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U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, DC 20555

Subject: Information Regarding Materials and Design Codes to be Used for the Reactor Pressure Vessel and Connecting Piping for the Pebble Bed Modular Reactor

References:

1. Nuclear Regulatory Commission (NRC) letter to Exelon Generation Company, LLC, dated September 26, 2001

2. Exelon Generation Company, LLC, letter to NRC, "Response to NRC Letter dated September 26,2001 Regarding the Pebble Bed Modular Reactor Technical Information Availability," dated November 15, 2001

Enclosed is information responding to the NRC request for information regarding materials and design codes to be used for Pebble Bed Modular Reactor (PBMR) Reactor Pressure Vessel (RPV) and connecting piping.

Please note that this information is based on the PBMR design at this point in its development. For example, in Section 4.1 of the enclosure, reference is made to a "Reactor C" configuration, when describing RPV service temperatures. This is the current reactor configuration as it pertains to reactor coolant flow.

Also, note that this information is intended to respond directly to your request regarding the service conditions associated with the RPV and connecting piping (i.e., the pressure boundary). The Conclusions Section of the enclosure, therefore, pertains to the assessment of the effects of high temperatures on the pressure boundary. Other information, such as design information associated with hot gas piping, for example, has been included to distinguish between the pressure boundary conditions and the conditions of piping used to convey the hot helium.

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If you have any questions, please contact me at (610) 765-5528.

Sincerely,

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Enclosure

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RPV AND CONNECTING PIPING - WHITE PAPER

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Revision History

Revision	Date	Changes
A	19 November 2001	Original draft document
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Product Data Management		Verified	G C Prinsloo
PBMR Quality Manager		Verified	D R Goode
Nuclear Safety and Licensing Manager		Authorized	A P George

Change Forecast

Subject to negotiated changes.

CONTENTS

TABLE

FIGURE

ABBREVIATIONS

Abbreviation or Acronym	Definition
CB	Core Barrel
DLOFC	Depressurized Loss of Forced Cooling
EPRI	Electric Power Research Institute
fpy	Full Power Years
HPTV	High Pressure Turbine Vessel
PCU	Power Conversion Unit
PLOFC	Pressurized Loss of Forced Cooling
PTV	Power Turbine Vessel
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
RUCS	Reactor Unit Conditioning System
THTR	Thorium High Temperature Reactor
vpm	Volumetric Parts per Million

1. SCOPE

This document describes the grade of steel, normal and off-normal service conditions and the design code to be used for the RPV and the Pressure Boundary Connecting Piping. The effects of high temperature helium with impurities and graphite particles on the degradation of the metal surfaces are also discussed.

2. APPLICABLE DOCUMENTS

The following codes are applicable to this document.

Table 2.1: APPLICABLE CODES

Document Title	Document Number
ASME Boiler and Pressure Vessel Code	ASME BPVC Section II Part D
ASME Boiler and Pressure Vessel Code	ASME BPVC Section III Div 1, Subsection NB - 1998
ASME Boiler and Pressure Vessel Code	ASME BPVC Section III Div 1, Subsection NC - 1998
ASME Nuclear Code Case	N-499-1

3. INTRODUCTION

The PBMR primary pressure boundary consists of a Reactor Pressure Vessel (RPV) and the Power Conversion Unit (PCU) pressure boundary, see Figure 1. The PCU pressure boundary consists of a manifold vessel to which is connected a number of component vessels, for instance the recuperator vessel, the intercooler vessel etc.

