FRAMATOME ANP
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BORDEREAU DE DIFFUSION No NOV-HT 17 ENV

AFFAIRE : HTR-E – RECUPERATOR

DOCUMENT(S) DIFFUSE(S)

Immatriculation	Indice	Titre	N? Interne
HTRE0208D210	B		HT P 185

SPECIFICATION OF TYPICAL OPERATING CONDITION FOR HTR

DESTINATAIRES		Objet	Nb exemplaires Document(s)	Nb exemplaires Bordereau(x)
EUROPEAN COMMISSION	M HUGON	ATT	1	1
COPIE(S) INTERNE(S)				
EVEI	E BREUIL – C MAUGET	ATT	2	2
EVEI	JD POUZADOUX	INF	1	1
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EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-E

High-Temperature Reactor Components and Systems

CONTRACT N°
FIKI-CT-2001-00177

HTR-E WP2 Recuperator
Specifications of typical operating conditions for HTR

C. MAUGET

FRAMATOME ANP

FRANCE

Dissemination level : RE
Document N°: HTR-E-02/08-D-2-1-0
Status : Final
Deliverable n°12
FRAMATOME-ANP
Identification n° : EVEI DC 02.0487/B

FRAMATOME ANP

NOVATOME

NUMERO D'OTP OU EOTP	NOMBRE DE PAGES : 34 NOMBRE D'ANNEXES : 0	RAISON SOCIALE FOURNISSEUR :	
12T.DT HTREW2NV	CONFIDENTIALITE : N	NUMERO DE COMMANDE	IMMATRICULATION FOURNISSEUR

CODE		DESIGNATION
AFFAIRE	HT	HTR
NATURE	DT	NOTE TECHNIQUE
THEME	CCP	CONCEPTION
MATERIEL	4500	RECUPERATOR

TITRE : **HTR-E - RECUPERATOR SPECIFICATIONS OF TYPICAL OPERATING CONDITIONS FOR HTR**

TITRE ABREGE : **HTR-E - RECUPERATOR - TYPICAL OPERATING CONDITIONS FOR HTR**

IND	DATE	ETAT	REDACTEUR NOM-VISA	VERIFICATEUR NOM-VISA	APPROBATEUR NOM-VISA	MODIFICATIONS – OBSERVATIONS – ACCORDS REFERENCES ET DATES
B	11/01/2003	DEF	C. MAUGET	E. BREUIL	JD. POUZADOUX	Final issue
A	30/08/2002	PRE	C. MAUGET	E. BREUIL	J.D. POUZADOUX	First issue

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IMMATRICULATION CLIENT : **HTR-E 02/08 D-2-1-0**

IMMATRICULATION INTERNE :	EVEI	DC	02	0487	/
	UNITE	TYPE	ANNEE	CHRONO	TRIGRAMMES

10, rue Juliette Récamier 69456 LYON CEDEX 06 - Téléphone : 04.72.74.82.21 - Télécopie : 04.72.74.84.90

Modifications

Revision	Date	Modifications
A	30/08/2002	First issue
B	11/01/2003	Final issue – FRAMATOME Paris la Défense meeting – January 10th, 2003

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Summary

The recuperator is a helium/helium heat exchanger inserted in the primary circuit to recuperate a part of the remaining energy at the turbine outlet to preheat the helium at the core inlet.

This component is specific to the direct cycle and its main function is to increase as high as possible the efficiency of the cycle.

The competitiveness of a modern HTR is directly linked to the feasibility of this component.

This preliminary document defines firstly the typical operating conditions and functional requirements for a modern HTR with direct cycle (GT-MHR type, PBMR type).

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List of notations

ANSI	:	American National Standards Institute
ASME	:	American Society of Mechanical Engineers
AVR	:	Name of German reactor
GT-MHR	:	Gas turbine Modular Helium Reactor
HP	:	High Pressure
HTR-E	:	Acronym for the European project on high temperature reactor components and systems
IAEA	:	International Atomic Energy Agency
IEEE	:	Institute of Electrical and Electronics Engineers
LP	:	Low Pressure
PBMR	:	Pebble Bed Modular Reactor
PCS	:	Power Conversion System
PCV	:	Power Conversion Vessel
TM	:	Turbo-Machine
ΔP	:	Pressure difference

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1. Introduction

The purpose of this document is to establish the typical steady state and transient operating conditions of the recuperator.

The organization of this document is as follows :

- function and general description of the recuperator,
- thermal and hydraulic steady state conditions,
- typical transient conditions,
- environment and the quality of fluid,
- the life time,
- the safety requirements,
- inspection requirements during manufacturing and operation,
- space requirements,
- loss of efficiency accepted,
- design rules.

2. General description and function

2.1 General description

2.1.1 GT-MHR project

The main characteristics of the GT-MHR project are gathered in table 1. These characteristics are not definitively established, and there is no consistent baseline for the project.

The direct GT-MHR cycle and the reactor module arrangement are on the figures 1 and 2.

The net plant efficiency can reach almost 50 % considering a high performance heat exchanger. More over, there is a strong constraint for the compactness of this heat exchanger in order to fit in the PCS vessel.

The compactness together with the severe operating conditions makes the design a real "challenge".

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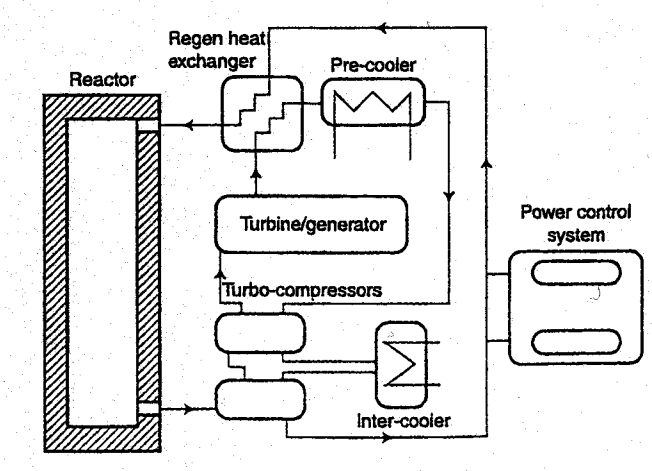
2.1.2 PBMR project

The PBMR project is an actual industrial project. Therefore information can only be given by published data. Data for the operating conditions of the PBMR recuperator are taken out of the published report :

IAEA-TECDOC-1198
Current status and future development
of modular high temperature gas cooled
reactor technology
February 2001

The main characteristics of the PBMR project are gathered in table 2.

A schematic layout of the PBMR is shown :



The general layout is presented more in detail in figure 5.

The Power Conversion Unit consists of the main components (figure 6) :

- HP turbo-compressor units.
- LP turbo-compressor units.
- Power Turbine Generator.
- Recuperator.
- Coolers.
- Hot pipe and valve.

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The dimension of the different pressure vessels of the PBMR can be seen in figure 7 and the tables 3 and 4.

The process cycle used is the Brayton cycle with a closed circuit water cooled Intercooler and Precooler.

The helium from the reactor (900 °C, 7 MPa) passes through the high and low pressure turbo-units, to the Power Turbine.

A high efficiency Recuperator is used after the Power Turbine to recuperate the thermal energy.

Lower energy helium is passed through the Precooler and Intercooler and the low and high pressure compressors before it is returned through the Recuperator to the reactor core at ~ 540 °C and at a pressure of 7.0 MPa.

The power Conversion Unit heat sink is based on a cooling water inlet-temperature at 22 °C and outlet at ~ 35 °C.

2.2 Function

The recuperator is a helium/helium heat exchanger inserted in the primary circuit to recuperate a part of the remaining energy at the turbine outlet to preheat the helium at the core inlet.

