	Residual heat removal after operation
No. 5.2	Residual heat removal after accidents
No. 8.1	Nuclear reactor containment
No. 8.2	Containment design basis

As these include HTGR characteristics they will be discussed in some detail.

3.1. Testability

Fundamentally, the safety criteria require that all parts of a nuclear power plant shall be so constructed and arranged that they can be tested and inspected to an extent corresponding with their significance for safety. However, in the HTGR design, there are components of high importance to safety with limited accessibility, e.g. the liner as a part of the reactor coolant boundary and some graphite structures in the pressure bearing vessel. Therefore special measures shall be taken for these components to compensate for the disadvantages of limited accessibility, e.g.:

Additional safety margins in the design
Special material properties, e.g. purity
Fabrication quality
Design of systems and components, e.g. redundant structures
Limiting and controlling of operational parameters
Periodic replacement of components.

As a result of these measures, a fault-free condition or function of components must be maintained or the consequences of failures must be limited, in order to assure safe shutdown of the reactor, residual heat removal and limitation of any radioactive release below acceptable limits under all operational and accident conditions.

3.2. Core design and systems for control and shutdown of the reactor

Similarly to LWRs, two independent and diverse reactivity control systems are required. One of these shall be capable of shutting down the reactor from all operational and accident conditions for a sufficient period; the second shall be capable of maintaining cold shutdown for unlimited time. A single failure which may result in a failure of control elements shall not impair the system from fulfilling its safety function.

The following inherent safety characteristics of the HTGR:

graphite structure with a high heat capacity, thermal conductivity and phase stability,

phase stability of the coolant helium,

fuel element not sensitive to overheating,

negative temperature coefficient of reactivity,

should be considered when specifying requirements for shutting down the reactor.

Therefore, a design is acceptable in which hot shutdown conditions are provided by increasing the average core temperature. This has been verified experimentally with the AVR-high-temperature reactor power plant by turning off the helium circulators without moving the control rods. This results in a reduction of the coolant flow and an increase of the core temperature. These means are now the usual shutdown procedure for this reactor [6].

In HTGR safety criteria it is proposed that inherent safety characteristics of the nuclear reactor may be taken into account to reduce shutdown system hardware.

HTGR-specific operation and accident conditions must be considered in core and shutdown system layouts, e.g. water ingress from a damaged heat exchanger into the reactor core which may result in an increased neutron multiplication factor.

The influence of the HTGR characteristics on the remaining core design criteria (3.1–3.3) of Ref. [1] is of minor importance.

3.3. Reactor coolant boundary and pressure-bearing vessel

In the case of LWRs, the reactor coolant pressure boundary including the pressure vessel consists entirely of metallic components; therefore one criterion in Ref. [1] proved sufficient for this system. According to HTGR design it is preferable to specify requirements for the metallic components which represent the enclosure of the reactor coolant and for the pressure-bearing vessel separately.

In detail, the reactor coolant boundary consists of:

the leaktight liner of the pressure bearing vessel,

penetrations through the vessel including their closures,

reactor coolant piping including the first isolation valves,

isolation lines including the first isolation valves, pipelines penetrating the vessel and interfacing with the reactor coolant at their outer surface (e.g. heat exchangers in the primary circuit).

In addition to general requirements for design, testing, materials and leakage monitoring instrumentation, HTGR-specific features are to be considered: The penetrations of the pressure-bearing vessel must be secured against outward forces, and consequences of closure failure must be mitigated by limiting the blowdown flow area, e.g. by provision of flow restrictors.

In current HTGR design, a prestressed concrete pressure vessel bears the pressure of the primary circuit in the liner region and together with the liner provides for the safe enclosure of the radioactive substances. Apart from general design requirements, the following special safety requirements have to be considered:

To provide a thermal protection of the vessel if necessary, e.g. an isolation or a heat removal system

To consider additional pressure and temperature loads by possible liner leakage of the reactor coolant

To withstand loads induced from pressure waves, airplane crashes and earthquakes

To achieve a sufficient safety margin for the stress limit of the pressure-bearing vessel in all relevant accident conditions.