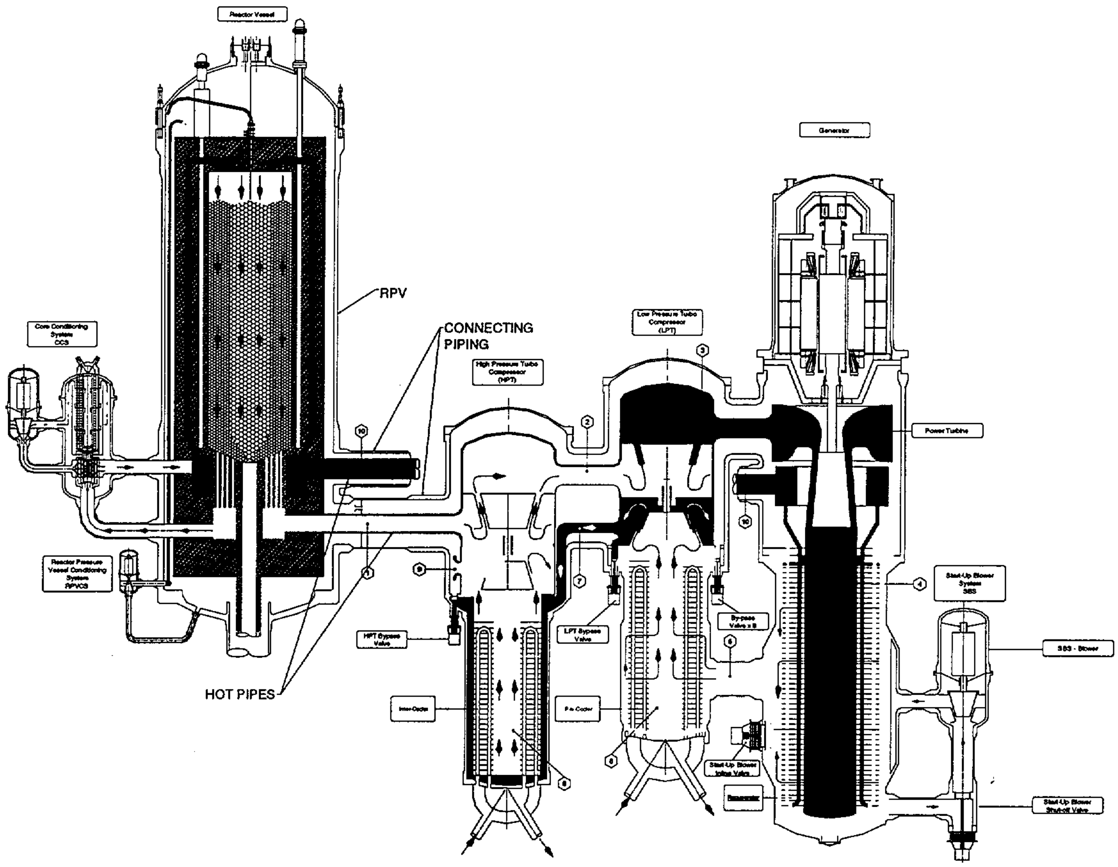

FIGURE 1: PBMR LAYOUT

The sections of the PCU pressure boundary that connects to the RPV is designated the "connecting piping" for the purpose of this document and they comprise the following:

- RPV-HPTV: the pipe connecting the RPV and the high pressure turbine vessel
- PTV-RPV: the two piping sections that connects the Power Turbine Vessel (PTV) to the RPV

These are the major load carrying nozzle connections to the RPV and their design limitations are considered to be enveloping the other RPV penetrations.

The "connecting piping" surrounds the concentric hot pipe sections (see figure 1), respectively connecting the core structure outlet plenum/core barrel to the HP Turbine internal casing and the recuperator outlet manifold to the core structure inlet plenum/core barrel. The design of the hot pipes utilizes an internal sleeve, made of Incoloy 800H, which is thermally insulated from the outer pressure pipe, made of 16Mo3. This results in the sleeve being exposed to the hot gas while the pressure pipe is exposed to "cold gas" on the OD and low temperature "hot gas" on the ID, refer to the detailed operating conditions in section 4.3.

4. OPERATING CONDITIONS

The approximate operating conditions, with respect to temperature and irradiation, are provided for the components. In addition to the conditions during normal operation, the components are also designed to withstand off-normal conditions. The first condition is a Pressurized Loss of Forced Cooling (PLOFC) event during which the pressure boundary is still pressurized but no helium flow is present, and the reactivity control systems are not inserted into the core. The second condition is a De-pressurized Loss of Forced Cooling (DLOFC) event during which the helium is lost and the pressure boundary is being de-pressurized, and the reactivity control systems are not inserted into the core. During these events the core decay heat is removed by radiation to the reactor cavity cooling system (RCCS), Consequently the temperature of the RPV is increased from the normal operating levels.

4.1 Reactor Pressure Vessel (RPV)

Operating Condition	Max Temperature (°C)*	Duration**
Normal	280 - 300	300 000hrs (35fpy)
Off-Normal		
PLOFC	410 (770°F)	5 040hrs
DLOFC	476 (888°F)	240hrs

Irradiation: Fast Fluence (E>1MeV): $2x10^{18}n/cm^2$ at end-of-life.

* - The temperatures are based on the thermo-hydraulic simulations of a "Reactor C" configuration and are subject to further refinement as the design progresses.

