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Table of Contents

1 Introduction

This report describes the design and design criteria for a horizontal hot gas duct between an HTR Module Reactor and a heat sink system (e.g. a helium turbine or a helium heat exchanger).

This description is confined to the continuous horizontal hot gas duct. Further reports will be generated for the special regions around the axial and angular bellows expansion joints and the connections between the horizontal hot gas duct and the core structure at one and the heat sink system at the other.

The description of the horizontal hot gas duct include answers to the following questions:

- Radial design of a horizontal hot gas duct.

- Axial design of a hot gas duct.

- Fixing the dimensioning parameters of the hot gas duct.

- Choosing the best materials for the hot gas duct.

2 Definition of working parameters

Various parameters have to be specified for design of the hot gas duct between the core and the heat sink. These break down as follows:

2.1 Interfaces

The boundary data given below are valid for the primary hot gas duct of an HTR module reactor irrespective of the heat sink systems. On the hot gas side the component starts at the hot gas plenum of the ceramic core structure and ends at the inlet of the heat sink system. On the cold gas side the component starts at the outlet nozzle of the heat sink system and ends at the inlet nozzle of the reactor vessel.

The pressure boundary formed by the gas duct pressure vessel is only considered in relation to assessing flow patterns in the cold gas duct.

2.2 General Design Criteria

The hot gas duct of the reactor coolant system, its internals and anchoring should be designed to withstand the loadings sustained during the unit's design lifetime.

Basis for design, analysis and materials selection is that the requirements relating to materials properties must be met throughout the unit's design lifetime.

The respective design rules should be based in particular on the importance to safety of the individual parts. Initial sizing calculations may be performed using familiar rules and regulations (e.g. in Germany AD Specifications, Technical Rules for Steam Boilers). Stress, deformation and fatigue analyses are performed in accordance with ASME Code and KTA Safety Standards or consistent with ASME Code.

2.3 Top-Tier Design Data

The unit design lifetime is taken as at least 40 years at a capacity factor of 80%. Consequently the design lifetime for the hot gas duct is at least 280,000 h. These data are to be documented in project-specific records.

The following tests and examinations to be conducted in the course of manufacture of the hot gas duct are to be stipulated in a supply specification and where necessary specified in detail:

- Material tests
- Inprocess examinations
- Final acceptance inspections
- Pressure tests
- Leak tests
- Inspections during installation, inservice inspections

The extent and depth of these tests and inspections have to be laid down in the course of the licensing procedure.

The hot gas duct is to be designed for the complete unit lifetime. Consequently no maintenance or repairs should be necessary during this lifetime. However, it should be possible in principle for the hot gas duct to be removed in order to rectify unforeseeable damage or damage due to failure of other items.

The top-tier boundary conditions stipulated below are to be determined and documented for the specific project. The important data for the hot gas duct are described below. The data for the reference designs for a power plant (AHR) or for a process heat generation plant (PNP) are collated in Appendix A.

The fluid passing along the inside and the outside of the hot gas duct will be the reactor coolant helium (coaxial flow). The helium atmosphere is expected to be reducing. The following impurities are to be specified for this atmosphere:

	HTR with gas turbine	HTR with heat exchanger
H_2O	in µbar	in µbar
H_2	in µbar	in µbar
CO	in µbar	in µbar
CH_4	in µbar	in µbar
N_2	in µbar	in µbar
CO_2	in µbar	in µbar
Dust content	in µg / m^3 STP	in µg / m^3 STP

Furthermore, radiation exposure and neutron fluence must be considered for the materials used. These are to be specified as follows:

Fast neutrons $Ø_{> 0.1\ MeV}$ = in → n/s cm^2

Thermal neutrons $Ø_{< 0.1\ MeV}$ = in → n/s cm^2

nv $t_{> 0.1\ MeV}$ = in → n/cm^2

nv $t_{> 0.1\ MeV}$ = in → n/cm^2

2.4 Design Data for Normal Operation, Rated Power

The following design data for normal operation and rated power output are to be specified (see Appendix A for specimen):