The main functions requested are as follows :

- heat exchange between cold and hot helium is required to maintain the plant efficiency (note), the primary circuit structure and core temperatures at their nominal values,
- leak-tightness between cold and hot helium leakage form HP cavity to LP cavity leads to loss of performances. Consequently, recuperator leak tightness must be improved as much as possible,
- path for the primary helium flow is needed to achieve the primary circuit structure good behavior and core coolability,
- structural integrity is required to avoid failure of the recuperator, which could damage the rotating machines like turbine and compressors or generate loose parts and potentially disturb the core cooling.

Note *: Depending on process requirements, the thermal effectiveness of the heat exchange can range from a few per cent to over 98 %. The exchange between the fluids can be cross-flow, co-flow, counter-flow or combinations of these arrangements.*

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3. Thermal and hydraulic steady state conditions

3.1 GT-MHR data

The normal conditions for steady state are given here under :

Name of parameter	Value
♦ Thermal capacity	635 MWth
♦ Thermal effectiveness	0.95
♦ Helium parameters on low pressure side	
• flow rate	316 kg/s
• inlet temperature	510 °C
• outlet temperature	125 °C
• inlet pressure	2.63 MPa
• pressure losses	not more than around 0.03 MPa
♦ Helium parameters on high pressure side	
• flow rate	313 kg/s
• inlet temperature	105 °C
• outlet temperature	490 °C
• inlet pressure	7.07 MPa
• pressure losses	not more than around 0.07 MPa
♦ ΔP between the high and low pressure sides	4.5 MPa

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3.2 PBMR data

From the Brayton cycle (figure 4) and from former studies, the following operating data for the recuperator can be taken as follows :

Name of parameter	Value
♦ Thermal capacity	310 MWth
♦ Thermal effectiveness	η = 0.97
♦ Helium parameters on low pressure side	
• flow rate	143 kg/s
• inlet temperature	554 °C
• outlet temperature	140 °C
• inlet pressure	26 bar
• pressure losses (ΔP)	around 0.6 bar
♦ Helium parameters on high pressure side	
• flow rate	140 kg/s
• inlet temperature	104 °C
• outlet temperature	536 °C
• inlet pressure	70 bar
• pressure losses (ΔP)	around 0.3 bar

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4. Typical transient conditions

4.1 Transient conditions classification

Transients conditions are classified among five categories, as follows :

Classification	Definition
♦ Category 1	Normal transients associated with modes of normal plant operation during its entire service life, frequency (> 1/year)
♦ Category 2	Design transients associated with any deviations from normal operation conditions, which require to decrease power or to shutdown reactor to eliminate these deviations without activation of the emergency core cooling system frequency (> 10^{-2}/year)
♦ Category 3	Design transients caused by defined in the design initial events and characterized by violation of limits and/or conditions established for operation, except safe operation limits for radioactive products release (10^{-4} < frequency < 10^{-2}/year)
♦ Category 4	Design accidental transients caused by defined in the design initial events resulting in exceeding the safe operation limits for radioactive product release beyond boundaries provided by the design for normal operation (10^{-6} < frequency < 10^{-4}/year)
♦ Design Extension conditions	Beyond design accidental transients caused by initial events that were not addressed in the design or accompanied by additional failures or personnel errors in comparison with design accidental transients ($\leq 10^{-6}$/year)

4.2 Normal and design transient conditions

The preliminary GT-MHR analysis of transients based on the magnitude of temperature and pressure by comparison with the normal operating shows that the most severe transients is the loss of offsite power with turbo-machine trip (figures 8, 9 et 10).

Cold shocks in transient conditions :

- ΔT = 335 °C for the LP recuperator inlet, in 5 seconds, from initial values : 508 °C
- (severe slope $\simeq$ 70 °C/s), then, the temperature rises again in 508 °C in 120 seconds after initiation
- temperature maximum = 650 °C in the end of the turbo-machine run-out
- number of scram occurrences : 500.

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4.3 Design accidental transients

The maximum temperature reaches 655 °C for the hot inlet early (in 1 second) at the beginning of the turbine deblading transient.

The pressure difference ΔP between the low and high pressure sides is 0.7 MPa.

5. Environment and quality of fluid

The helium impurities contents are specified as follows :

H_2O < 2 vpm
$CO + CO_2$ < 6 vpm
H_2 < 5 vpm
CH_4 (not yet specified for GT-MHR project)

The solid particles content may induce a risk of turbine erosion and fouling of the recuperator elementary channels.

Taking into account the AVR feed back (5 µg/m^3) which is an experimental reactor it was plausible to take a lower value in GT-MHR project.

The dust concentration is taken to 0.5 µg/m^3, which seems to be more appropriated for a prismatic block fuel reactor such as the GT-MHR.

The average dust particle diameter is 0.6 µm (most of the particles in AVR coolant has a size between 0.2 and 1 µg).

There is not risk of deviation of average diameter 0.6 µm dust particles at nominal operating conditions through inertia effects.

Sedimentation risks do not exist at nominal conditions. However, during all the reactor life time, and considering all other operating conditions, reactor and PCS bottom parts are suspected to be subject of deposits.

In addition, for unsteady cases, transient flow should lead to helium gusts within the primary circuit, which could induce unsticking of dust particles localized in the quasi-stagnant zones and displacements of these particles in the whole primary circuit. The worst case is a change of operating conditions during the reactor lifetime, as observed in the German reactor AVR, which led to dust remobilization.

6. Life time

The service life is 60 years.

7. Safety requirements

The first step for determining the safety classification of this equipment is to identify the safety function it performs, mentioned before in chapter 2.2.

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7.1 Safety classification

The recuperator (GT-MHR type) is not a safety classified as it is explained hereafter.

Indeed the safety classification of an equipment is based on the functions performed by the equipment, the consequences of the failure of the equipment to perform its safety functions, the probability that the equipment has to perform its safety function, the failure of the equipment.

The consequences of the failure of the safety function are judged with regard to the radiological risks in the environment : if the consequences lead to potentially exceed the design basis radiological limits, the equipment performing the safety function has the highest safety classification ; if the radiological consequences don't exceed the radiological releases accepted for normal operating conditions, the equipment is not safety classified ; Intermediate safety classifications are defined for intermediate radiological consequences.

The failure of the equipment has also to be examined with regard to the potential hazards on other safety-classified equipment.

In normal operating conditions, any significant disturbance in the core/structure cooling function should be detected and lead to shut down the reactor.

The disturbances in the cooling function have to be considered with regard to the potential radiological releases in the environment.

If the consequences of the disturbances in the cooling function can lead to radiological releases in the environment, the monitoring of the primary cooling function in normal operating conditions, has to be considered as a safety function ; the level of the classification depending on the level of the radiological consequences, although the cooling function itself is not a safety function. Considering the recuperator, the cooling function in normal operating conditions is not a safety-classified function.

After the reactor shutdown, the core/structure cooling function has to be performed in shutdown conditions. The core/structure cooling in shutdown conditions is a safety function. Nevertheless, taking into account the inherent characteristics of the GT-MHR concept, the core/structure cooling function should not require primary helium circulation.

If this is confirmed, the recuperator need not be safety classified from this point of view, the other equipment assuring the helium circulation also need not be safety classified (e.g. the Reactor Shutdown Cooling System need not be classified).

Concerning the structural failure of the recuperator, it can be assumed conservatively that this is not acceptable because this could damage the primary helium containment function and therefore this could potentially leads to radiological releases in the environment.

Nevertheless, the radiological releases should be limited and the safety classification of the equipment assuring the structural integrity of the recuperator could be limited.

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7.2 Conclusion of the analysis

The recuperator heat exchanger is not a safety classified because the cooling function of the core and the structures, in normal and shutdown conditions should not be a safety function.