3.4. Residual-heat-removal systems

Reliable residual-heat-removal systems are required for operational and accident conditions. However, the accident residual-heat-removal system can be used for residual-heat removal in normal operation, if it is adequately designed, e.g. with respect to reliability. This may be essential for process heat application of the HTGR because the heat sink for normal operation might not be suitable for all residual-heat-removal conditions.

The following features have to be considered when establishing requirements for the accident residual heat removal system:

No total loss of coolant occurs in an HTGR system so that a minimum helium pressure remains in the primary circuit.

Ingress of foreign media, e.g. water, air into the primary circuit or chemical reactions may occur.

Inherent safety characteristics should be considered, e.g. the properties of graphite and the fuel element.

The accident residual-heat-removal system is required to be reliable and redundant. It has to fulfil its safety-related functions even in maintenance during operation with simultaneous occurrence of an additional single failure. An emergency residual-heat-removal system with special requirements, e.g. core flooding, is not necessary.

The proposals for the design requirements include the following aspects:

Ingress of foreign media, e.g. water, into the primary circuit or chemical reactions has to be considered in some accidents

The residual-heat-removal systems for normal operation and accidents may possess common components, if the reliability and the requirements for maintenance of the accident system are not negatively influenced and the quality of these components is adequate

If inherent characteristics can assure residual-heat removal or storage after accidents so that design limits are not exceeded, hardware requirements can be softened, e.g. the requirement for meeting the single-failure criterion with respect to the residual-heat-removal system during its maintenance can be suspended for an adequate time period.

A three-hours interruption of residual-heat removal has been investigated theoretically for the THTR-300 power plant [7]. According to this, the structure of the core is preserved in order that the residual-heat removal can be resumed by the active systems after three hours and that the reactor can be brought into a safe state without exceeding radiological limits at all times.

3.5. Nuclear reactor containment

For HTGRs which are at present in the design phase, a concrete containment with an inner liner is planned. The following containment criteria are proposed:

No. 8.1	Nuclear reactor containment
No. 8.2	Containment design basis
No. 8.3	Leakage tests of the containment
No. 8.4	Containment penetrations

The requirements of the last two are not HTGR-specific.

In the design requirements of the containment the option to have a high-pressure containment rather than a controlled vented containment is left open. It has been explicitly stated that during external events

– the containment shall remain both leaktight and structurally intact, if it cannot be shown that the requirements of the Radiation Protection

Ordinance [8] with respect to radioactive releases are adhered to as a result of accident or operational leakage from a non-leaktight structure, or

– the containment need remain only structurally intact, if it can be shown that even without leaktightness the requirements of the Radiation Protection Ordinance are met.

To prevent damage of the containment or the safety systems from possible inner explosions, it is required that the formation of potentially combustible gas mixtures or the consequences of the reaction of these mixtures to the containment are to be limited during potential accidents in order that the fulfilment of the containment function be maintained.

This requirement has to be considered especially for process heat application of the HTGR.

It is required that the containment and the safety systems in the containment be designed to withstand ambient accident conditions, e.g. the temperatures arising. Therefore, a system for heat removal from the containment does not seem to be necessary if the interior of the containment is designed adequately and is not explicitly required in HTGR criteria.

4. CRITERIA APPLICABLE TO LWRs AND HTGRs

This group of safety criteria in principle could be applied to LWRs and HTGRs without modifications but could be improved in some aspects following experience gained with nuclear power plants and during establishing standards, e.g. the KTA-Standards. The group comprises the following criteria:

No. 2.1[2]	Quality assurance
No. 2.4	Radiation exposure in the plant
No. 2.5	Working conditions
No. 6.1	Reactor protection system
No. 6.2	Accident instrumentation
No. 6.3	Operational instrumentation
No. 6.4	Control room and emergency control station
No. 7.1	Electrical power supply
No. 8.3	Leakage tests of the containment
No. 8.4	Containment penetrations
No. 8.5	Liquid contaminant barrier

[2] The numbers refer to Ref. [2].