** - The duration of the loadings are based on the following conservative assumptions for design purposes, see subnote (1):

PLOFC – 3 times per year, for a period of 48hrs each time.

DLOFC – 5 times in the life of the plant, for a period of 48hrs each time.

(1) – The expected frequencies are far lower than these values.

4.2 Connecting Piping

Operating Condition	Max Temperature (°C)	Duration
Normal	110	300 000hrs (35fpy)
Off-Normal	110	5 280hrs

Irradiation: Fast Fluence (E>1MeV): Insignificant, primarily due to streaming.

4.3 Hot Piping, Core Outlet

Operating Condition	Pipe Section	Max Temperature (°C)	Duration
Normal	Pressure Pipe	250	300 000hrs (35fpy)
	Sleeve	900	300 000hrs (35fpy)
Off-Normal	Pressure Pipe	<250	5040hrs
	Sleeve	<900	5040hrs

Irradiation: Fast Fluence (E>1MeV): Insignificant, primarily due to streaming.

4.4 Hot Piping, Core Inlet

Operating Condition	Max Temperature (°C)	Duration
Normal	500	300 000hrs (35fpy)
Off-Normal: Operation at low Helium Inventory	600	100 000hrs (30% of life)

Irradiation: Fast Fluence (E>1MeV): Insignificant, only present due to streaming.

5. DESIGN CODES AND MATERIAL SELECTION

To a great extent the selected design code restrict one to the choice of material, as only certain materials are qualified for use with certain codes. The design code and subsequent material choice for the RPV and the connecting piping is discussed below.

5.1 Reactor Pressure Vessel

Due to the normal operating temperature and the secondary function of the RPV, in addition to containing the helium, to ensure a stable configuration of the core, it has been decided that ASME III, subsection NB (Class 1 components) would be the appropriate design code. Due to the radiation environment (temperature and fluence) the material selected is ASME SA 508, Grade B, Class 1 for the forged ends and cylindrical parts of the RPV. This material had been used extensively for PWR pressure vessels and has been characterized well with regard to its response to irradiation embrittlement.

The allowable temperature and stress limits for ASME III, Subsection NB, for normal operation (operating temperature is below 371°C (700°F)) are given by ASME II, Part D Tables 1A and 2A. For off-normal conditions the temperature and stress limits are provided in ASME Code Case N-499-1, which is specific for this material grade. This code case allows for limited periods of exposure to temperatures in the range of 371°C to 538°C (700°F to 1000°F).

5.2 Connecting Piping

The connecting piping is subject to relatively low temperature operation (<371°C) and due to its negligible neutron exposure it is being designed in accordance with ASME III, Subsection NC. The material selected is SA 508 Grade 3, Class 2 (forgings) and SA 533 Type B, Class 2 (plate sections). This class of material has a higher strength level than the Class 1 specification and therefore results in lower component masses due to reduced section thicknesses. These pipes will be designed as pressure vessels and not as pipes, thus in accordance with ASME 111, subsection NC 3300 and not NC 3600.

6. HELIUM IMPURITY AND GRAPHITE DUST EFFECTS ON CREEP AND FATIGUE LIFE

6.1 General

Although the nuclear properties of helium are unaffected by traces of impurities, the impurities certainly have an impact on the chemical properties. These impurities can originate from various sources including:

- residual air trapped in the system
- the de-sorption of the adsorbed gases in the graphite of the core and reflector
- in-leakage of air and water (a reaction ensues with the hot graphite to produce a 'reducing' environment in which hydrogen and carbon monoxide predominate. The hydrogen reacts with very large amounts of graphite below 600°C to produce methane – a reaction that is catalyzed by radiation).

Note that the impurities emerging as a result of de-sorption from the metal surfaces is negligible.

The PBMR helium gas will be subjected to an on-line purification system to ensure the following impurity levels in the helium:

Contaminant	Impurity Level (vpm)
H_2O	0.1
CO	1
CO_2	0.5
N_2	<5000
H_2	5
CH_4	<50

In addition to these gaseous impurities, the Helium gas will also carry graphitic aerosol particles ("dust"), of 5µm average diameter . This dust is primarily generated by the movement of fuel spheres and graphite spheres in the fuel handling system as well as their movement through the core. A study [1] has indicated that most of the dust produced will be removed by the filters in the fuel handling system and that about 7.8kg/fpy of dust will be distributed throughout the main power system. Due to flow and temperature conditions, the largest part of this dust will settle out in the recuperator and on lower temperature components. The amount of dust that will settle out on the inside of the reactor pressure vessel and pressure boundary will be negligible. The contribution of this dust as a source of carbon for carburization will therefore be ignored.