Nevertheless, the features assuring the support and the structural integrity of the recuperator could be safety classified if their failures could lead to damage safety classified equipment or the containment of the primary helium.

8. Inspection requirements during manufacturing and operation

8.1 Choice of the modularity concept

A modular design is provided for modules repair or replacement in case of damage without disassembly of the whole heat exchanger.

A sectionalized module is provided to find and plug the damaged section without modules disassembly.

This requirement leads to a restraint concerning the level of modularity and the minimum number of elements which is required to operate with a good cycle efficiency after plugging of the faulty elements.

8.2 Manufacturing

Manufacturing requirements concerning non destructive examination from western countries standards on examination of surfaces to be welded, during welding operation and after welding operations, has to be specified.

A choice of leak testing method (preferably helium test), has to be checked performed and a procedure defined in order to get the sensitivity required 5.10^{-8} $Pa.m^3/s$.

8.3 In-service Inspection and repair

The chemically inert and clean coolant, the small pressure drop and the small temperature difference by which heat is transferred at the nominal, steady-state operating conditions, make the recuperator a component suitable for continuous operation over the HTR time life.

Nevertheless the component is not free from risk of mechanical damage, particularly because of the rather severe thermal transients.

Its location inside the pressure boundary, which makes the recuperator inaccessible to hand on interventions, requires high reliability, which must be ensured by design backed up by in-service monitoring of mechanical and process parameters in order to timely detect any symptom of deviation and to take corrective actions.

There are two different candidate types of recuperator, namely the helical, finned-tube bundle and the plate-type recuperator with different potential failures and hence different ISI requirements.

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8.3.1 Helical and finned-tube recuperator design concepts

Helical, finned tubes heat exchanger are proven-technology components and can easily withstand the operating conditions within the HTR. Tubes can easily sustain internal pressure and thermal displacements can be accommodated by the flexibility of the helical tube runs in normal operation and transient conditions.

Monitoring of the thermal cycle will give evidence of no significant fouling. In any case fouling would scarcely affect the heat transfer coefficient or the pressure loss of the component.

Support vibration will be monitored and acoustic surveillance will detect any tube rupture or collector leakage, though this is unlikely for this type of component. Tube failure would merely cause internal helium bypass and no activity release, so that the need of repair or component replacement will depend on the amount of associated degradation of the reactor performance or on the excessive level of component vibration.

8.3.2 Plate-type recuperator design concept

Even if industrial experience exists for the plate-type recuperator, the operating conditions which combine high temperature, high pressure loads and thermal transients are new.

The component surveillance should therefore include monitoring of the process parameters temperature and pressure loss. Increase of the component pressure loss could occur because of fouling owing to reduction of the gas flow rate across the small-bore helium channels. In case of fouling, recovering the quality of the coolant would prevent any further degradation.

Thus continuous surveillance of the helium gas purity is a more stringent requirement for this component type than for the alternative, helical-tube design.

Support vibration will be monitored and acoustic surveillance will detect any collector leakage.

The plate-type recuperator may suffer of the predicted severe thermal transient (reportedly 335 °C in 5 sec) because of its configuration. The actual heat exchanger namely is a package of thin assembled plates with different thermal inertia between the heat transfer region and the solid border connected to the collectors. Thus thermal stresses occur between the thick and the thin structures of the recuperator, which may lead to local progressive deformation with consequent modification of the component outline dimensions.

Strain gauges will be used first for ensuring that local stresses remain within the calculated levels and then surveillance will be pursued forwards to ensure that permanent deformations remains within allowable limits over the lifetime of the component.

9. Space requirements

The PCS arrangement is on the figure 2.

The recuperators are located inside the PCS vessel at the turbine outlet level. The envelope for the recuperator modules is an annular space, which is occluded by the system inlet duct (figure 3).

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10. Loss of efficiency accepted

Loss of efficiency accepted has to be defined.

But note that the GT-MHR considers a failure intensity of 4 10^{-5}/h for the recuperator, and the design provides a margin of 2 % in the heat exchange surface with allowance for repair.

11. Design rules

The recuperator is not safety classified but it works in the significant creep domain. An "over classification" is therefore recommended, which means that this component must be analyzed with the class 2 component.

The recuperator development shall be performed on the basis of the western countries standards, American or European (ASME, ANSI, IEEE, ...).

However, the nuclear design codes do not give recommendations for all the design and the fabrication of this component. There is a lack of specific rules for such components, which shall be developed, and regarding the fabrication process.

12. Conclusion

The recuperator is a helium/helium heat exchanger inserted in the primary circuit to recuperate a part of the remaining energy at the turbine outlet to preheat the helium at the core inlet.

This component is specific to the direct cycle and its main function is to increase as high as possible the efficiency of the cycle.

The competitiveness of a modern HTR is directly linked to the feasibility of this component.

This preliminary document defines firstly the typical operating conditions and functional requirements.

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Table 1

GT-MHR characteristics
(3 pages)

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SYSTEM		
Reactor		
Thermal power	MW	600
He temperature at core inlet	°C	490
He temperature at core outlet	°C	850
He flowrate through the core	kg/s	316
He pressure at core inlet	bar	70,7
Power conversion system		
Turbine power	MW	561
He temperature at turbine outlet	°C	510
He pressure at turbine outlet	bar	26,3
Recuperator power	MW	625
He temperature at recuperator hot side outlet	°C	125
Precooler power	MW	173
He temperature at precooler outlet	°C	26
He temperature at LP compressor outlet	°C	107
He pressure at LP compressor outlet	bar	43,4
Intercooler power	MW	133
He temperature at intercooler outlet	°C	26
He temperature at HP compressor outlet	°C	105
Nuclear power plant		
Gross electrical output	MW	285
Net electrical output	MW	278
Efficiency	%	47
Plant capacity factor		0,8
Load change following	%/min	< 5
He inventory loss	%/y	< 10

REACTOR		
Core		
Number of fuel assembly columns		102
Number of fuel assemblies per column		10
Fuel assembly height	cm	80
Fuel assembly width across flats	cm	36
Core equivalent inner diameter	cm	296
Core equivalent outer diameter	cm	484
Average power density	MW/m3	6,5
Number of control rods		48
Number of reserve shutdown system channels		18
Top / bottom reflector thickness	cm	80
WG-Pu fuel cycle		
Fuel residence time	efpd	840
Refueling interval	efpd	280
Refueling duration	d	20,7
Total core loading	kg	700
Average fuel burnup at discharge	MWd/t	642000
Burnup of initially loaded Pu-239	%	0,886
Axial power peaking factor		1,5
Power peaking factor over fuel compacts		1,6
Isothermal temperature coefficient at BOC	pcm/°C	-7,5
Isothermal temperature coefficient at EOC	pcm/°C	-5,3
Side reflector rod system worth at BOC (dk/k)	%	7,9
In-core rod system worth at BOC (dk/k)	%	6,8
Reserve shutdown system worth (dk/k) at BOC	%	11,6

OTHER		
Turbo-machine		
Maximum diameter (generator)	cm	392
Length	cm	3038
Rotor mass	t	105,4
Turbine adiabatic efficiency	%	> 93
Number of stages in the turbine		12
LP compressor adiabatic efficiency	%	> 88
Number of stages in the LP compressor		16
HP compressor adiabatic efficiency	%	> 87
Number of stages in the HP compressor		24
Content of impurities in helium under normal operation		
H2O	vpm	< 2
CO2 + CO	vpm	< 6
H2	vpm	< 5
Economy for a FOAK		
Design and development cost	M$	320
Plant capital cost	M$	273
Fuel fabrication capital cost	M$	47
Annual operation cost	M$	44
Power generation prime cost	$/kWh	0,022
Economy for a 4 module NOAK plant		
Plant capital cost	M$	928
Fuel fabrication capital cost	M$	126
Annual operation cost	M$	102
Power generation prime cost	$/kWh	0,013

