1. INTRODUCTION

1.1. BACKGROUND

Gas cooled reactors have had a long and varied history which dates back to the very early days of the development of nuclear energy. An IAEA technical report issued in 1990 [1] is a compilation of information on the status of the design and safety for gas cooled reactors at that time. The evolutionary process, along with significant advances in supporting technologies, have culminated in the modular high temperature gas cooled reactor (MHTGR). The MHTGR is expected to achieve the goals of safe, efficient, environmentally acceptable and economic production of energy at high temperature for the generation of electricity and for industrial process heat applications early in the twenty-first century [2].

The MHTGR concept originated in Germany in 1979. There were parallel design variations in the USA and other countries during the 1980s and early 1990s. The specific prismatic block steam cycle design developed in the USA was called an MHTGR, but for the purpose of this report, the term MHTGR is used to indicate a general family of modular HTGRs with common characteristics as defined in Section 2. Design concepts were developed in considerable detail and subjected to review by several regulatory agencies. After several years of limited activity on high temperature gas reactors, a new interest for this technology is appearing in several Member States. A 30 MW(t) reactor (HTTR) was built in Japan and reached the first criticality at the end of 1998. A 10 MW(t) reactor (HTR-10) was constructed in China and the first criticality was achieved in December 2000. A 110 MW(e) pebble bed modular reactor (PBMR) has been proposed by Eskom, the South African Electric Utility, and an international project is under way. The IAEA has been directly involved in the review of the technical and economic feasibility as well as the safety of this reactor. A 270 MW(e) gas turbine modular helium reactor design is being developed in an international project led by the USA and the Russian Federation. Summary descriptions of these concepts as of 2000 are provided in IAEA-TECDOC-1198 [2].

Due to the MHTGR's innovative design approaches, advanced technologies and passive safety features, the safety assessment and the licensing of these reactors may require specific consideration, and the current LWR-based safety requirements may need, special interpretation or adaptation.

The IAEA has a comprehensive programme to update all the IAEA Nuclear Safety Standards (under the oversight of the IAEA Nuclear Safety Standards Committee, NUSSC), and has published some revised reports in particular, the Safety Requirements for Design [3]. These requirements and the derived Safety Guides have been mainly developed for water reactors, and their applicability to MHTGRs is not always straightforward. For example, in MHTGR designs, the fundamental safety functions are achieved with extensive use of passive and/or inherent features. The implementation of defence in depth for MHTGRs is quite different from that of water reactors. These differences can have significant impacts on the licensing approach for plant design, construction and operation.

Today's operating nuclear plants were largely designed following a defence in depth strategy. According to INSAG-10 [4], "Defence in depth consists of a hierarchical deployment of different levels of equipment and procedures in order to maintain the effectiveness of physical barriers placed between radioactive materials and workers, the public or the environment, in normal operation, anticipated operational occurrences and, for some barriers, in accidents at the plant. Defence in depth is implemented through design and operation to provide a graded protection against a wide variety of transients, including incidents and accidents, equipment failures and human errors within the plant and events initiated outside the plant”. This safety approach is reflected in the existing IAEA Safety Standards for the design of nuclear power plants.

To provide guidance in licensing and safety assessments of MHTGRs, there is a need to develop an applicable set of safety requirements derived from the generally accepted principles of nuclear safety. The IAEA has recently developed a methodology for screening the defence in depth of nuclear power plants [5] starting from the basic safety principles as proposed in INSAG-12 [6]. This methodology is used here to develop safety requirements for MHTGR design and operation.

1.2. OBJECTIVE

The objective of the present publication is to propose a technical basis and methodology, based on principles of defence in depth, for conducting design safety assessments and in the long term generating design safety requirements for innovative reactors. The MHTGR is used as an example to illustrate this process. For this purpose, the document provides an overview of the safety related features of current MHTGR technology, examines how the defence in depth principle can be implemented/adopted by the MHTGR design, and how MHTGR designs could satisfy the three fundamental safety objectives:

- general nuclear safety;
- radiation protection;
- technical safety.

A discussion of these objectives and principles in Section 3 provides a framework for development of future IAEA publications related to the MHTGR safety case.

1.3. SCOPE

This report focuses on the MHTGR, as defined in Section 2. The family of designs identified as MHTGRs incorporates some unique features. In particular the coated fuel particles, without metallic cladding, have the potential to retain radionuclides at temperatures well above their normal operating conditions, including the full range of design basis accident conditions. The helium coolant is an inert gas having no possibility of chemical interaction with other materials and no significant reactivity effects. For designs within this family, the decay heat is removed by thermal conduction, convection and radiation, and the design uses simple and reliable passive means that ensure fuel temperatures are maintained within allowable limits even without reliance on the presence of the primary system coolant.

To apply the defence in depth screening approach, this report considered the three fundamental safety functions (control of reactivity, core heat removal, and confinement of radioactive materials), and the challenges to the performance of these functions. Provisions identified are mainly based on design features of current PBMR and GT-MHR concepts, and are identified to illustrate the process for assessing MHTGR concepts.

This report does not consider challenges to the safety functions during various shutdown modes, or fuel storage and radioactive waste issues. A complete analysis, however, should also investigate all plant states and sources of radioactivity.

1.4. STRUCTURE

Section 2 of this TECDOC presents a discussion of specific safety characteristics, particularly inherent safety features that form an integral part of the safety case. This discussion serves to define the family of concepts referred to in this report as MHTGRs.

In Section 3, current general nuclear plant safety principles are addressed. Safety objectives, concepts and principles are described as a framework for design and operation of both current and future reactors. The structure of the IAEA nuclear safety standards is briefly described, identifying the role of the design requirements to ensure safety, and noting the logic underlying their development.

Section 4 introduces a method to prepare design safety requirements for the MHTGR, starting from the current requirements [3] (mostly developed for light water reactors, LWRs), adopting a top-down approach applicable to MHTGRs, and taking credit for recently-developed methodology [5] for screening defence in depth in nuclear reactors.

Section 5 presents a “critical review” of the reference requirements, analysing the defence in depth implemented for advanced reactors. For each level of defence in depth and for each fundamental safety function, the section illustrates the acceptance criteria for a successful achievement of the safety functions. The challenges to this successful behaviour are identified as well as the mechanisms that originate the challenges. Finally the identification of the provisions to cope with these mechanisms create the basis for the definition of the design requirements.

Characteristics of reactor designs considered may be such that established LWR requirements are unnecessary, ineffective or even counterproductive. This requires an analysis of the specific design characteristics and safety features of the family of reactor designs and a full understanding of the role played by these features in achieving a safe design.

Finally, Section 6 summarizes the conclusions from the systematic investigation of the defence in depth of MHTGRs, hopefully contributing to the future work of preparing design requirements for this family of future reactors.

The appendix contributes to this goal by providing a comparison of safety characteristics of LWRs and MHTGRs.