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# "IMPORTANT VIEWPOINTS PROPOSED FOR A SAFETY APPROACH OF HTGR REACTORS IN EUROPE" Final results of the EC-funded HTR-L project.

ABSTRACT

The inherent safety features of modular HTRs make events leading to severe core damage highly unlikely and constitute the main differentiating aspects compared to LWRs. Furthermore, while a known and stable regulatory environment has long been established for Light Water Reactors, different ways of thinking may help to develop a more appropriate licensing process for HTR-based power plants.

The HTR-L project funded by the European Commission in the 5th Framework Programme is dedicated to the definition of a common and coherent European safety approach and the identification of the main licensing issues for the licensing framework of the modular HTRs. Several topics were developed during the course of this project.

Due to the characteristics of the HTR design, it has been necessary to define specific defence-in-depth requirements which have then been evaluated for implementation in the safety approach. Safety-related functions appropriate for the HTR design have also had to be identified and listed.

On one hand, the different possible challenges of the fuel particles constituted the starting point for the identification of the accidental conditions (by means of the master logic diagrams methodology); these accidental conditions were classified and the most appropriate methods to consider ultra low probability severe accidents were examined.

On the other hand, the elements constituting the source term and, in particular, the requirements for the confinement of radioactive products and the conditions required to prevent the need for a "conventional" containment structure have been discussed.

In the definition of the safety approach, attention has been paid to the need to maintain the potentially interesting economic perspectives of HTR reactors. Key issues to be addressed in the licensing process of the HTRs have also been identified. An innovative Systems, Structures and Components classification method has been developed and rules that will govern equipment qualification proposed.

The purpose of this paper is to present the outcomes of the discussions between the HTR-L partners, and to explain the project main results.

# I. INTRODUCTION

The major issues related to public acceptance of nuclear technology are non-proliferation, safety and nuclear waste. It appears that HTRs could generate a significantly improved level of public acceptance compared to existing reactors. The inherent safety features of the Modular HTR (which make events leading to severe core damage highly unlikely), its potential for use in high temperature industrial processes and the possibility of using direct cycle gas turbines are some of the main aspects that set it apart from LWRs.

The designs of High Temperature Reactors (HTRs) are very different from those of Light Water Reactors (LWRs) for which a known and stable regulatory environment has been established for many years. In LWRs the possibility of core meltdown has largely driven the safety philosophy. The existing known and stable regulatory environment established for Light Water Reactors is not well suited for the licensing of Modular HTR power plants and, therefore, a different approach is necessary. A tailored set of safety requirements derived from the general consolidated principles of nuclear safety should be developed incorporating the specific characteristics of this kind of reactors.

# II. THE INHERENT SAFETY OF THE MODULAR HTR REACTORS.

The modular HTR reactors (MHTRs) appear as very simple to operate, with inherent passive safety features, low possibility of reactivity incidents ; moreover decay heat removal can be ensured by natural convection. The main inherent safety characteristics of the HTRs are the result of several design features, i.e. :

- the use of refractory coated fuel particles embedded in a graphite matrix which retain the fission products. Kernels coated with carbon and silicon carbide (SiC) layers have greater heat-resistance than those coated with metallic materials : this provides a unique robustness of the first barrier for the fission products (Figures 2 and 5),
- the strong negative temperature coefficient of the core, which tends to passively shut down the reactor with relatively modest temperature rise above normal temperature,
- the use of inert, single phase Helium gas as coolant and of graphite with high temperature stability and long response times as moderator,
- a very slow temperature transient of the reactor if the active cooling of the core is lost (see figure 1). This is made possible by the high thermal inertia of the graphite and the core structure, and the low power density of the core (less than 10 MW/m³, compared to at least 50 MW/m³ for a LWR),
- possibility for passive decay heat removal and core cooling. The core can be configured to have a large core surface-to-volume ratio ; combined with the low power density and an annular core, this makes possible passive heat removal (by thermal radiation, heat conduction and free

Figure 1 : Typical maximum core temperature

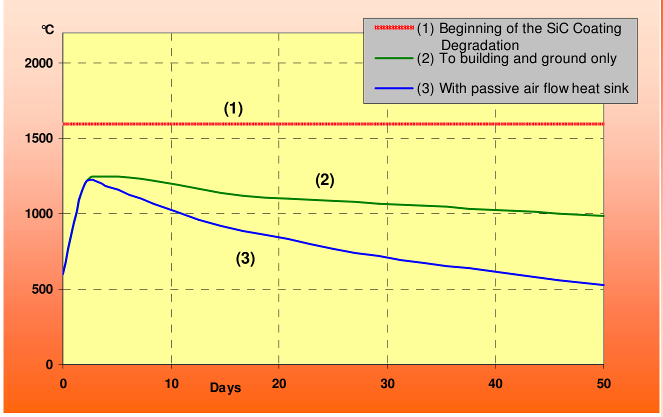
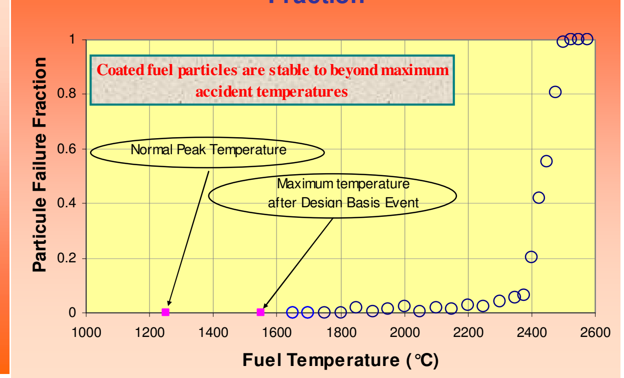



Figure 2 : Evolution of the Particule Failure Fraction



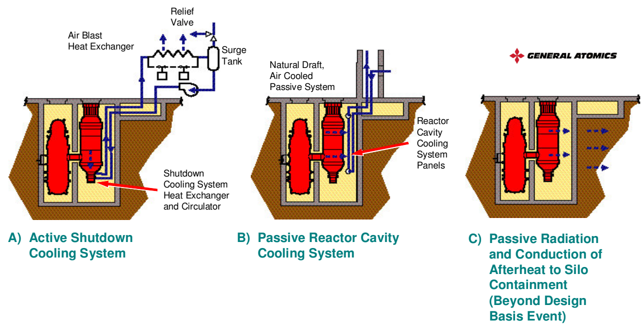



**Figure 3 : GT-MHR possible decay heat removal paths**

convection – see figure 3) from the core and the outer surface of the pressure vessel, even under the worst accident conditions. In these conditions the maximum fuel temperature can be maintained below the integrity limit of the ceramic-coated fuel (Figures 1 and 2).

The modular HTR represents a fundamental change in reactor design and safety approach : the safety is achieved through the combination of inherent safety characteristics of the HTRs design and selection of features that maximize these inherent safety characteristics.