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VESSELS		
Reactor vessel		
Maximum wall thickness	cm	27
Inner diameter	cm	730
Outer diameter	cm	864
Height	cm	3117
Number of blocks		2
Total mass	t	1362
Lifetime	y	60
PCS vessel		
Maximum wall thickness	cm	28,5
Inner diameter	cm	730
Outer diameter	cm	874
Height	cm	3700
Number of blocks		4
Total mass	t	1840
Lifetime	y	60
Cross vessel		
Maximum wall thickness	cm	10
Inner diameter	cm	230
Outer diameter	cm	250
Height	cm	290
Number of blocks		1
Total mass	t	17
Lifetime	y	60

FUEL		
Standard assembly		
Number of fuel compact channels		202
Fuel compact channel diameter	mm	12,7
Number of coolant channels		108
Coolant channel diameter	mm	16
Number of burnable poison compact channels		14
Total number of fuel compacts in the assembly		3030
Control assembly		
Number of fuel compact channels		164
Number of coolant channels		89
Number of burnable poison compact channels		10
Total number of fuel compacts in the assembly		2460
Control rod hole diameter	mm	130
Fuel compact and particle		
Fuel compact diameter	mm	12,5
Fuel compact height	mm	50
Kernel diameter	µm	200
Kernel density		> 10
Buffer thickness	µm	100
Buffer density		1
Inner PyC layer thickness	µm	35
Inner PyC density		1,8
SiC layer thickness	µm	35
SiC density		3,2
Outer PyC layer thickness	µm	40
Outer PyC density		1,8

References

IAEA TECDOC 1198
Current status and future development of modular HTGR technology
"Review of the Gas Turbine Modular Helium Reactor (GT-MHR) plan
Transactions of the International HTR Fuel Seminar
February 1-2, Brussels, Belgium
"The international GT-MHR fuel program", D.W. McEachern and al.

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Table 2

General data PBMR

Reactor core thermal output	265 MW_{th}
Net electrical power output	116.3 MW_e
Thermal hydraulic cycle efficiency	45.3 %
Net plant efficiency	42.7 %
Core inlet temperature	536 °C
Core outlet temperature	900 °C
Helium mass flow rate through core (nominal)	140 kg/s
Nominal pressure at core inlet	7 MPa
Pressure drop over core	0.175 MPa
Average core power density (fuel spheres only)	4.3 MW/m^3
Brayton cycle pressure ratio	2.7
HP & LP compressor efficiency	89 %
HP & LP turbines efficiency	89 %
Power turbine efficiency	90 %
Generator efficiency	98 %
Ramping capability “up + down” between 0 → 100 power load	10 %/min
Step function, % of current power betw. 0 → 100 power level	10 %

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Table 3

Data for the RPV of the PBMR

Design pressure	7 MPa
Design temperature	350 °C
Inside diameter	6 200 mm
Flange outside diameter	6 930 mm
Bolt circle diameter	6 630 mm
Height of pressure vessel without lid	18 850 mm
Overall pressure vessel height	21 200 mm
Minimum thickness of cylindrical shell	140 mm
Reinforced thickness of bottom part	240 mm
Estimated pressure vessel weight	~ 600 tonnes
Pressure vessel material	SA 508

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Table 4

Data for the main vessels of the PBMR

Manifold vessel	
Design pressure	7.2 MPa
Design temperature	200°C
Maximum internal diameter (horizontal)	3,800 mm
Maximum internal diameter (vertical)	5000 mm
Maximum nominal wall thickness (horizontal)	165 mm
Maximum nominal wall thickness (vertical)	225 mm
Material	SA 508
Recuperator/Precooler enclosure	
Design pressure	5 MPa
Design temperature	150°C
Internal diameter	4800 mm
Nominal wall thickness	65 mm
Material	SA 508
Generator enclosure	
Design pressure	5 MPa
Design temperature	150°C
Internal diameter	4800 mm
Nominal wall thickness	65 mm
Material	SA 508
Intercooler enclosure	
Design pressure	5 MPa
Design temperature	150°C
Internal diameter	2100 mm
Nominal wall thickness	30 mm
Material	SA 508