No. 10.1	Radiation protection monitoring
No. 10.2	Activity monitoring in exhaust air and waste water
No. 10.3	Environmental monitoring
No. 11.1	Handling and storage of nuclear fuel and other radioactive substances.

Examples of modifications are as follows.

Within criterion 2.4 it is explicitly required that provision be made in advance that maintenance operations of inspection, periodic tests, repair or replacement of components can be performed in accordance with the requirements of the Radiation Protection Ordinance [8]. These provisions may cover transport equipment, storage facilities, shielding and the corresponding space.

A separation into two parts and separate specifications of the accident instrumentation, namely the accident event and accident consequence instrumentation is proposed within criterion 6.2, "Accident instrumentation".

A criterion not previously included in the Safety Criteria of Nuclear Power Plants [1] was added to provide a barrier against release of radioactive liquids in the plant buildings for building and ground-water protection (Criterion 8.5 "Liquid contaminant barrier"). Such a barrier is to be provided inside the building and should allow for easy decontamination.

5. COMMON CRITERIA

Because of their general nature, the following safety criteria of Ref. [1] were found to need no modifications:

No. 1.1	Basic principles of the safety precautions
No. 2.3	Radiation exposure of the environment
No. 2.6	Effects from external events
No. 2.7	Protection against fire and explosions
No. 2.8	Access control, off-limit areas
No. 2.9	Escape routes and means of communication
No. 2.10	Decommissioning of nuclear power plants
No. 9.1	Ventilation and air filtration systems.

6. APPLICABILITY OF THE IAEA STANDARD "DESIGN FOR SAFETY OF NUCLEAR POWER PLANTS, A CODE OF PRACTICE" TO HTGRs

On the international level, the Code of Practice "Design for Safety of Nuclear Power Plants" [9] published within the IAEA Safety Standards corresponds to the national "Safety Criteria for Nuclear Power Plants" [1]. The discussion whether this is applicable to HTGRs without detailed interpretation can be restricted to the five parts of section 3, because the other parts of the standard are citing fundamental protection objectives or, as already discussed above, contain requirements that are not plant-specific.

6.1. Provision for in-service testing, maintenance, repair, inspection and monitoring (Section 2.9 of Ref. [9])

In principle, here measures are required for in-service testing, maintenance, repair, inspection and monitoring of the functional capability of components. As described above, for some of the HTGR components there is restricted accessibility. In section 2.9 of [9] this restricted accessibility is taken into account by requiring "adequate safety precautions" to compensate for potential undiscovered failures. These adequate measures should especially be considered in the case of HTGRs as described and particularly emphasized in the corresponding German criterion 2.2 "Testability".

6.2. Reactor core (Section 4 of Ref. [9])

The criteria for core and fuel design and reactor control and shutdown system layout are kept sufficiently general so that they can be applied also to HTGR power plants. In the German proposal for a shutdown criterion we emphasized inherent safety characteristics by which hardware measures for the shutdown systems may be simplified.

6.3. Reactor coolant system (Section 6 of Ref. [9])

Section 6 of Ref. [9] comprises design requirements for the residual-heat-removal systems and for the reactor-coolant boundary including the pressure vessel. The requirements for the reactor-coolant boundary are general, so that they can be applied to HTGRs as well. However, for criteria more specific to HTGRs, it is better to differentiate between the enclosure of the coolant and the pressure-bearing vessel as discussed above.