The safety features of the HTR module are based on the design condition that, even in the case of failure of all active cooling systems and complete loss of coolant, the fuel element temperatures would not exceed the limits at which all radioactive fission products remain confined within the fuel elements. For example (Figure 3), the GT-MHR [3] has two active heat removal systems, the power conversion system and the shutdown cooling system that can be used for the removal of decay heat. In the event that neither of these active systems is available, the reactor cavity cooling system (RCCS) surrounding the reactor vessel ensures the removal of core decay heat : this constitutes an independent passive means. Core decay heat is transferred by conduction to the pressure vessel and then by radiation from the vessel to the natural circulation RCCS. If the RCCS is assumed to fail, heat is removed by conduction into the reactor cavity walls and surrounding earth : this mechanism is sufficient to maintain maximum core temperature below the design limit.

The low core power density (about 6.5 MW/m³ vs. above 50 MW/m³ for a LWR), the limited [1] core diameter (effective core diameter of about 3 m) and the annular core configuration are chosen to allow the passive decay heat removal from the core and the reactor cooldown entirely by passive heat transfer mechanisms after accidental events without exceeding the temperature at witch the coated particles fail. These MHTR design limitations (low core power density and small core diameter) taken in order to make the concept inherently safe are expected to allow to reduce the measures to be considered for the situation with degraded core.

The passive features of the modular HTR ensure that even for extreme accidents having very low probabilities of occurrence, the cumulative fission product release at the site boundary remains below the acceptable limits without the need for AC powered systems or operator action.(i.e. the system is meltdown proof).

Furthermore, the large core graphite heat capacity makes core heatup very slow. A substantial time (of the order of days, compared to minutes for other reactors) is available to take corrective actions to mitigate abnormal conditions.

Among the accidents to be considered for licensing purpose, one of the most severe is expected to be the complete loss of coolant accident (LOCA), which renders all the active cooling systems

[1] In order to have a sufficiently high power, the core height is chosen as large as possible.

unavailable ; this is also the case for the reactor circuit depressurization and for the loss of forced cooling helium flow. Other accidents have to be considered, e.g. :

- reactivity accidents due to core or absorbers configuration modifications,
- blockage of coolant channels,
- reactor coolant pressure boundary failure,
- air ingress, with the potential for combustion of the core graphite,
- water ingress, for which the risks seem limited compared to previous HTRs with steam generators, because they concern only low pressure water circuits;
- radiological contamination in normal and accidental conditions, even if the past operating records of HTRs have shown that they were very clean reactors. This can have very significant impacts on the source term in case of accident.
- deblading accident of the gas turbine.

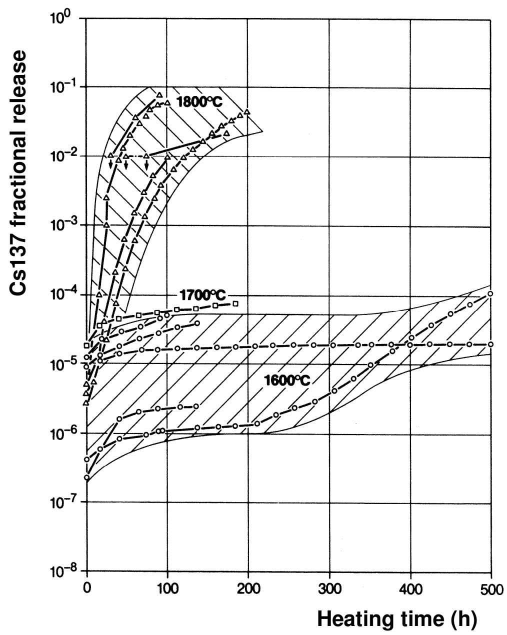



**Fig. 4 : Caesium release from heated particles as a function of heating times.**

## III. HTR-L PROJECT OBJECTIVES.

The high-temperature (HTR) and gas-cooled reactors (GCR) have been developed within Europe over many decades and considerable expertise in this technology is still available within the European Union countries. A common European approach to the renewal of HTR technology under the direction of a European HTR Technology Network - HTR-TN (1) has been established to enable and encourage work-sharing structures within this nuclear R&D field [1].

European Union Framework Programmes have been launched in 2000-2001 to consolidate and press forward the modular HTR technology in Europe. These involve partnerships of principal industrial and research organisations from countries of the European Union, including the JRC, in order to develop and consolidate European expertise and experience.

(1) Present-day members are : Ansaldo Nucleare, Belgatom, BNFL, CEA, CEN-SCK, Cogema, EdF, Empresarios Agrupados, FRA-ANP (SAS and GmbH), FZJ (Forschungszentrum Jülich) and FZR (Forschungszentrum Rossendorf), Nuclear Research Institute Rĕz, Paul Scherrer Institute (PSI), Universität Stuttgart (IKE), IPM Zittau, IRI Delft University, NNC, NRG, Graftech Limited, UCAR, VTT, Vüje, JRC (Joint Research Centre - EC)and E. C. (DG RTD and TREN).

Among the projects awarded to the HTR-TN partners and partially funded by the European Commission (5th Framework Programme [2]), the HTR-L project for defining a safety approach and identifying main licensing issues started on the 1st of October 2001 and lasted 36 months. Its final outcome constitutes the basis for further developments (i.e. the establishment of more detailed requirements) ; it is to be noted that neither code development nor system analyses were performed in the scope of the 5th FP projects.

The studies of HTR-L focussed on low power, annular core modular (making possible a short term passive heat removal and meaning several modules on the same site with common equipment like the Control Room) HTRs with direct cycle concept, using both pebble and block type of U-based fuel for electrical power generation. Uranium fuel is assumed with a moderated burnup and temperature (previous fuel properties remain valid). The reference plants are the GT-MHR (US) and the PBMR (RSA).

The main purpose of HTR-L was to establish a common and coherent European safety approach for the licensing framework of the modular direct cycle HTRs. A large consensus on an approach, which can take into account the specific safety features of modular HTRs and which thus leads to a simplification of the reactor design (e.g. suppression of (automatically) engineered safety featured systems, limitation of the number of components with a safety classification, reduction of the loads on the third barrier, …), is very important for consolidating the economic competitiveness of these reactors.

| **TABLE 1 : HTR-L deliverables** |
|---|
| • Review of existing safety approaches for HTR<br><br>• Report about operating conditions classification methodology for a direct cycle modular HTR<br>• Report about the operating conditions classification for a direct cycle modular HTR with blocks<br>• Report about the operating conditions classification for a direct cycle modular HTR with pebbles<br>• Report about the requirements for the safety analyses and computer codes.<br><br>• A list of key HTR safety functions<br>• Report about current international equipment classification and qualification standards<br>• Report on an Structure, System and Component classification methodology suitable for a direct cycle pebble bed and/or block fuel modular HTR taking into account safety and cost considerations<br>• List of equipment qualification rules suitable for an HTR<br><br>• Current requirements for the containment<br>• Confinement barriers for a direct cycle HTR and their elements : their roles and requirements<br>• Report on the containment needs and requirements.<br><br>• Report on key licensing aspects that can be considered by different European safety authorities<br><br>• Licensing specificities of a limited selection of plants other than the reference plants<br>• List of potential parameters to be monitored in future modular HTRs for control and surveillance<br><br>• Proposal of a European safety approach - final report |

As nuclear licensing is based mainly on national rules and regulations and as there is worldwide a lack of HTR-specific rules and regulations, the option retained is to not develop HTR-specific rules and regulations, but to compare HTR design features with well-known reactors (rules and regulations) and find solutions.