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Figure 1

Direct GT-MHR cycle overview

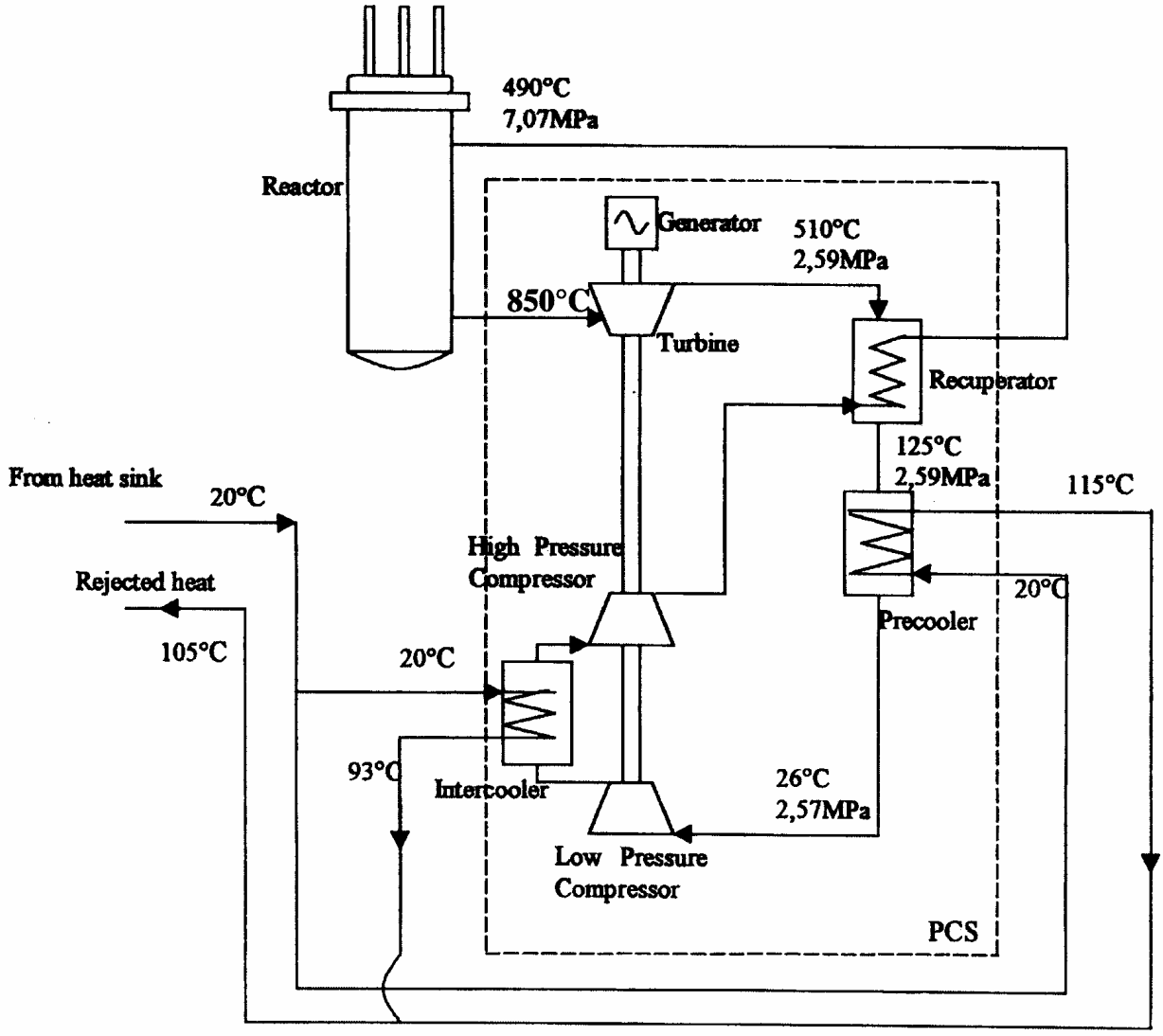

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Figure 2

GT-MHR reactor module arrangement

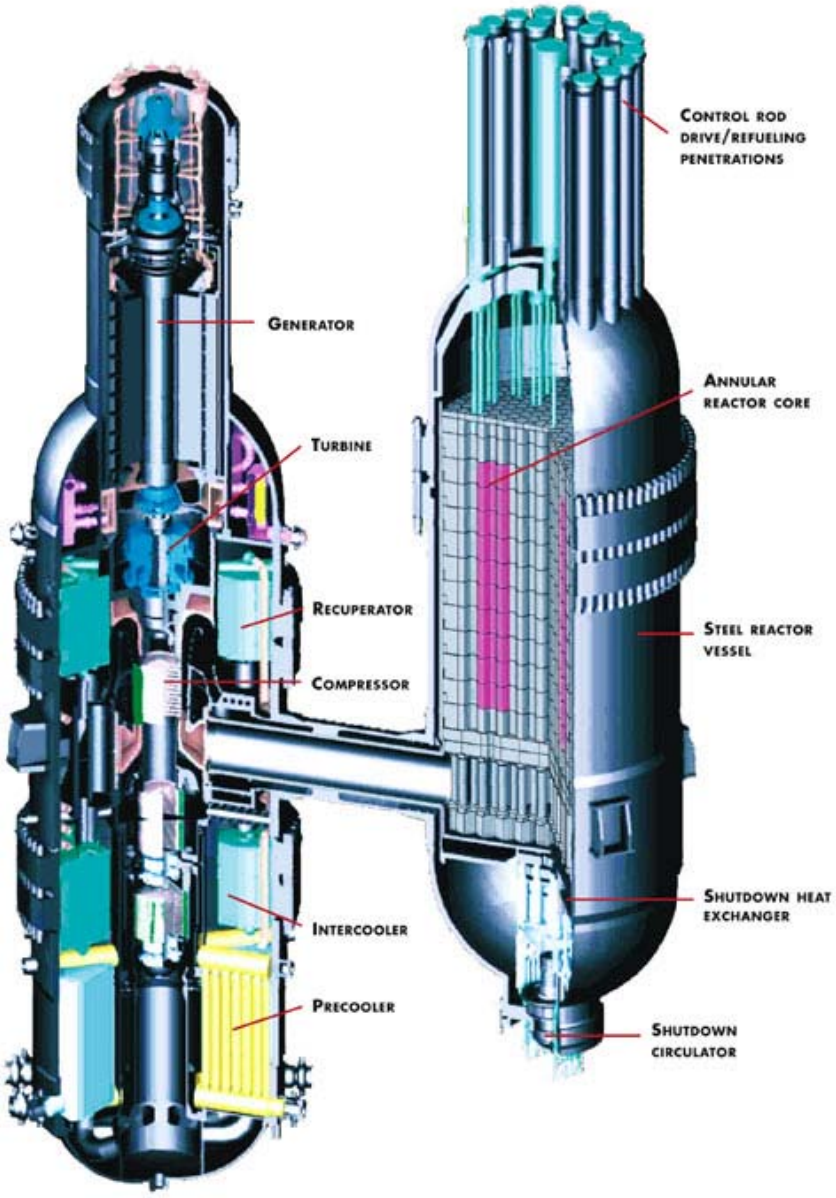

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Figure 3

Layout of the recuperator modules in the power conversion vessel (arrangement example)