	HTR with gas turbine	HTR with heat exchanger
Hot gas side		
Helium inlet temperature	in °C	in °C
Helium outlet temperature	in °C	in °C
Normal fluctuations	± in K	± in K
Helium pressure	in bar ± 0.5 bar	in bar ± 0.5 bar
Pressure fluctuations	in bar	in bar

Helium mass flow	in kg/s ± 5%	in kg/s ± 5%
Temperature distribution over cross section in K	+ in K - in K	+ in K - in K
<u>Cold gas side</u>		
Helium inlet temperature	in °C	in °C
Helium outlet temperature	in °C	in °C
Normal fluctuations	± in K	± in K
Helium pressure	in bar ± 0.5 bar	in bar ± 0.5 bar
Pressure fluctuations	in bar	in bar
Helium mass flow	in kg/s ± 5%	in kg/s ± 5%
Temperature distribution over cross section	± in K	± in K

2.5 Design Data for Normal Operation, Load Cycling

The following load cycling transients are considered in design of the hot gas duct (see Appendix A for specimen):

	HTR with gas turbine	HTR with heat exchanger
Temperature change rate	± in K/min	± in K/min
Mass flow change rate	in kg/s	in kg/s
Hot gas side limiting temperature	in °C	in °C
Cold gas side limiting temperature	in °C	in °C
Pressure loss	in bar	in bar

2.6 Design Data for Residual Heat Removal (RHR) Operation after Reactor Trip

Reactor trip is followed by changes in mass flow and by peak temperatures on the hot and cold gas sides; these are to be considered in the design of the hot gas duct. In detail the following parameters are to be specified (see Appendix A for specimen):

Hot gas side

Peak temperature	+ in K
Temperature transient	+ in K/min
Mass flow transient	- in kg/s per minute

Cold gas side

Peak temperature	+ in K
Temperature transient	+ in K/min
Mass flow transient	- in kg/s per minute

2.7 Design Data for Failure of RCS Interfacing Piping

Depressurization transients are of particular importance for design of the hot gas duct. For this purpose it is necessary to specify the maximum credible event to be assumed for the unit. The pressure transient is predominant in determining the structural design of the hot gas duct. The following parameters are to be specified:

Peak temperature	+ in K
Temperature transient	+ in K/min
Depressurization	to 1 bar
Pressure transient	in bar/s

3 Listing of the Characteristic Design Conditions

The following parameters are to be evaluated in detail when selecting a basic layout for the hot gas duct:

- Hot gas temperature
- Hot-gas-side helium flow velocity
- Hot-gas-side axial dynamic pressure
- Hot-gas-side axial pressure transients
- Design lifetime

The following decision-making criteria can be formulated on the basis of experience with gas-cooled reactors in Great Britain, the USA and France and in the light of tests performed at the THTR and KVK:

<u>Hot gas temperature</u>

A metallic system can be used for the hot gas duct if nominal service temperatures are not more than 900°C and design lifetime is not more than 140,000 h. A ceramic system is necessary for the hot gas duct if these limits are exceeded. The basic layout of these variants are described below.

<u>Hot-gas-side helium flow velocity</u>

A metallic system must be used if flow velocities in the free cross section of the hot gas duct are greater than 60 m/s. Either variant can be used below this limit.

<u>Hot-gas-side axial dynamic pressure</u>

The axial dynamic pressure in the free cross section is obtained as $\Delta p = \frac{\varphi}{2} \bullet w^2$ per meter. If the pressure is greater than 5000 Pa, a metallic system must be used for the hot gas duct. Either variant can be used below this limit.

Hot-gas-side axial pressure transients

Based on extensive tests on insulation systems at testing facilities at Interatom and the Jülich nuclear research center, a limit of 2 bar/s was determined for the use of a metallic system for the hot gas duct. A ceramic system or a special, elaborate design of metallic system must be used for the hot gas duct if depressurization rates are higher.

Design lifetime

A metallic system is acceptable for the hot gas duct at design lifetimes not exceeding 140,000 h. A ceramic system is to be preferred if this limit is exceeded.