The results of the HTR-L project were presented to European Safety Authorities : a workshop has been organised in order to collect their first reactions to the proposed safety approach ; at this occasion, the Safety Authorities of Europe, foreign countries (e.g. US and South-Africa) and International Organisations (IAEA) were also invited to present their approaches and activities on the safety and licensing of HTRs or innovative reactors.

The project was organised around five work packages (WP) covering the most important topics for a safety approach :

- WP1 : General assumptions and basis of the approach
- WP2 : Initiating events classification
- WP3 : Confinement requirements/Source term
- WP4 : SSC classification principles
- WP5 : Identified issues being potentially important for the licensing

For each workpackage, an inventory of existing approaches was first established and the licensing materials available from old and current HTR projects were used. The issued deliverables are listed in the table 1.

## IV. GENERAL ASSUMPTIONS AND BASIS OF THE APPROACH

Although detailed safety analyses have still to be performed to demonstrate the case for a particular design, the modular HTR reactors can be considered, due to the potential for passive cooling, as "**core meltdown proof**". This makes the safety approach quite different from that developed for LWRs.

The behaviour of HTRs in accidental conditions relies on high-quality fuel : the high level of safety of HTRs results from the capability of coated fuel particles to confine the radiological fission products even at high temperatures under the worst postulated accident. This can be obviously achieved if other design options such as annular core geometry, low core power density, use of helium as coolant are considered and adequate operational parameters selected. Furthermore, favourable inherent phenomena (integrity of core graphite structures at high temperature, high negative temperature reactivity feedback, high thermal conduction and inertia of the graphite, heat transfer by radiation…) make accident management much more easier and lead to a large period of grace allowing operators to implement corrective actions.

The common European safety approach for HTRs must take into account the inherent safety features of these reactors and the unique robustness of the first barrier while respecting the general reactor safety approach principles. LWR can (and must) be an inspiration source, but the approach for HTR must depart from the approach considered for these reactors if it is not appropriate.

References for the project are the IAEA guides, the EUR requirements documents and the approaches developed within the EFR (European fast reactor) and EPR (European pressurized reactor) projects.

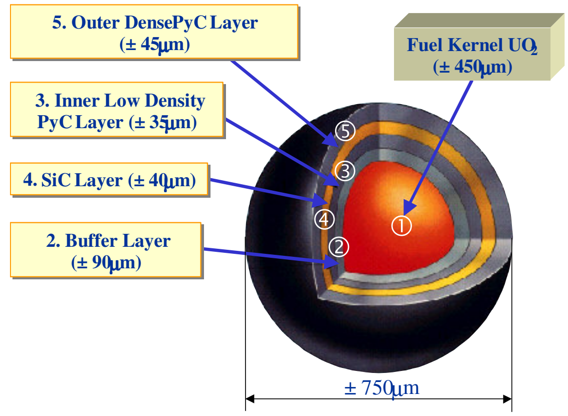
A tentative answer to the following topics is one of the project objectives :

- Physical barriers and application of Defence in depth (passive features, inherent safety)
- Adequate equilibrium between prevention and mitigation
- Initiating events classification principles. Beyond design basis accidents and severe accidents (no core meltdown for an HTR) : "events with possible significant release"
- Single failure criterion / Accident management (vs. operator grace time of ~24 h)
- Safety functions and safe shutdown state
- Acceptance criteria (fuel) and dose limits (radiological release).

The objective is to define the main safety concepts and principles applicable to modular HTRs. For this purpose, the internationally accepted applicable standards, principles and methodologies (e.g. IAEA Safety Guides, OECD/NEA recommendations) and licensing materials available for old (e.g. HTR-Modul, THTR and other German Projects, MHTGR in the US) and current (e.g. PBMR in South Africa as well as the GT-MHR initiative in the US) HTR projects were considered as well as the EUR (1) utility requirements.

For sure, the general guidelines and principles must be adapted to modular direct cycle HTRs taking into account the inherent and unique safety features of modular HTRs, in particular, the greatly reduced probability of accidents with severe fission products release.

**Figure 5 : HTR Coated Fuel Particule**




The overall proposed safety approach can be summarized as follows :

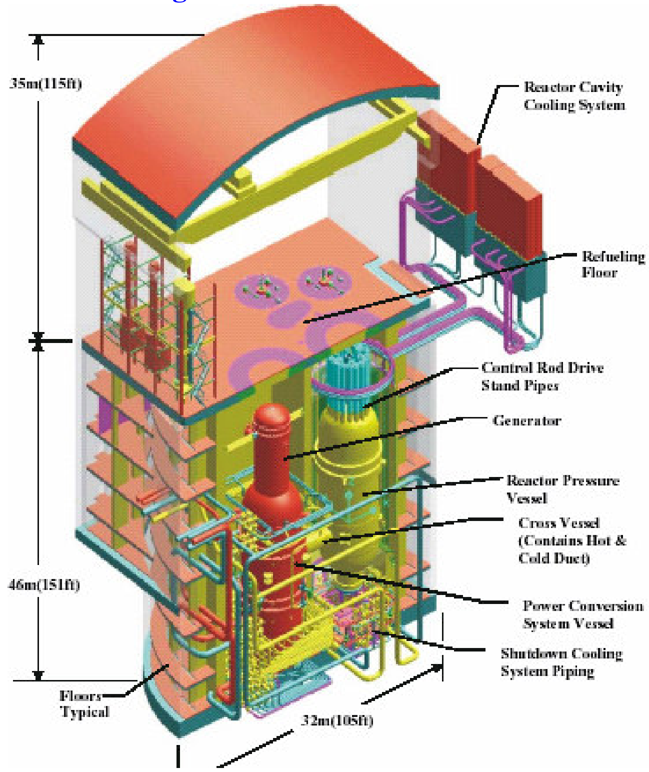
- Modular HTR design favours intrinsic safety and provides options to exclude severe core damage. The safety approach should make the most of these design options to benefit from a reduction of the requirements currently associated with the consideration of severe core damage for future reactors (EPR and EFR in Europe). The promotion of a safety approach mainly based on severe core damage exclusion is a ambitious challenge since such an approach has never been recently accepted by Safety Authorities
- A very convincing demonstration of severe core damage exclusion, going beyond that provided for other projects such as EPR and EFR (provision of a sufficient set of mitigating active or passive features, PRA) is needed. This demonstration should rely on
  - an exhaustive determination of initiating faults likely to challenge the fuel particle
  - the study of a set of bounding events with consequences mitigated by inherent behaviour
  - the use of reliable passive systems and corrective actions during the long term period after the accident initiation
  - the excellence of the main confinement barrier, i.e. the fuel particle, meaning high manufacturing quality and very good behaviour during normal and accidental conditions
- The determination of initiating faults should be performed deterministically though a top/bottom approach (i.e. assessment of the challenges on the fuel particles and deriving to the equipment or operator failure). The events could be classified in accordance with the state of the art. The bounding events would include accidents with failure of safety systems (if any) and design-specific events such as large air ingress.
  No need for a PRA level 1 to provide the demonstration but probabilistic demonstrations can be used to show the reliability of a system.
- An adequate methodology for safety equipment identification and classification should be defined allowing to take advantage of the safety approach strategy consequences : no need for active safety systems for the short and mid term period following accident initiation ; no need for power supply for the safety and if corrective actions are needed, no need for the short and mid term period following accident initiation. Systems nevertheless required should be very reliable (passive, redundant, diverse, inspectable and reparable).