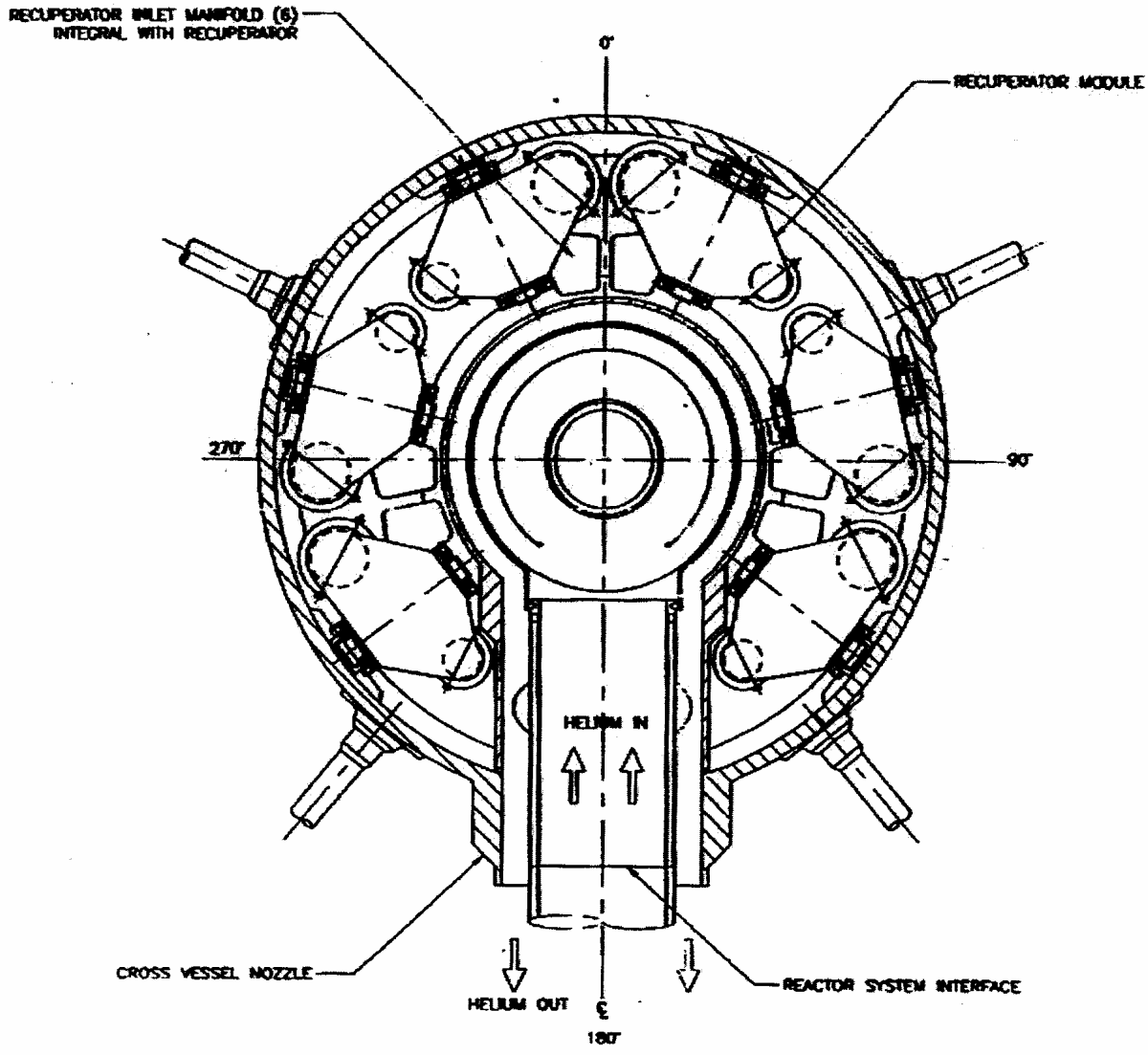

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Figure 4

PBMR Brayton cycle

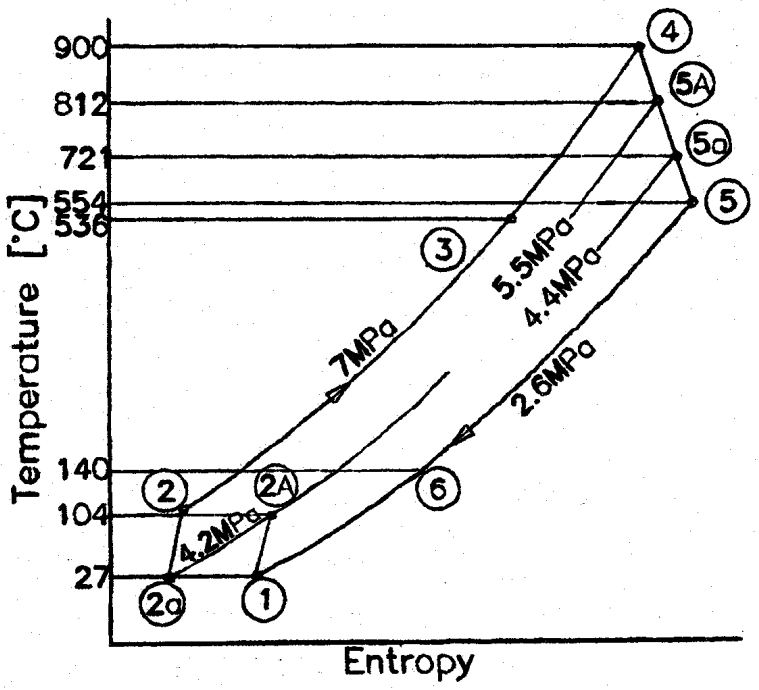

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Figure 5

PBMR system layout

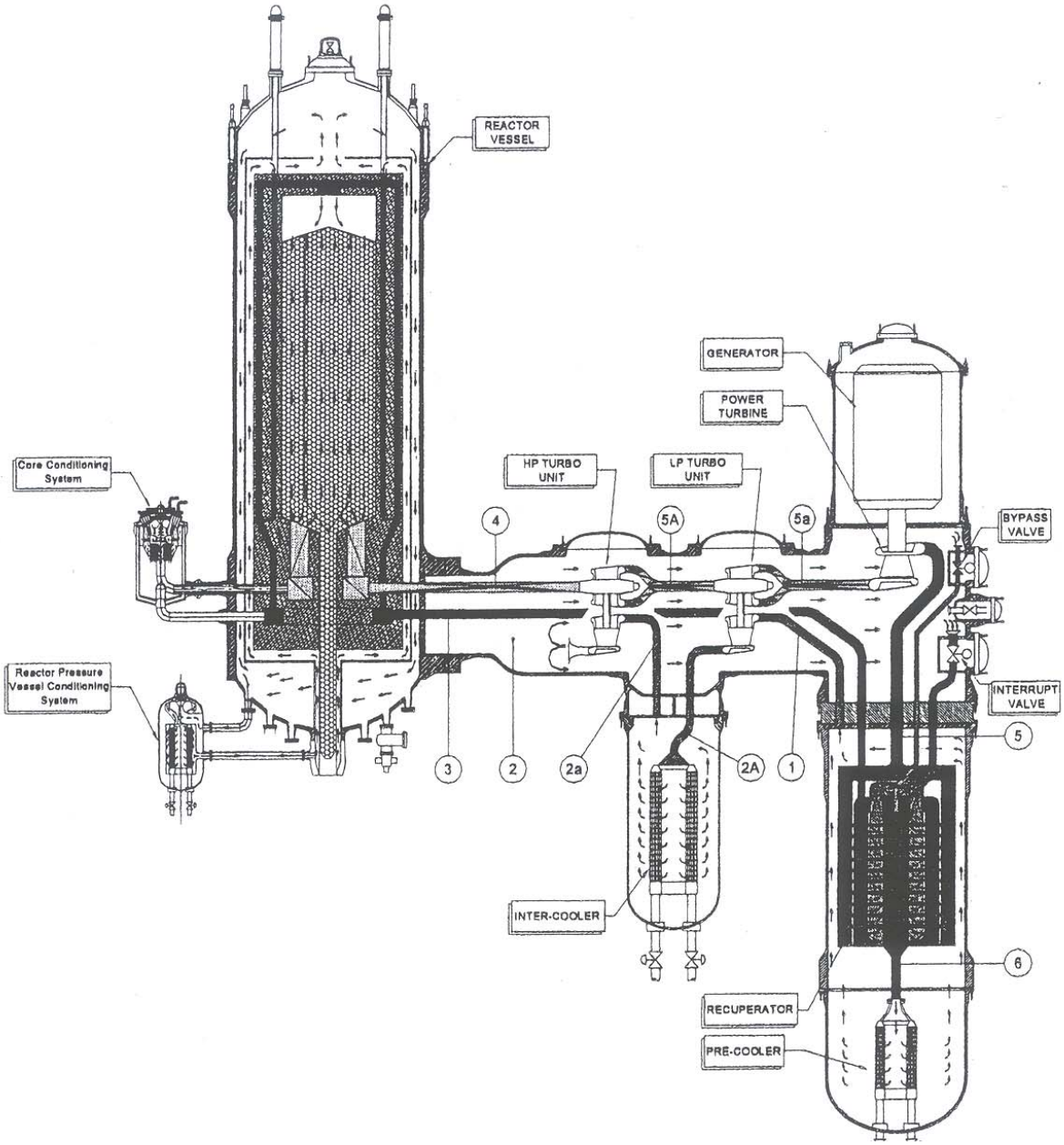

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Figure 6

PBMR – PCU arrangement

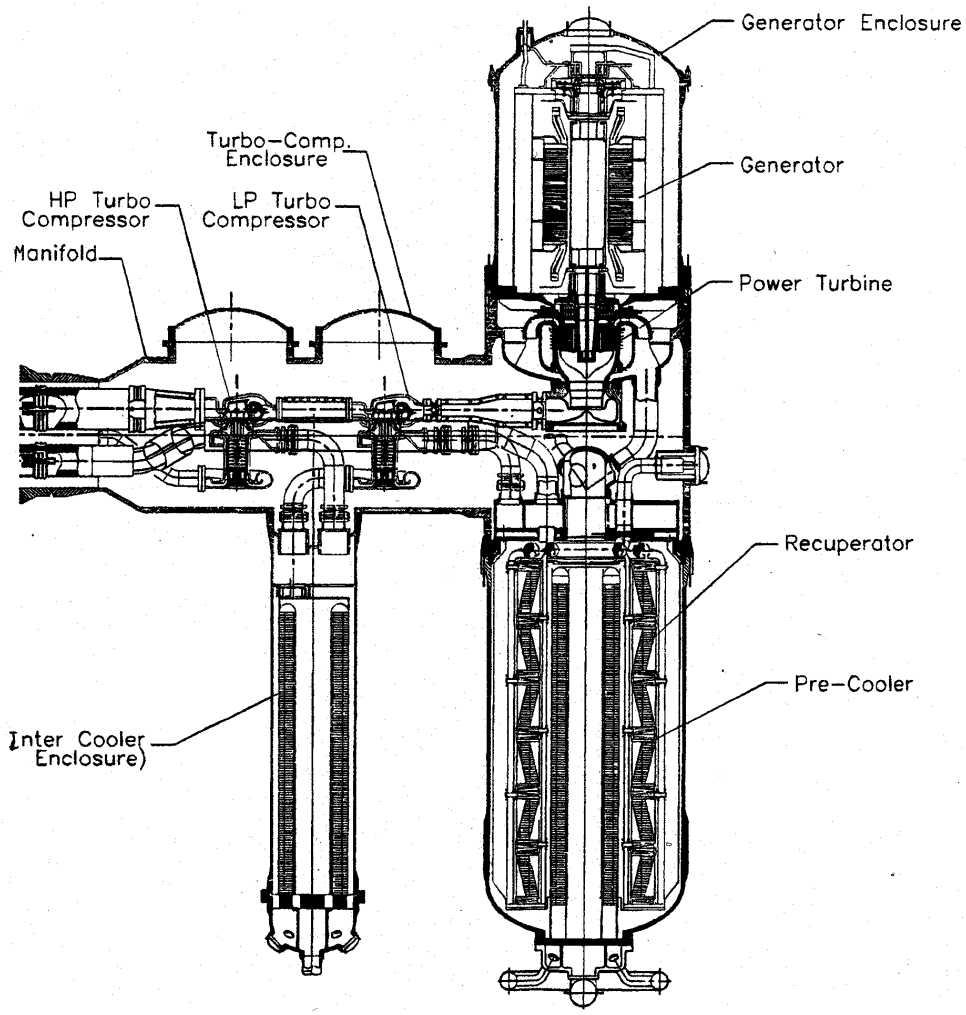