Decision-Making Procedure

A critical appraisal of the above selection criteria will reveal that the individual parameters are mutually exclusive. For this reason it is necessary to consider additional criteria. These are in particular:

- Accessibility of the hot gas duct and therefore relative ease of removal
- Space available between core and heat sink system necessitates small hot gas duct dimensions
- Thermal losses from hot to cold gas side must be reduced to a technically practicable minimum

The following parameters are obtained for a unit equipped with a gas turbine GMTR:

Nominal hot gas temperature	850°C
Hot gas temperature during depressurization accident	max. 900°C
Hot-gas-side helium mass flow	316.19 kg/s
Hot-gas-side helium pressure	71.459 bar
Depressurization rate in the event of turbine failure	84 bar/s
Design temperature for support pipe	540°C

4 Definition of the Material List

Based on the extensive studies on materials performed in Germany in the course of development of the HTR Module the following materials should be selected for the above-mentioned application:

Metallic materials for the temperature range above 550°C

Metallic materials must be classed as materials for elevated temperatures with sufficient tensile strength and creep resistance in this temperature range. These materials are included in the scope of DIN EN 10095 and DIN EN 10302.

For reasons of good manufacturing and fabrication practice and for economic reasons, material 1.4876 should be used for parts of the hot gas duct exposed to temperatures above 550°C in normal operation.

Insulation materials

Because of the small insulation thicknesses of the hot gas duct, it is not expedient to to select different materials for different service temperatures. As a general rule, only fibrous materials consisting of at least 85% Al_2O_3 can be used at temperatures above 600°C. Mixed-oxide fibers (e.g. Al_2O_3/SiO_2) can be used in the 400 to 600°C temperature range, and mineral insulants can be used below 400°C.

Owing to the specific requirements of the application placed on the fibrous insulation of a hot gas duct a long-fibered alumina matting (e.g. SAFFIL) is to be used exclusively. Fiber mats only are to be used as product forms from which packing pads can be made for the packed region within the insulation system.

The characteristic data of SAFFIL alumina matting are collated in Appendix 2.

Support pipe

On account of the functions to be fulfilled and the above-mentioned temperature range the design of the support pipe shall be performed in accordance with the standards referenced in the above. Consequently, materials per AD Specification W2, for example, are to be used.

On account of the elevated temperature level at 540°C, material 1.4571 with a controlled cobalt content is to be used.

5 Definition of radial and axial design and of materials including special requirements

The insulation system layout in a continuous section of the hot gas duct is described below. The diagram shown in Appendix 3 is intended as an aid to understanding.

The radial layout is as follows:

- Liner as a closed metal cylinder
- Depressurization gap for controlled discharge of gas volume from fibrous fill on depcompression
- Perforated pipe with mesh cover enclosing the insulant space
- Wrapped fiber mat insulation made of 95% alumina and 5% silica
- Intermediate layer of metal foil to reduce free convection volume
- Wrapped fiber mat insulation made of 95% alumina and 5% silica
- Support pipe housing the internals and serving as pressure boundary between hot and cold gas channels

Axially this arrangement in interrupted approx. every 1000 mm by a vee-shaped spacer. These metallic thermosleeves have the task of supporting the internal flow guides and preventing axial flow through the insulation. The insulant is packed in the region of the vee-shaped spacers (cf. Appendix 4).

<u>Liner</u>

The high gas flow velocity of approx. 60 m/s and the attendant axial pressure losses give rise to a differential pressure which would cause hot gas to flow through the insulant. This flow would be small because of the small differential pressures and would not cause damage to the insulant but would cause excessive temperatures in the support pipe because of the latter's high specific heat capacity.

A high-temperature material must be used because of the nominal design temperature of 850°C. It must be possible to obtain product forms as sheet and forgings. This is the case with material 1.4876 with the added advantage that it is not as expensive as straight nickel-base alloys.

Depressurization gap

The very high decompression rates of approx. 84 bar/s in the event of a turbine failure cause the hot gas pressure pressure to fall almost instantaneously to a limit of approx. 60 bar. Consequently the liner is subject to an external differential pressure loading of up to 20 bar at 850°C in the event of delayed discharge of the gas inventory in the insulation. This duration of this condition needs to be limited. For this purpose, a drainage gap is located in the material between the liner and the insulation space to allow rapid discharge of the gas inventory. The size of the depressurization gap depends on the gas inventory in the insulation space, the design temperature of the liner and the allowable differential pressure loading of the liner.