(1) EUR stands for European Utility Requirements(for LWR Nuclear Power Plants). This document giving the design requirements for Light Water Reactors was produced by the utilities from nine European countries.

# V. DETERMINISTIC AND PROBABILISTIC APPROACHES

According to the EUR (Vol.1, Chap.3, 3.1.) and in accordance with the general present-day requirements of the European safety Authorities, it is proposed that the safety approach adopts combined deterministic methods and probabilistic methods.

Fig.6 : The GT-MHR reactor




- The deterministic approach should be used for the safety analysis of Design Basis Conditions (DBC). The deterministic approach is well-established through practice, and calls for internationally recognised assumptions and criteria while using a conservative methodology.

- The probabilistic approach should be used to assess compliance with the overall probabilistic safety objectives and to provide assurance of the overall homogeneity and consistency of the design. It should also be used as part of the process of selecting the events to be considered in the Design Extension Conditions (DEC). The probabilistic approach calls for realistic methods of analysis, and for a broad assessment of the full range of fault sequences.

The risk-informed regulation allowing a much more robust safety case is promoted in the United States. However, a HTGR risk assessment approach may present the following difficulties :

• Lack of risk metrics as the core damage frequency [CDF] and the large early releases [LERF] are not `applicable
• Very limited PRA experience for the Levels 2 and 3
• Lack of methods, data and tools for modelling HTGRs
• Available SSC data
• Lack of digital I&C models
• Identification of passive system failure modes and development of associated models
• Little experience for low power and shutdown conditions
• Determination of the uncertainties

However, this kind of assessment should make it possible to

• Identify and quantify initiating events
• Be a help for the preliminary design process with an optimal risk profile.
• Conduct human reliability analysis for long-term operator actions
• Conduct PRA for multiple HTR modules
• Have a probabilistic (reliability) criterion to replace the single-failure criterion.
• Develop performance requirements and criteria for (filtered) confinement performance.
• Integrate source term studies and confinement criteria to develop a basis for the size of the emergency planning zone.

# VI. INITIATING EVENTS CLASSIFICATION

## A. PRINCIPLES

As for the other nuclear reactors, different levels of defence-in-depth should be considered in the design :

- ♦ Prevention of abnormal operation and of failures
- ♦ Control of abnormal operation and detection of failures
- ♦ Control of the design basis accidents
- ♦ Control of severe plant conditions, including prevention of the accident progression, and mitigation of the consequences of severe accidents with core damage
- ♦ Mitigation of radiological consequences of significant releases of radioactive materials.

If the first three levels are to be considered without any doubt, the HTR reactors' characteristics make severe core damage (i.e. degradation of the first barrier confinement capability of a large number of fuel particles) and therefore core melting very unlikely ; furthermore, design features allow to overcome the (thermal, chemical, mechanical…) challenges on the fuel particle. This should allow to eliminate the costly and complex provisions associated with severe core damage mitigation and to declare unnecessary the off-site emergency plan.

It is therefore imperative to develop a very convincing demonstration of the safety performance of the modular HTR. This demonstration should :

- ♦ establish an exhaustive list of events challenging the fuel particle,
- ♦ classify these events according to the associated risks and consequences
- ♦ perform studies for the bounding events showing the robustness of severe core damage exclusion.

A major effort is needed to develop the safety case for HTR designs that rely solely on the fuel to provide containment. For the safety demonstration and licensing purposes, these fuel capabilities have to be demonstrated in the different situations to be considered ; furthermore, detailed safety analyses extended to all potential design basis events (design basis conditions and design extension conditions) that can be postulated to occur, have to be performed to confirm that the design features are suitable and that the safety objectives are met.

The main objectives of the work performed in the HTR-L project for the initiating events classification were the following :

- ♦ To define a methodology to identify and classify the events to be considered in the design of a modular and HTR, and important for the safety demonstration
- ♦ To apply the methodology to the modular HTR reference reactors, i.e. on a direct cycle concept with block or pebble-type core

Note that the internal and external hazards are not considered for this classification exercise ; obviously, they will have to be taken into account in the design. Furthermore, the event analysis rules were not considered.

An event classification is needed to provide the safety demonstration identifying the risks : the identified events are analysed and their consequences are demonstrated to be tolerable. It is to be noted that for a new concept like a modular HTR, the existing rules (event analysis rules and equipment design rules) and regulations can not necessarily be adapted.

- Initiating faults are identified and their consequences analysed with adequate rules to assess the impact on the public, the workers and the plant. Acceptance criteria might be adapted to the frequency of the events.
- Mitigating systems might be needed to limit the radiological consequences.

- Sequences with the complete failure of those mitigating systems might be considered in accordance with the strategy of prevention of large radiological releases.
- The non consideration of the consequences of some events has to be justified (list of residual risk accidents).

The following categories of events issued from the background developed for modern LWR and LMFBR European reactors are considered in the European framework:

- ***Design basis events*** are initiating faults (single representative fault) analysed with conservative analysis rules (e.g. single failure criterion) considering the action of mitigating means. Four categories:

**TABLE 2 : Design basis initiating events categories**

| Category | Description | Occurrence frequency | Dose limit |
|---|---|---|---|
| Cat.1 | normal operation | | <1 mSv per reactor year + ALARA |
| Cat.2 | Anticipated operational occurrences | > 10-2 per reactor year) | <1 mSv per event (combined with cat.1 release) |
| Cat.3, 4 | Accidents | cat.3: <10-2/reactor year<br>cat.4: <10-4/reactor year | no necessity of protective measures (sheltering and evacuation) for people living in the vicinity of the plant |

- ***Design extension conditions*** : analysed in general with realistic assumptions:

  - Complex sequences: initiating faults combined with failure of one or several mitigating means. They are determined by PRA or line-of-defence method. No necessity of protective measures for people living in the vicinity of the plant.
  - Limiting events: design-specific issues (e.g. bounding air ingress scenario) analysed independently from their frequency and in order to show that no cliff edge effect occurs
  - Severe accidents: accidents potentially involving large radiological releases and analysed to show the robustness of the confinement system

- ***Residual risk accidents*** : a justification of their exclusion has to be provided (e.g. very low frequency of the consequences)

For the design basis events, an exhaustive set of ***enveloping situations*** is studied to provide a convincing demonstration of the exclusion of severe core damage (giving large radioactive release), relying on inherent phenomena and on a grace time period allowing to implement corrective actions. Depending on the gravity of the consequences, these situations have to be adequately prevented. The complete achievement of the assessment of the safety case (e.g. justification of exclusion of the residual risk accidents) should confirm the set of the events, for which the consequences are analysed.

Enveloping situations are initiating faults analysed considering only :

- For the control of power, a negative temperature coefficient and corrective actions if sufficient grace time is available (e.g. Reactor shutdown system insertion) ;
- For the decay heat removal, the conduction and radiation in the vessel, the radiation to the external structures and corrective actions if sufficient grace time is available.

## B. METHODOLOGY TO GENERATE THE LIST OF EVENTS

A comprehensive set of events that encompasses both the anticipated occurrences and the conceivable malfunctions and failures that pose challenges to the integrity of the physical barriers (fuel, primary system, containment) and may result in radioactivity release to the environment has to be constituted for the analysis of the safety case.

