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
Consultations of manufacturers

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FRANCE

Dissemination level : RE
Document N°: HTR-E-03/06-D-2-2-2-1
Status : Preliminary
Deliverable n°14
Internal Identification number :
NFPVEI DC 03 0402 UME/A

FRAMATOME ANP

NOVATOME

NUMERO D'OTP OU EOTP	NOMBRE DE PAGES : 23 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**
CONSULTATIONS OF MANUFACTURERS

TITRE ABREGE : **HTR-E - RECUPERATOR**
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IND	DATE	ETAT	REDACTEUR NOM-VISA	VERIFICATEUR NOM-VISA	APPROBATEUR NOM-VISA	MODIFICATIONS – OBSERVATIONS – ACCORDS REFERENCES ET DATES
A	24/06/2003	PRE	C. MAUGET	E. BREUIL	J.D. POUZADOUX	First issue

IMMATRICULATION CLIENT : **HTR-E 03/06 D-2-2-2-1**

IMMATRICULATION INTERNE :	PVEI	DC	03	0402	UME /	
	UNITE	TYPE	ANNEE	CHRONO	TRIGRAMMES	

Modifications

Revision	Date	Modifications
A	24/06/2003	First issue

Summary

This document analyses and evaluates each technology versus objective criterions in order to perform consultations of the main manufacturers for the recuperator which is an helium/helium heat exchanger operating in HTR direct cycle conditions.

In Europe, HEATRIC and NORDON have been identified as more promising.

Contents

List of notations

CEA	:	Commissariat à l'Energie Atomique
GT-MHR	:	Gas turbine Modular Helium Reactor
HTR-E	:	Acronym for the European project on high temperature reactor components and systems
HTGR-GT	:	High Temperature Gas-cooled Reactor – Gas Turbine
IRES	:	Ingersoll Rand Energy Systems
MHI	:	Mitsubishi Heavy Industries Ltd
PCHE	:	Printed Circuit Heat Exchanger
PFHE	:	Plate Fin Heat Exchanger
PCS	:	Power Conversion System

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(1) HTR-E-02/08-D-2-1-0, indice B
Specifications of typical operating conditions for HTR
Deliverable n° 12

(2) HTR-E-02/03-D-2-1-0, Preliminary
HTR-E – Recuperator technical survey
Deliverable n° 13

(3) IAEA – TECDOC – 1210
Safety related design and economic aspects of HTGRs.
Proceedings of a Technical Committee meeting held in Beijing, China, 24 November 1998
Present activity of the study of HTGR-GT system

1. Introduction

The objective of this document is from the list of potential manufacturers for the recuperator and its HTR requirements, to analyse and evaluate each technology versus objective criterions.

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.

2. Recuperator main requirements

The typical operating conditions and functional requirements for a modern HTR with a direct cycle (GT-MHR type, PBMR type) to be taken into account are extracted from “HTR-E-Recuperator, specifications of typical operating conditions for HTR” (Ref.1).

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

The recuperator is located inside the PCS vessel at the turbine outlet level. The strong constraint for the compactness of this heat exchanger in order to fit in this vessel, together with the severe operating conditions makes the design a real “challenge”.

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

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 analysed with the class 2 component.

3. Potential recuperator manufacturers

From “HTR-E-Recuperator technical survey” written by CEA (Ref.2), a preliminary list of potential recuperator manufacturers is established.

Different technologies are proposed and each concept is analysed. Technological risk, thermal and hydraulic performances and compactness, are particularly dealt with in this task.

This document mentions an interesting issue, which is to investigate a large range of manufacturers who could modify their “standard” product to respect HTR direct cycle specifications.

4. Analysis and evaluation of each technology

The objective of this paragraph is to present different technologies and manufacturers and to analyse and evaluate each technology versus a list of objective criterions, such as :

- degree of maturity of the technology and technology risk,
- thermal and hydraulic performances,
- compactness,
- flexibility of the design and integration in the PCS vessel,
- reliability of the manufacturer,
- reliability of the product,
- cost.

4.1 Presentation of each technology

Main technologies investigated for recuperator are described as follows :

- Plate Fin Heat Exchanger (PFHE).

  This concept is based on plate and very thin fins assembled by brazing, increasing the heat exchange surface and including some turbulence in the flow favourable for the thermal exchange coefficient.

  Different designs for the fins can be proposed.

  The two fluids are separated by a plate which support the fins and the exchanger is a counter flow type.

  The main identified manufacturers are : INGERSOLL RAND, NORDON and MHI.

- Printed Circuit Heat Exchanger (PCHE).

  This concept is based on plate sheets chemically etched and assembled by diffusion bonding.

  This technology is considered as a primary surface heat exchangers.

  The company HEATRIC – MEGGIT is all over the word, the only manufacturer of PCHE.

4.2 Manufacturers

This chapter is devoted to present mainly recuperator design concept, which would be able to respect HTR direct cycle specifications.

From the list of potential manufacturers, four “products” from HEATRIC, INGERSOLL RAND, NORDON and MHI have been selected and each concept presented here under.

4.2.1 INGERSOLL RAND

The construction of a single unit cell, PFHE concept, is shown in the figure 3.

A heat exchanger is a plurality of individual heat exchanger elements comprising a top plate and a bottom plate having an inlet aperture and an outlet aperture, the rings are a part of plates and are not added after plates stacking.