For the above-mentioned decompression rate the depressurization gap can be expected to be at least 20 mm wide.

Perforated pipe with mesh cover

A mesh-covered perforated pipe is provided to separate the depressurization gap from the insulation space. The perforated pipe is dimensioned such that the total area of the perforations is approximately equal to the flow cross section present in the depressurization gap. The mesh covering over the perforations prevents insulant entrainment during gas discharge. The mesh size is selected to be at most one tenth of the length of the shortest fiber.

Wrapped mat insulation

The insulant can only be made of a suitable fibrous matting in order to ensure maximum flexibility whilst ruling out gaps in the insulation space. All other kinds of insulation system (e.g. shaped blocks, cassette panels, carbon bricks) inevitably have fitting clearances and create gaps between parts at the latest at temperature. Helium would then flow through these gaps, thus causing unacceptably high temperatures in the support pipe.

For this reason the insulation space is filled predominantly with wrapped insulation. The use of wrapped fibrous matting minimizes the fraction of fragmented fiber (dust) and thus increases the insulation efficiency of the system. This also minimizes the creation of cavities during the long service life. A further feature of wrapped matting is highly uniform packing density of the insulant without the risk of low density pockets. At packing densities below approx. 100 kg/m³ such pockets allow significant temperature peaks in the support pipe because of the enhanced free convection of helium within the insulation space.

Conversely packing densities above 200 kg/m^3 do not improve the thermal conductivity of the overall system as the incidence of fragmentation is higher at such densities thus giving rise to greater conduction.

Intermediate foil

At radial insulation thickness within the insulation space greater than 40 mm an intermediate foil should be inserted to reduce free helium convection. This foil need not be gas tight at the ends or over the axial length but must only provide a high flow resistance to the convective circulation of helium within the insulation space. Without such intermediate foils the effective thermal conductance of the insulation system is approx. 30% higher.

Support pipe

The above-mentioned internals are housed in a gas tight support pipe which separates the hot and cold gas regions from one another. Material 1.4571 is to be used as it is suitable for the above-mentioned design temperature and other design parameters and is also available in the product forms sheet and forgings. This material usually has a cobalt content of 600 to 1000 ppm. This must be reduced to 300 ppm to minimize activation potential. Special heats meeting this requirement can be obtained at no great extra cost if sufficiently large quantities are purchased.

Vee-shaped spacers (thermosleeves)

Vee-shaped spacers are provided as gas tight connecting elements between support pipe and liner. This geometry optimizes the positioning of the liner relative to the support pipe. Furthermore sufficient flexibility is present in the radial direction to accommodate differential thermal expansion between support pipe and liner. The flexural stiffness in the axial direction prevents a significant displacement of the liner which is supported as a cantilever. To ensure optimum stress conditions in the vee-shaped spacer the connecting regions to the support and liner and also the tip of the vee will be fabricated by machining from forgings. The welded joints will be remote from the zones under greatest loading.

Packed fiber areas

A wrapped insulation system could only be fabricated in the region of the spacer vees with a considerable assembly effort. Because of the small volumes to be filled around and within the spacer vees it is possible to use packed insulation in these regions. However, mass-produced mineral wool is not suitable for this purpose because of the large fragment fraction; instead 10 by 10 cm pads are cut out of the fiber matting used for the wrapped insulation. These are then packed into the above mentioned volumes to a density of 160 kg/m^3.

6 Experimental Verification

The complexity of the task of developing a suitable primary insulation system for high-temperature reactors necessitated a comprehensive testing program for the purpose of experimental verification addition to the theoretical analyses performed.

In addition to numerous small-scale test rigs used to fabrication, compatibility and component testing, particular mention should be made of three facilities used for practical trials in the context of the consortial cooperation program for the PNP project.

- High-pressure gas channel (HP channel) of the Reactor Components Institute at the Jülich Nuclear Research Center with the task of studying insulation concepts concentrating on minimizing thermal losses, radial and axial temperature profiles and free and forced convection within the insulation.