Two approaches can be taken in identifying the accident initiating events:

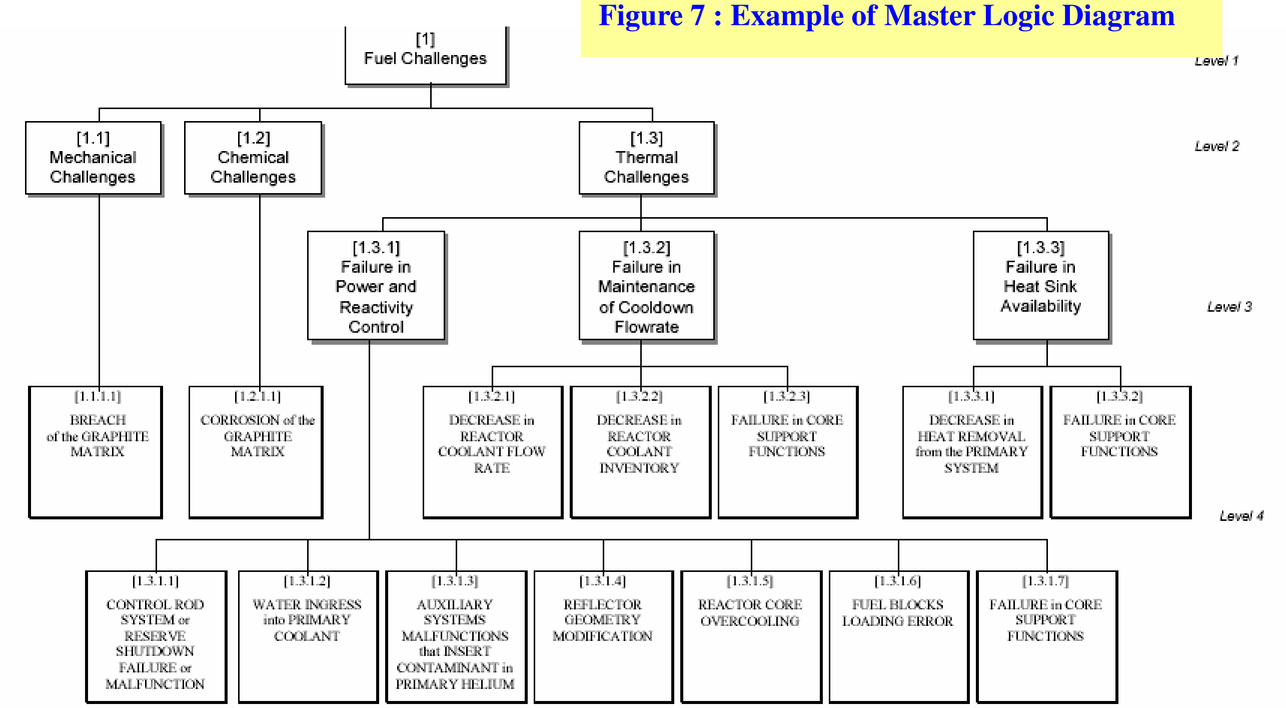
- One based on comprehensive engineering evaluation, taking into consideration information from previous risk assessments, documentation reflecting operating histories and plant-specific design data ;
- A more formally organized search for initiating events by constructing a top-level logic model (called **Master Logic Diagram**)

The second approach has been adopted for our exercise for two reasons : firstly because the prior objective is to provide a convincing demonstration for severe core damage exclusion and not for system design and secondly because of the lack of plant specific and operating data for direct cycle modular HTRs.

The methodology proposed to generate the list of events to be considered in the design consists of the different following steps :

1. Identification of the initiating faults by a top/down approach (see figure 7). The list has to be completed when detailed design of the plant is provided.
2. Categorisation of the identified events by using the European state of the art and by applying general rules derived from engineering judgment. The result of this preliminary categorisation might change with the actual detailed plant design.
3. Definition of the residual risk accidents: the plant design has to allow their exclusion.
4. Determination of enveloping situations, i.e. initiating faults combined with the complete failure of mitigating systems. The design has to be improved if needed.

**Figure 7 : Example of Master Logic Diagram**



# VII. CONFINEMENT REQUIREMENTS AND SOURCE TERM

An important discussion topic for the HTR reactors is whether a "conventional" containment structure or some other mitigating system or process should be required in order to provide adequate protection of the public. The decision to stipulate a containment has to be made on the basis of technical judgement, taking into account the design features of the HTR reactors.

According to the ANS definitions, confinement means the structure, system or component provided for the purpose of controlling the release of radioactive particulate matter; it may be either a physical barrier or a high efficiency filtration system. Containment means a testable enclosure on the overall facility (for example, a reactor room) that is in the normally closed configuration and can support a defined pressure differential for functional purposes.

One significant advantage of the HTR reactors is the high resistance for fission products release of the fuel particles, as the fuel and its successive protective shells constitute the most effective confinement barrier for the radioactive elements (Figure 5). The requirements for the confinement/containment function provided by the third barrier will therefore be re-assessed considering the properties of the first barrier of HTR fuel, the nature of the design basis accidents to be considered for licensing modular HTRs and the almost complete exclusion of core melting situations for this type of reactors.

The confinement requirements will be closely related to the fuel barrier efficiency and fuel quality control process. Safety analyses results and especially those related to fission products transport are important data for the definition of quantitative confinement requirements.

The integrity of the safety barriers will be also assessed in relation to accidental events originated outside of the plant (external events such as airplane crashes).

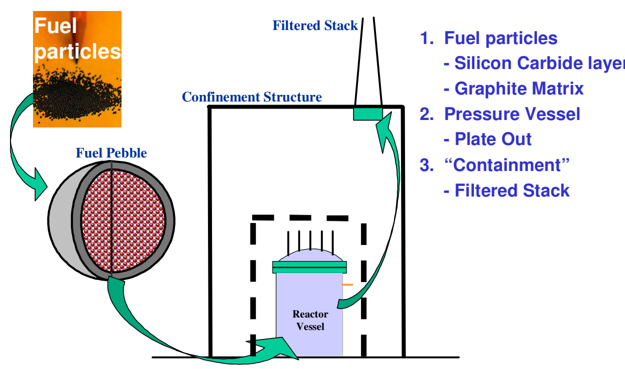



**Figure 8 : Fission Product Barriers and Transport**

The issues concerning fission product retention / transport / deposition / remobilization as well as the thermal-hydraulic behaviour of the reactors have to be analysed and studied. The knowledge about retention factors of the fission products in the primary system components and structures is important in order to evaluate without excessive conservatism the environment release during normal operation and during accidents. The need for "conventional" containment structure or other kind of confinement can only be deduced from these evaluations.

Therefore, as far as the needs for a reactor containment are concerned, the following elements should be considered in order to define the needs for a reactor containment :

- It must be in line with the defence-in-depth approach and the need of several barriers in series, if any ;
- A robust demonstration of absence of fuel particle failure and of fission product retention capabilities is required to avoid a containment structure ;
- The needs will depend on the situations to be taken into account (release). Containment can ensure a prevention role for the air ingress accident (Design Basis Accidents) ;
- The containment can play a mitigation role for the Design Extension Conditions consequences (Beyond Design Accidents) to be evaluated considering a best estimate approach ;
- A containment structure can help to cope with external hazards.