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Figure 7

PBMR – Primary system vessel arrangement

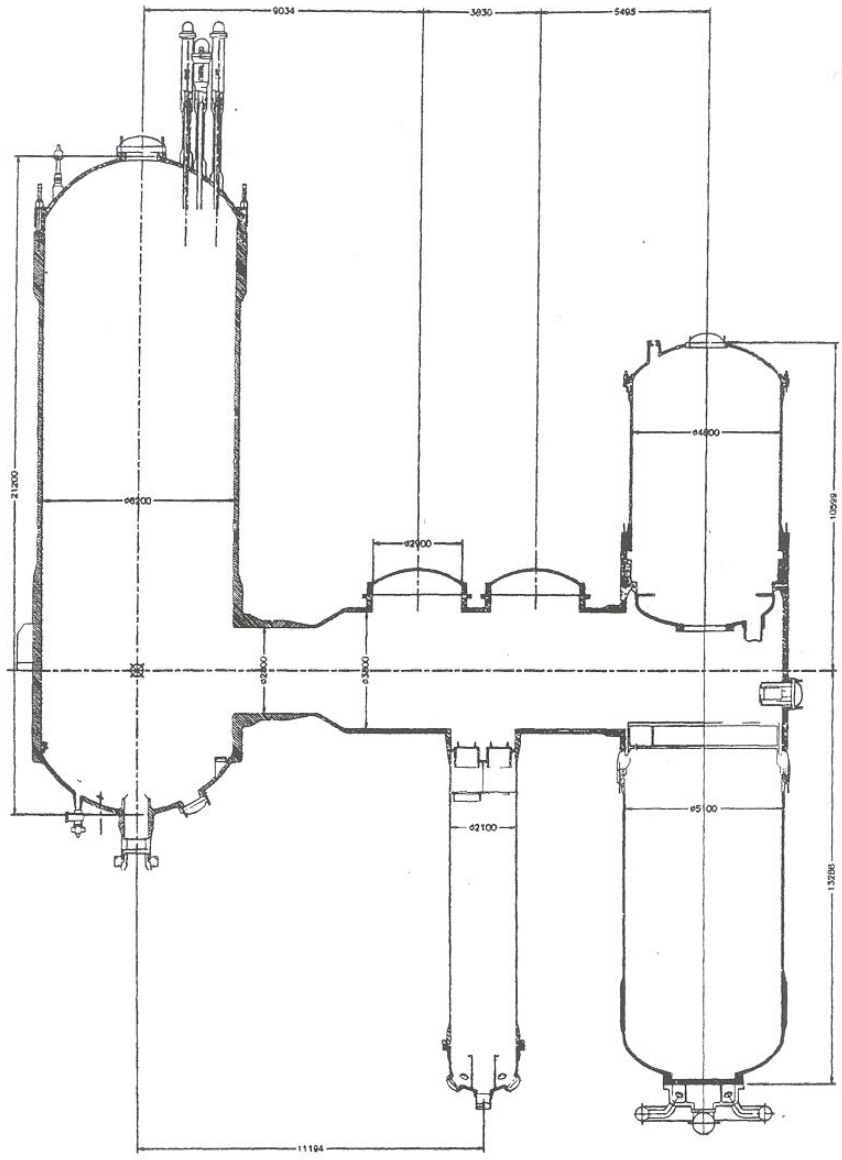

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Figure 8

Parameters during a loss of offsite Power with turbomachine trip

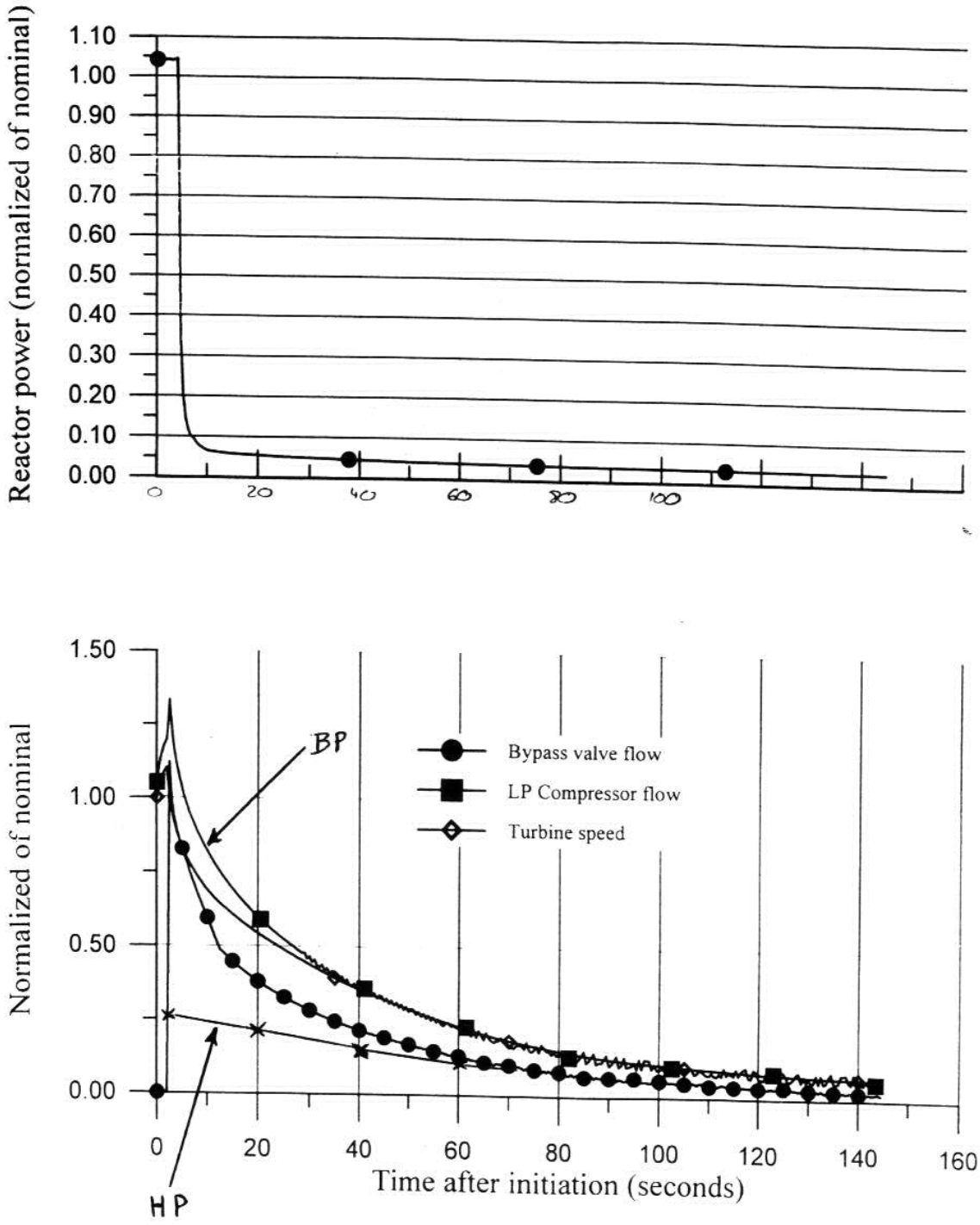

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Figure 9