It has been reported in [2] that the predominant interaction of the helium impurities with HTGR materials would lead to either carburization or internal oxidation. These processes could in turn then affect the creep and fatigue properties of the materials. The majority of experimental testing have been performed on high-temperature materials e.g. Austenitic Stainless Steels and Ni-base alloys. The results of these tests will not be addressed in this report, but the general conclusion is that the impurity effects are only appreciable at high temperatures (>550°C).

Huddle [3] has postulated that since carbon and low alloy steels would be used at temperatures below 550°C, serious surface attack, which would depend on diffusional properties would not be expected.

Literature [4] also indicates that the rate of carburization (r) for a conditioned mild steel surface at 500°C has been given by the equation:

$$r = 5 \times 10^4 (p_{CO}p_{H2})^{0.8}\ \mu g/cm^2h \text{ with the pressure in atmospheres.} \quad \text{-------------(1)}$$

With a low alloy steel the rates may be lower by a factor of 5, probably due to the formation of some chromic oxide. The protection provided by oxide films on stainless steel can be significant and can reduce deposition by a factor of 10^4.

The potential for carburization in the PBMR has been evaluated in [5]. It has been found that carburization is thermodynamically possible at temperatures below 550°C and that it would be dependent on the partial pressure ratios of H_2/H_2O and CO/CO_2, as well as the CH_4-content. At temperatures below 300°C the carburizing potential is negligibly low.

Expressions similar to (1) has been used to estimate the increase in carbon content of low alloy steel at 500°C under PBMR conditions. The increase in carbon content after 35EFPY has, very conservatively, been estimated to be 0.14% by weight.

6.2 Reactor Pressure Vessel

From paragraph 4.1 it is evident that the RPV will operate below 300°C for most of the time. During the abnormal operating conditions (PLOFC and DLOFC), the RPV will operate at higher temperatures, but still below 500°C, for short periods of time. No appreciable oxidation or carburization is therefore expected to occur and the RPV will be designed in accordance with the limits permitted by ASME Code Case N-499-1. The allowable stress intensities of code case N-499-1 is considered extensions of the values provided in ASME II, tables 2A, 2B and 4 (time-independent properties). The creep and fatigue analysis will be done in accordance with the rules of ASME III, Division 1, Subsection NH for those events where the temperatures exceed 371°C (700°F) and the data provided in Code Case N-499-1. The results of these analyses will be incorporated in the in-service inspection (ISI) requirements for the PBMR. The inspectability of components is a serious consideration in the design of the components as is the demonstration of the leak-before-break criteria.

6.3 Connecting Piping

From paragraph 4.2 it is evident that the connecting piping will be operated at relatively low temperatures and no appreciable helium effects will be considered. The fatigue analyses of the connecting piping will be done in accordance with the rules of ASME III, Subsection NC – as applicable to vessels. Due to the low operating temperature no creep analyses to be performed.

7. CONCLUSIONS

7.1 Reactor Pressure Vessel

Published results have indicated that due to the low operating temperature and short periods of exposure to higher temperatures, the effect of the PBMR helium on the mechanical properties of the RPV would be insignificant. Fatigue and creep analyses will therefore be done in accordance with the ASME code, utilizing ASME allowable properties.

7.2 Connecting Piping

The connecting piping to the RPV are subjected to lower temperatures than the RPV and analyses will also be performed in accordance with the ASME code.

8. REFERENCES

[1] – Westinghouse Reaktor GmbH Report No. GBRA 053 112, “Distribution and Lift off of Dust Particles in the PBMR”.

[2] – ERPRI Report No. ER/NP-7372, “Research on Very High Temperature Gas Reactors”.

[3] – R.A.U. Huddle, “The Influence of HTR Helium on the Behaviour of Metals in High Temperature Reactors”, Paper 17, Presentation on the effects of the Environment on Material properties in Nuclear Systems, July 1-2 1971.

[4] – J.E. Antill et al, “The Transfer of Carbon from an Inert Gas Containing Carbon Monoxide or Methane to Iron and Nickel Base Alloy”, Paper 15, Presentation on the effects of the Environment on Material properties in Nuclear Systems, July 1-2 1971.

[5] - Westinghouse Reaktor GmbH Report No. GBRA 052 354, “PBMR:Investigation of Carbon Deposition on Steel”.