Acceptance conditions for HTR without conventional containment are given by the NRC (NUREG 1338) may be summarized as follow :

- Multiple barriers should be foreseen in order to respect the dose limits for all the events ;
- Fission product retention capability must be demonstrated (for example, via a test program on a full-size prototype plant) ;.
- Adequate qualification of the new and innovative Systems, Structures and Components that contribute to performing the confinement function (cf. fuel) has to be ensured ;
- The plant must be protected against sabotage and external events : this protection must be at least equivalent to that for current generation LWRs (this requirement does not take into account the 11th September events) ;
- Specific measures must be taken to prevent any core melt accident, reactivity accidents or large release accidents (like graphite fires) ;
- The potential improvement in safety if a containment building were added must be assessed. Judgment to determine the need for a containment building based on the cost and change in risk.

Finally, the containment design must take into account the following technical constraints :

- ♦ It is quite difficult to guarantee leak tightness, considering Helium at a possible high pressure ;
- ♦ The containment pressure may be high after an accident (pressurized gas in the RCS) : the technical feasibility may be questioned ;
- ♦ A pressurized containment may prevent interventions in the long term after an accident (grace period) ;
- ♦ The containment building offers retention mechanisms for the fission products ;
- ♦ The presence of a containment may facilitate the acceptance of the absence of an emergency planning zone outside the site limits (Public Acceptance) ;
- ♦ Confinement and Reactor building functions may be separated ;
- ♦ A higher plant investment cost must be balanced with the reduction of the residual risk (Economical aspects).

# VIII. HTR SOURCE TERM AND RADIOACTIVE RELEASE [5], [6], [7]

During normal operation, the contamination of the primary circuit is due to the fission products (FP) fraction released by diffusion from the intact fuel particles and directly from the defective particles. An important part of metallic fission products and of the iodine isotopes are deposited on the inner surface of the primary circuit, particularly on the colder parts (plate-out). The dominant sources of radioactive release in normal operation are the following :

- the leakage of contaminated helium from the primary coolant loop and from the storage tanks,
- the activation of the air contained argon located in the reactor cavity,
- the release due to the maintenance and inspection work.

After an accident with a core temperature remaining below 1600°C, the most effective barrier to FP is the coated fuel particle and only a small amount of FP is normally released; after the end of the depressurization induced release the release by temperature increase occurs slowly over a period of days as the core heats up. The source term is composed of three terms of radioactivity :

- the radioactivity contained in the helium of the primary circuit and potentially that contained in the helium purification system,
- the desorption of the FP deposited during normal operation on the primary loop surfaces,
- the radioactivity associated with the remobilized dust (mainly debris of graphite).

The fission products inventories escaped from the coated particles in normal operation constitute thus an important part of the source term after an accident for modular HTRs.

In order to evaluate the radioactive release and associated doses, the FP transport in the TRISO particles, the plate-out in the primary circuit and in the reactor building and the retention by the graphite structures have to be taken into account (Figure 4). There is an additional attenuation by the reactor vessel and the confinement for the small amount released from the core. The safety criterion to avoid offsite sheltering is normally satisfied with a margin of more than an order of magnitude.

**FP RELEASE.**

As far as their transport through the particle kernel, the multilayered fuel particle coatings and the graphite matrix of the core is concerned, three groups of FP have to be distinguished in HTRs (see table 3) : non metals (I, noble gases), reactive metals (Cs, Sr) and noble metals (Ag).

1. ***Non metals*** (gaseous FPs) (I, Kr, Xe) are retained very well by particle coatings (SiC and outer pyrocarbon layers); there is probably no release by diffusion through intact coatings. However, because the retention in fuel element graphite is not present for noble gases, respectively negligible for iodine at temperatures > 800°C, particles with defective coatings lead to a relevant release during normal operation and because core heat-accidents were never detected for modern fuel up to moderate burn-ups, a certain failure rate is assumed in safety analyses because of the limited number of irradiation experiments.

   Release from U-contamination in fuel graphite plays a limited role for normal operation (even by recoil and knock-out) ; coated particles becoming defective in the course of a temperature increase are detected by a burst-like release of non-metals. Over 90 % of the amount of gaseous FPs that are released is due to the small amount of initially failed particles and heavy metal contamination.

2. ***Reactive (non noble) metals*** (Cs, Sr) diffuse to some extent through intact coatings, particularly at temperatures > 1200°C. However, these FP released from intact and defective particles are efficiently retained in the fuel matrix graphite by chemisorption, as long as their mole fraction in graphite is smaller than 10-5 – 10-6. Fuel element matrix graphite, containing coked binder, shows a better retention capability than standard graphite. Caesium release from the hotter regions of the core also plates out in the cooler parts of the core.

   Increasing the mole fraction over this level enhances dramatically the diffusion rate in graphite (surface diffusion changes to in-pore gas diffusion).

3. ***Noble metals*** (Ag) diffuse relatively fast through intact particle coatings and their retention in graphite is limited ; accordingly, the release rate is already high in normal operation (maintenance problems), but particularly in core heat-up accidents. Fortunately, the formation yield of Ag in standard U-fuel is small.

   Further on, graphitic dust is formed, containing FP and absorbing FP from the gas phase.

**TABLE 3 : Important Fission Products**

| FP | Half Life | Properties |
|---|---|---|
| $^{134}$Cs<br>$^{137}$Cs | 2.1 y<br>30 y | Quick but moderate release from fuel kernel<br>High graphite retention (buffer, matrix) |
| $^{90}$Sr | 29y | Quick but moderate diffusion through SiC<br>Very good retention in fuel kernel and matrix |
| $^{131}$I | 8 d | Released from defective particles |
| $^{110m}$Ag | 250 d | Quick migration through coating and matrix<br>Highest release from fuel elements<br>Significant release during normal operation (SiC permeability) |
| $^{85}$Kr<br>$^{133}$Xe | 11 y<br>5.3 d | Similar to Iodine. Indication of particle defects.<br>Collected in the Helium purification system |

It is also to be noted that :

- Maximum core temperatures and maximum fuel burn-up (the combination of both is important) must be limited to values, which do not lead to pronounced particle failures or pronounced diffusive release of non-noble metals from particle and through the fuel graphite (<1650°C at burn-up < 10% FIMA).
- The formation yield of noble metals (Ag), which cannot be efficiently retained, should be minimized by fuel composition; Pu-burning leads to an increased Ag-formation.

**QUANTIFICATION OF SOURCE TERMS**

Because only permanent gases are involved, there is an efficient FP transport out of the circuit to the building and the environment only during the depressurization phase; highest core temperatures in core heat-up events – and accordingly highest release from fuel elements - are achieved for a depressurized reactor, i.e. when the transport is already small.

This leads to the fact that most relevant accident source terms of small, well designed HTRs are not necessarily related to the core heat-up, but to the depressurisation-induced release of FP stored in the circuit during long term normal operation (dust, plate-out): After 40 years of normal operation a fraction of the average core inventory of about $10^{-3}$ for Ag and about $10^{-4}$ to $10^{-5}$ for Cs and I is present outside the fuel element of origin. Whereas core heat-up induced source terms can be easily reduced by an adequate design, that is not the case for the release into the circuit during normal operation.