- Facility for long-term insulation testing (ADI) at Hochtemperatur-Reaktorbau (HRB) Jülich with the task of conducting long-term tests on optimized systems passed by the HP channel. This included tests relating to transient temperature response.

- KVK test rig (Komponent-Versuchs-Kreislauf = component test rig) of Interatom for testing prototype hot gas ducts for the primary and secondary sides of the PNP facility (Projekt-Nukleare Prozeßwärme = nuclear process heat project).

The following main features of the hot gas duct design presented here were demonstrated:

- Optimized insulation design with fiber mats and convection sheet in the HP channel
- Long-term stabiity of the insulation system at ADI
- Depressurization response on a special test rig at Jülich Nuclear Research Center
- Verification of manufacturability as a reactor component of the straight hot gas duct, a 90° elbow, an axial bellows expansion joint, an angular bellows expansion joint and special components such as the core connection at KVK

The straight pipe was proof-tested on the component test rig KVK. The thermal conductivity of the overall system increases with hot gas temperature in proportion to the increase in thermal conductivity of helium alone, with the associated factor being more or less constant. A dependence of the thermal conductivity of the overall system on helium pressure is not apparent.

The following test results were verified at these test facilities.

- The insulation system effectively prevents free and forced convection of the helium within the insulant.
- In the tested configuration the thermal loss is max. 5 kW per meter length of pipe and is therefore approx. 30% less than the planned target.
- The support pipe surface temperatures are approx. 15% lower than the planned target.
- The insulation system is so homogeneous that temperature differences are so small that they need not be considered in structural analyses.
- The thermal conductivity of the insulation system including the heat transfer from helium to the liner and from the support pipe to the cold helium is approx. 30% greater than the thermal conductivity of helium alone at the corresponding median temperature.

7 List of figures

Appendix 1: Examples of Main Design Data

Impurities in helium:

	AHR	PNP
H_2O	6.0 µbar	1.5 µbar
H_2	300 µbar	500 µbar
CO	120 µbar	15 µbar
CH_4	60 µbar	20 µbar
N_2	60 µbar	5 µbar
CO_2	30 µbar	--
Dust content	20 µg / m^3 STP	20 µg / m^3 STP

Fast neutrons $Ø_{> 0.1\ MeV} = 2×10^7$ n/s cm^2

Thermal neutrons $Ø_{> 0.1\ MeV} = 3x10^9$n/s cm^2

nv $t_{> 0.1\ MeV} = 2x10^{16}$ n/cm^2

$nvt_{> 0.1\ MeV} = 3x10^{18}$ n/cm^2

The following data apply in normal operation at rated power output:

Hot gas side

	AHR	PNP
Helium inlet temperature	701°C	953°C
Helium outlet temperature	700°C	950°C
Normal fluctuations	± 18 K	± 18 K
Helium pressure	60.1 bar ± 0.5 bar	40.5 bar ± 0.5 bar

Pressure fluctuations	approx. 0.1 bar	approx. 0.1 bar
Helium mass flow	85.4 kg/s ± 5%	50.3 kg/s ± 5%
Temperature distribution over cross section	± 30 K	+ 18.5 K - 16.0 K

Cold gas side

	AHR	PNP
Helium inlet temperature	249°C	297°C
Helium outlet temperature	250°C	300°C
Normal fluctuations	± 18 K	± 18 K
Helium pressure	61.0 bar ± 0.5 bar	41.3 bar ± 0.5 bar
Pressure fluctuations	approx. 0.1 bar	approx. 0.1 bar
Helium mass flow	85.4 kg/s ± 5%	50.3 kg/s ± 5%
Temperature distribution over cross section	± 10 K	± 15 K

The following transients are to be considered on load cycling between 100 and 50% in the case of the AHR and between 100 and 65% in the case of the PNP

	AHR	PNP
Temperature change rate	± 2 K/min	± 1 K/min
Mass flow change rate	± 4.42 kg/s	± 0.08 kg/s
Hot gas side limiting temperature	600°C	625°C
Cold gas side limiting temperature	210°C	300°C
Pressure loss	less than 0.5 bar	less than 0.5 bar