Section 6.6 of Ref. [9] "Emergency core cooling" is LWR-specific in essential aspects so that interpretations for the application to HTGRs are necessary. Thus, section 6.6 requires an emergency-core-cooling system for the case of the loss-of-coolant accident in order to comply with the design value of the cladding temperature of the fuel elements. Since a total loss of coolant does not occur in HTGRs, we think it is useful to establish the criterion considering all accident conditions including the depressurization accident. This system can also be used for the residual-heat removal in normal operation, provided it is adequately designed. The requirements for this system have been discussed in section 3.4.

6.4. Containment system (Section 8 of Ref. [9])

Within the requirements of section 8.1 of Ref. [9] "Purpose of containment system" it is possible to have a vented or a hermetically sealed containment depending on other means of limiting the release of radioactive substances. These features are consistent with the requirements for an HTGR-containment within section 3 of this paper. Effects of potential HTGR-specific energy sources on the containment structure, e.g. from reactions of air with graphite or the formation of combustible gases, are included within section 8.2 of Ref. [9] "Containment structure strength". Our opinion is that the requirements of the Code of Practice cover the HTGR containment requirements as well.

7. STATE OF HTGR CRITERIA DEVELOPMENT

A draft of Safety Criteria for High-Temperature Reactors [2] has been established in the FRG. At the moment this draft version is being discussed with the different groups participating in the licensing process.

REFERENCES

[1] Der Bundesminister des Innern, Sicherheitskriterien für Kernkraftwerke, Bonn (1977).

[2] TÜV-Arbeitsgemeinschaft Kerntechnik West, Sicherheitskriterien für gasgekühlte Hochtemperatur-Reaktoren, Entwurf Nov. 1979, Essen (1979).

[3] AMERICAN NUCLEAR SOCIETY, Nuclear Safety Criteria for the Design of Stationary Gas Cooled Reactor Plants, ANS 23 Subcommittee, Draft No. 9, Rev. 2, Illinois (Jan. 1974).

[4] Code of Federal Regulations 10 CFR Part 50, Draft Appendix A, General Design Criteria for High Temperature Gas Cooled Reactors, US Government Printing Office, Washington (1975).

[5] Kerntechnischer Ausschuß, Auslegung der Reaktorkerne von gasgekühlten Hochtemperaturreaktoren, Teil 1: Berechnung der He-Stoffwerte, Fassung 6/78.

[6] KNUEFER, H., Abschaltvorgänge beim AVR-Hochtemperaturreaktor, Brennstoff-Wärme-Kraft 26 12 (1974).

[7] KIETZER, K., et al., "Safety analysis of the THTR-300 MW(e)-prototype-reactor and future HTRs under extreme accident conditions", Nuclear Power and its Fuel Cycle (Proc. Conf. Salzburg, 1977), Vol. 5, IAEA, Vienna (1977) 375.

[8] Der Bundesminister des Innern, Verordnung über den Schutz vor Schäden durch ionisierende Strahlen (Strahlenschutzverordn.-StrlSchV), Bonn (1976).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Design for Safety of Nuclear Power Plants, A Code of Practice, IAEA, Vienna (1978).

DISCUSSION

O.J.A. TIAINEN: In developing your safety criteria for high-temperature gas-cooled reactors did you take the closed-cycle gas-turbine system into account?

K. HOFMANN: Yes, we wanted to establish criteria of a basic character applicable to different HTGR systems, e.g. pebble bed core, block fuel core, or HTGRs for process heat application.

J. DECKERS: The Ministry of the Interior has issued special safety guidelines requiring high toughness, low stresses, and meticulous fabrication and testing for the pipework, pressure vessels, etc. of the auxiliary systems of light-water reactors in the Federal Republic of Germany. This constitutes the so-called "basic safety" framework. Is it intended to develop similar requirements which take into account the high temperature in the reactor and the use of special materials for high temperatures?

K. HOFMANN: In my opinion it is too early to establish specifications for "basic safety" with respect to HTGRs because of the high temperatures involved and the special operating conditions. For instance, before we can think about the process-heat application of HTGRs we must first develop special materials.