Conservative release estimations for a fast depressurisation with follow-up core heat-up in an advanced small HTR, fulfilling the criteria defined before but without a gas-tight reactor building lead to the following (environmental) source terms:

- some $10^{-7}$ of the total inventory for I and about $10^{-6}$ for Cs;
- although relative Ag source terms are at about $10^{-5}$, their radiological relevance in accidents remains small;
- Sr release remains negligible due to its excellent retention in graphite;
- metallic FP can be reabsorbed on colder fuel elements and on graphite reflectors; this effect was conservatively not up to now taken into account in the HTR safety analyses (additional R&D is required);
- knowledge on dust borne activities is still limited and requires a conservative treatment.

The doses associated with the above source terms remain slightly below (German) DBA limits, although no gas-tight containment was taken into account.

For steam-cycle HTRs relevant DBA source terms are expected to be larger, due to a significant additional release by several mechanisms in the course of a water ingress event.

Air ingress with graphite burning is far beyond DBA for well-designed HTRs and therefore detailed source terms are not required. Experimental and theoretical studies on severe air ingress were however performed and will be continued, e.g. in the large scale facility NACOK. These studies indicate that, for most scenarios several hours of time remain before a substantial FP release may happen; this time span might be used for mitigating measures.

**TRANSPORT OF FP INTO THE ENVIRONMENT**

The FP behaviour in the reactor building is not very different from that in other reactor types (except that there are no condensation phenomena, which are relevant in LWRs). A deposition of FP may occur on surfaces, as a settlement of dust. The same applies to filtering and/or release pathways via a stack.

If we assume a no pressure-retaining containment, there is in case of fast depressurisation an efficient transport out of the primary circuit to the environment. No filtration is feasible. During core heat-up (highest temperatures for a depressurized circuit), the transport efficiency is substantially smaller (no phase changes like boiling as in LWRs); filtration of emissions is in this case possible.

Accordingly, the release of activity deposited during long term normal operation and remobilised in case of depressurisation accident is more relevant for accidental source terms and plays a greater role for most nuclides than the release by core heat-up.

# IX. QUALIFICATION OF THE HTR FUEL

To demonstrate fuel qualification (for in reactor integrity) the fuel must be manufactured to precise design and manufacturing specifications, irradiation performance tested conducted to simulate the normal operating core environmental envelope and the fuel must be tested for all postulated off-normal conditions via post irradiation heat up tests. The quality of the fuel manufacture with respect to heavy metal contamination and defective particles is determined by the destructive burn leach test of a small sample of manufactured fuel elements from each lot.

For German reference LEU U02 fuel elements, the test results indicate a manufacturing detect rate of about $5.10^5$ (see figure 9 [8]). The figure 9 also shows the impact of the burnup and of the temperature on the failure rate.

**Fig. 9 : Trumpet curve - maximum particle failure fraction versus fuel element temperature. Limits are shown for (a) defects during fuel element fabrication; (b) failures due to irradiation; and (c) additional failures under off-normal conditions**

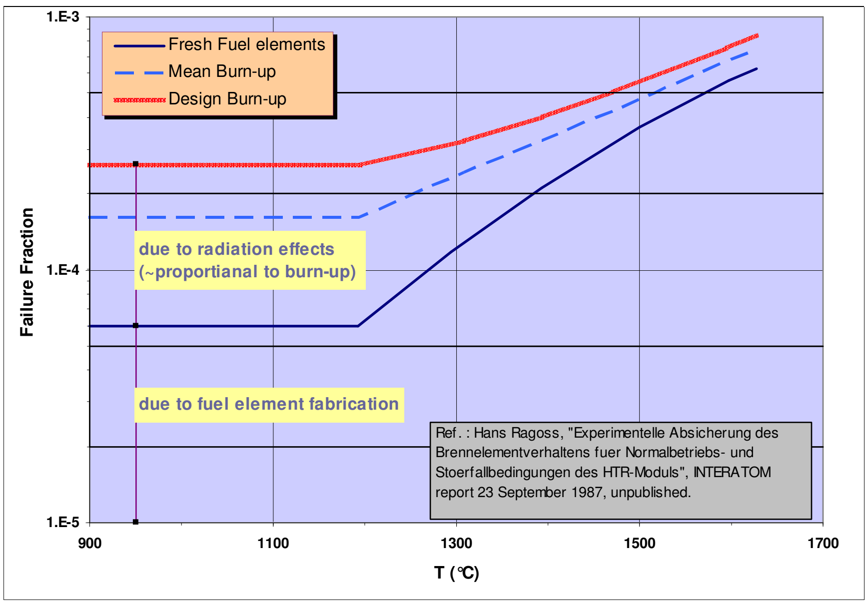
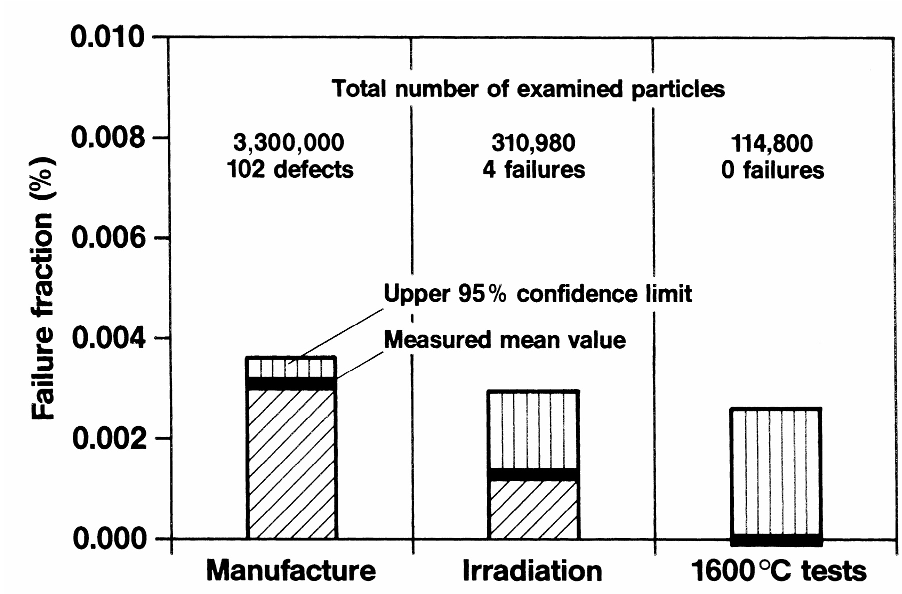


**Figure 10 : Quality of German TRISO particles manufactured 1978-1988 (source : H. Nabielek, FZJ, Germany)**




## X. CLASSIFICATION PRINCIPLES

The purpose is to establish a safety classification for the systems, structures and components, and to define the principles, rules and methodology for equipment qualification starting from the applicable international standards. This has to be realised with the objectives to avoid undue cost penalties of using unnecessary high quality levels, and to respect the safety criteria during design basis conditions.

As a first step, the key safety functions with their quality levels have been identified.

Various possibilities for an equipment classification methodology for an HTR have been reviewed. It is proposed that the EFR (European Fast Reactor) approach be adopted as the basis for the HTR system, taking into account the safety approach for Modular High Temperature Gas Cooled Reactors discussed in IAEA TECDOC 1366 and the approach used in the HTR-10 reactor.