Design Data for Residual Heat Removal (RHR) Operation after Reactor Trip

Hot gas side

Peak temperature	+48 K
Temperature transient	+25 K/min
Mass flow transient	- 27 kg/s per minute

Cold gas side

Peak temperature	+38 K
Temperature transient	+25 K/min
Mass flow transient	- 27 kg/s per minute

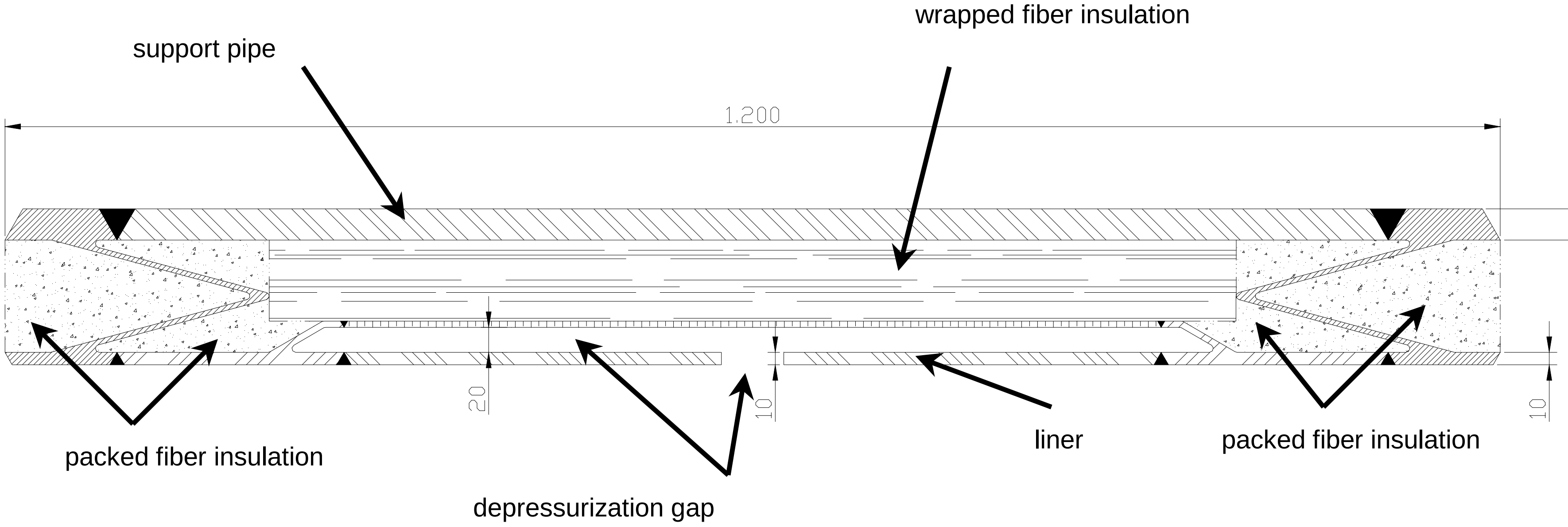
Design Data for Failure of RCS Interfacing Piping

Peak temperature	+48 K
Temperature transient	+25 K/min
Depressurization	to 1 bar
Pressure transient	-0.5 bar/s

Appendix 2: Typical Property Data: Fiber Mat

Type	Saffil, 95% Al_2O_3	
	Nuclear Grade A or B	
Bulk Density	53 ± 7 kg/m^3	
Packed Density/Tensile Strength	160 kg/m^3	
Thermal Conductivity in Air	400°C	0.127 W/mK
1 bar, 160 kg/m^3	600°C	0.163 W/mK
	800°C	0.204 W/mK
	1000°C	0.243 W/mK
Thermal Conductivity in Helium	400°C	0,296 W/mK
40 bar, 160 kg/m^3	600°C	0,465 W/mK
	800°C	0,571 W/mK
	1000°C	0,682 W/mK

Appendix 3: Layout of Metallic Hot Gas Duct



Appendix 4: Thermosleeves