Parameters during a loss of offsite Power with turbomachine trip

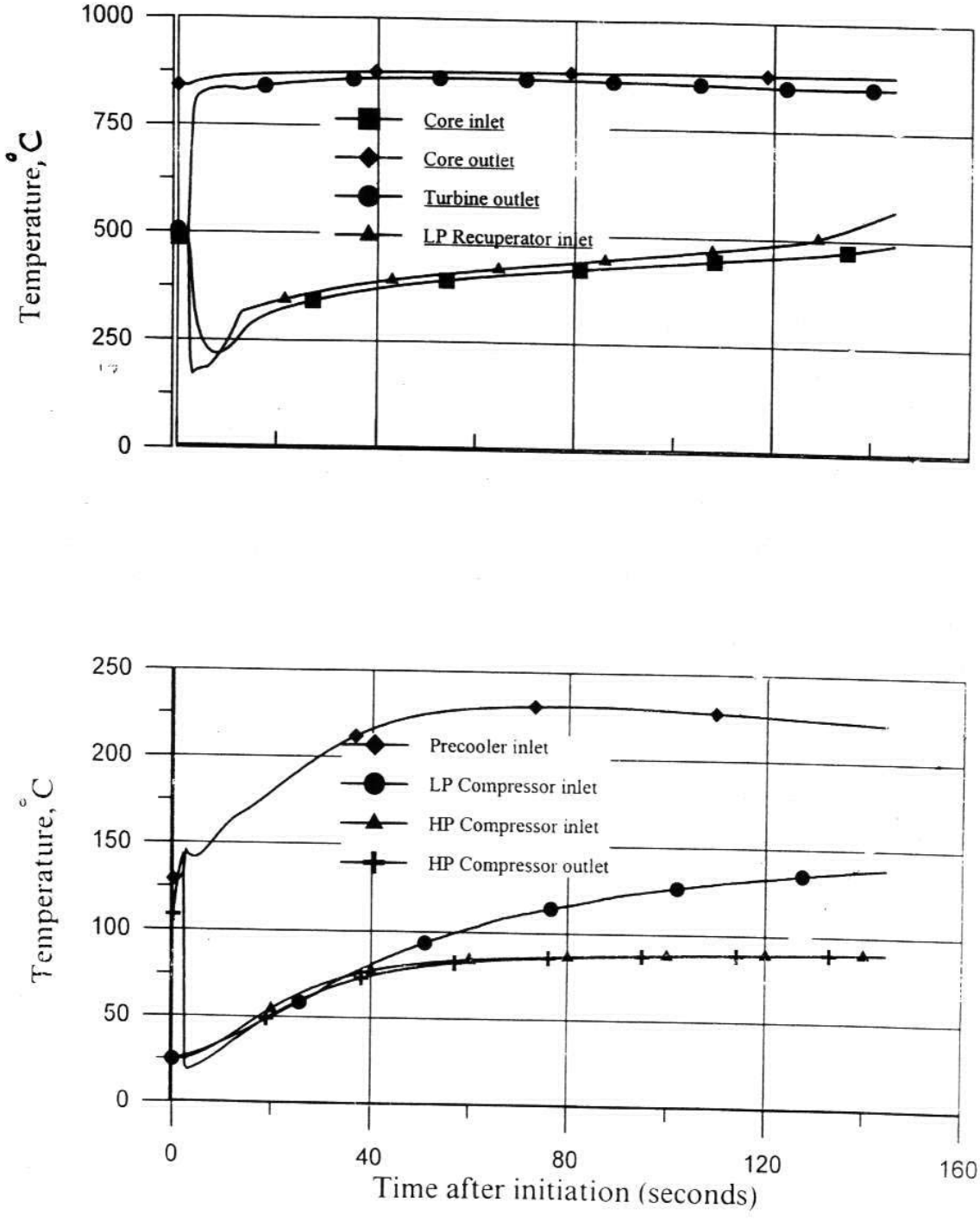

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Figure 10

Parameters during a loss of offsite Power with turbomachine trip

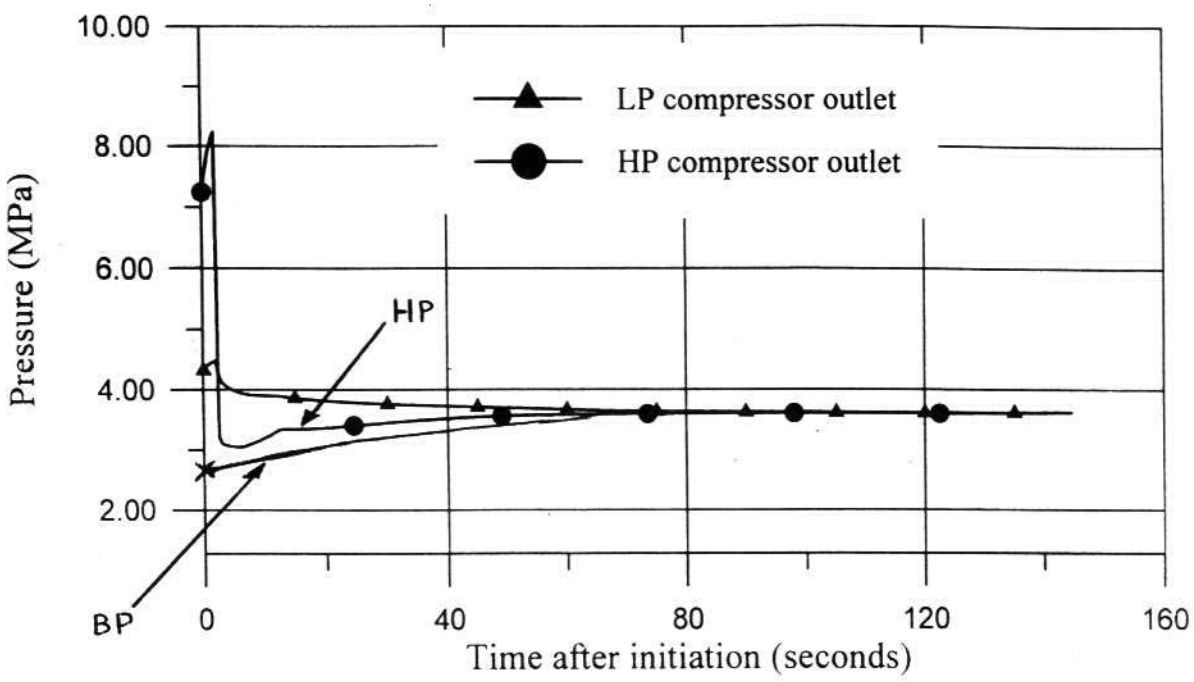

Figure 2.6-3 Parameter during a loss of offsite Power with turbomachine trip.

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