A detailed SSC classification methodology has been derived, which can be applied at any stage in the evolution of the HTR design; relying on engineering judgement in the early phases, but becoming more refined as the design and its underlying safety case are developed.

A series of steps are involved in deriving the classification of individual SSC. These are:

1. the identification of the subordinate safety functions challenged by initiating events
2. an assessment of the radiological consequences of each initiating event
3. an estimation of the initiating event frequency
4. the identification of the role of the SSC involved in each subordinate safety function and assessment of their relative importance
5. the assignment of each SSC to an appropriate safety class

Three safety classes plus a non-safety class for SSC have been defined. Rather than a subjective grading of relative importance, a particular reason for the assignment to each Safety Class is proposed. Thus, assignment to Safety Class 1 means that the individual SSC is essential to limit the radioactive release following an Event Category 1 or 2 initiating event and assignment to other classes define their relative importance.

By working from the potential initiating events identifying the challenges these may pose and identifying only those SSC involved in ensuring the SSF have been successfully maintained, the safety of the plant is assured but each SSC is only categorised to the level of the threat posed by its failure. Although a considerable amount of effort will be necessary to undertake the safety classification process, it is hoped that the clear evidence as to the relative importance of particular SSC will bring benefits in the amounts of equipment that will be needed. Once completed, this safety classification can then be used to identify the appropriate standards of manufacture, construction, inspection, maintenance and operation. This will ensure reliable operation of all safety related structures, systems and components under all foreseeable circumstances, whilst at the same time justifying the purchase of lower quality equipment where safety is not involved. It is only by a process of detailed justification that it will be possible to bring the undoubted benefits of the HTR design into acceptable Safety Case arguments.

# XI. POTENTIALLY IMPORTANT ISSUES FOR THE LICENSING

It is important to identify the key **technical and non-technical** safety aspects for which the Safety Authorities may be attentive **and that need to be addressed in the licensing process of the HTRs**, in order to consolidate the developed safety approach and to anticipate the difficulties that can be encountered in the licensing process.

Key safety issues identified for the High Temperature Gas Cooled Reactors that we have been identified during the project are listed below :

**For the reactor power control safety function :**

- How to define the safe plant shutdown state?
- What about the plant shutdown phase (antireactivity margin)?
- How many shutdown systems are required to fulfil the safety function?

**For the residual heat removal safety function :**

- What and where are the margins to be included?
- Which is the acceptable time span for mitigating measures?
- Which kind of mitigating measures are acceptable in which time span?
- Can we consider a completely Passive System for Ultimate Heat Sink and Cavity Cooling?

**For the confinement of radioactive materials safety function :**

*First barrier (coated fuel particles)*

- For the fuel performance and qualification is QA & QC e.g. batchwise (not 100%) acceptable?
- When will there be enough experience in order to not need margins from estimated to design data?
- When will we have enough experience in order to reduce margins for other relevant parameters?

*Second barrier (primary system boundary)*

- What about the qualification of high temperature metal for the reactor pressure vessel?
- As the first barrier is very tight, do we need nuclear grade material for the RPV?
- In the case LWR-material is used (2), are the cooling systems to be safety related if the temperatures exceed the allowed material limits?

2 The cold vessel design concept (except for the hot duct and heat exchanger) makes it possible to use well known LWR reactor grade material, for which an experience feedback of more than 30 years is available.

- What are the needs for reactor vessel instrumentation?

*Third barrier (containment/confinement function of the reactor building structures)*

- do we need filtering during normal operation?
- is the absence of "conventional" containment and a partly pressure retaining structure acceptable?
- is filtering during heat-up phase after a depressurisation required?
- Which methodology can be used for the calculation of the source term and the fission product transport

Other items :

- Air Ingress accident
- Accident management : benefit of the grace period without operator actions
- Turbine deblading/disc failure
- Vertical lay-out of the turbo-group [3]

# XII. HTR-L WORKSHOP

At the end of the project, a workshop was organized to present the project results to a panel of European and International Safety Bodies representatives, , inform them about our main conclusions and collect the very first feedback from them (are we on the right path?). Naturally, no formal response from the Safety Authorities was expected.

The workshop is also important because it may have a possible impact on the future HTR R&D European programme and in the view of the next 6th FP VHTR project where regular contacts with the Safety Authorities and the IAEA are planned.

# XIII. CONCLUSION

It is most likely that HTRs will emerge on the world industrial scene in the next 10 years. The objective of the HTR-L project was to establish a common European safety approach for modular direct cycle HTRs. A way to look into the safety issues and to demonstrate that the safety functions are respected in all conditions were developed. A substantial pan-European consensus on a safety approach is necessary and very important for consolidating the economic competitiveness of HTRs.

The adaptation of the usual internationally accepted safety guidelines and principles to modular direct cycle HTRs were examined, taking into account the unique safety features of modular HTRs (exceptional strength of the first barrier, large negative temperature coefficient, very large thermal inertia and inherently safe design).

The work was not based on a actual plant design and is certainly an incomplete exercise, but it constitutes a first trial for defining a common European safety approach for the future HTR reactors in Europe : this exercise will be the basis and the input (iterative process) for further more detailed developments and much more detailed requirements, similar to those of EUR applicable to LWRs and in the light of safety analyses. The HTR-L project rallies industrial partners (manufacturers and energy producers) and research centres from different countries. Furthermore, it was also open to international co-operation.

3 Typical requirement for a nuclear reactor is the following : the orientation of the turbine generators shall be positioned so to avoid missile risks to the Nuclear Island. Furthermore, the vulnerability of emergency water and electricity supplies shall also be considered. (see EUR requirements, Vol2, Chap11, 1.1.1.3.D).

## REFERENCES


1. The Renewal of HTR Development in Europe (ICONE 10)
   D. Hittner, Framatome ANP, Paris la Defense.
2. Advanced concepts for waste management and nuclear energy production in the EURATOM Fifth Framework Programme - Global 2001 (09/01) – Paris
   M. Hugon, V. P. Bhatnagar and J. Martin Bermejo (European Commission).
3. The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment
   Malcolm P. LaBar (General Atomics), April 2002
4. Draft preapplication Safety Evaluation Report for the Modular High Temperature Gas cooled reactor.
   NUREG 1338
5. Fission product release and its environment impact for normal reactor operations and for relevant accidents – Nuclear Engineering and Design, Vol 218/1-3, 2002
   Liu Yuanzhong, Cao Jianzhu (INET)
6. Gaseous and metallic fission product transport characteristics of a modular pebble bed HTGR during loss of core cooling accidents
   S.B. Inamati, M.B. Richards, c.G. Hoot, GA Technologies, Inc.
7. Source term estimation for small-sized HTRs : Status and further needs, extracted from German safety analyses,-- Nuclear Technology, Vol 135, Sept. 2001,
   R. Moormann, W. Schenk and K. Verfondern, Forschungszentrum of Jülich.
8. Criteria for a High Performance Particle (HTR-TN International HTR Fuel Seminar, Brussels, Belgium, February 1-2, 2001
   Heinz Nabielek, Forschungszentrum Jülich, Germany and Dan Goodin and Bill Scheffel, General Atomics, San Diego, USA