Two first finned members, one first finned member being attached to an exterior side of the top plate, the other first finned member attached to an exterior side of the bottom plate.

A second finned member located between the inlet and outlet apertures is sandwiched between the top plate and the bottom plate.

In the heat transfer zone, fins are undulated.

The plates are brazed along seams and the rings welded by plasma process.

Nota : *The connection between rings and plates is in operation, an important stress concentration area and could be a weak point of this concept.*

4.2.2 NORDON

The PFHE designs in aluminium proposed by NORDON are based on this main principle as follows : finned material, from corrugated sheets, sandwiched and brazed between two flat plates forming passages which are closed by bars, with openings for the inlet and outlet of fluids (figure 4).

Three families of fins are made using a stamping process which can be very precise for the channel heights (within 10 microns about) allowing a very regular and consistent brazing, to sustain high pressure :

- straight channel fins,
- Straight channels with perforations,
- Serrated channels where the fins are of a limited length and side ways displaced a half channel width there by breaking the laminar flow into turbulent flow and enhancing the heat exchange.

The heat exchangers are manufactured in the following way :

- prior to stacking, fins, separated sheets and bars are degreased, acid etched, detergent washed, rinsed and oven fried. Once stacked, the assembly is then brazed,
- a brazed core is then fitted with headers and nozzles.

4.2.3 MHI

The basis of the MHI technology remains the same than the other ones, like NORDON :

- stack of corrugated sheet (fins) separated by flat sheet between fluids,

- separating plane sheets are covered with a brazing alloy,
- brazing operation is made in a furnace in which the brazing alloy is heated to its point of fusion,
- all parts in contact are bonded by capillary action : the brazing alloy has solidified, the assembly becomes one single block.

4.2.4 HEATRIC

The heat exchanger is constructed from flat plates stacked together and diffusion bonded (figure 5). On the plates, semi-circular channels with diameter 1 mm or less are manufactured by chemical etching, hence, the channels become the flow passages.

A new core module geometry still under development is shown in the figure 6.

4.3 Objective criterions

4.3.1 Degree of maturity of the technology and technological risk

The PFHE technology is well known by INGERSOLL RAND, MHI and NORDON, and the technological risk is reduced.

Nevertheless, NORDON has the ability to manufacture modules, which can fit to the HTR recuperator requirements, but has only a short experience of austenitic stainless steel and no experience in nickel alloys.

A large technological development program is necessary to validate each step of manufacture with these materials.

The first step is the manufacturing by NORDON of a mock-up in austenitic stainless steel (316L low carbon), which could be tested in the CLAIRE loop under HTR direct cycle conditions.

The PCHE technology is well controlled by HEATRIC.

In 2002, HEATRIC manufactured a mock-up in austenitic stainless steel (304L), which has been tested successfully in FRAMATOME ANP technical center. The performances given by experimental test results on this mock-up (figure 5) confirm the expected thermal hydraulic performances (experimental effectiveness of 95 %) of the HEATRIC concept and valid prediction formula for heat transfer performance and pressure loss of core section in straight channels.

This design could be considered as validated.

Concerning the ability of the new core concept HEATRIC (figure 6) to operate satisfactory in operation in HTR direct cycle conditions and to confirm its merits like, fabrication simplified, maldistribution reduced, performances increased, …, it is necessary to manufacture a new mock-up and to perform validation tests in high temperature.

4.3.2 Thermal and hydraulic performances and compactness

The thermal and hydraulic performances and compactness are developed in the document (Ref.2), the main characteristics are presented in table 2.

4.3.3 Flexibility of the design and integration in the PCS vessel

The PCS arrangement is in the figure 2.

The recuperator modules are located inside the PCS vessel at the turbine outlet level.

The envelope for the recuperator modules is a “limited” annular space, which is occluded by the system inlet duct.

4.3.3.1 Flexibility of the design

A modular design is provided for modules repair or replacement. Each concept has to be able to respect this requirement.

- HEATRIC is able to propose a “standard” module in austenitic stainless steel (80 are needed) and a new concept using “integrated” headers (8 blocs are sufficient) more compact.

- Concerning NORDON, we are awaiting for a plate fin heat exchanger design proposal to meet HTR direct cycle needs.

- With JAERI, MHI has carried out several studies and manufactured and tested mock-up in order, to develop a recuperator for the HTGR-GT project very closed to the GT-MHR ones. MHI is able to manufacture with flexibility, module in austenitic stainless steel (304 SS) and nickel alloy (Hastelloy XR).

  Note : *A recuperator heat transfer core sectional model of 200 m x 200 mm x 200 m in austenitic stainless steel (Ref.3) has been manufactured and tested. The fin size is 1.15 mm height and 1.4 mm pitch and thickness 0.15 mm. This mock-up is a cross flow type.*

  A representative mock-up (scaled model test, 100 mm x 100 mm), cross flow type configuration, has also been manufactured in Hastelloy XR by brazing process, and tested. The main goals were both to check the feasibility of this technology and to check thermal and hydraulic performances.

  Additional technological actions are running by MHI to validate this concept in Hastelloy XR.

- INGERSOLL RAND is also able to manufacture module in Inconel 625. The optimum module size has to be defined.

4.3.3.2 Integration in the PCS vessel

The principle of modules arrangement of different concepts into the PCS vessel is presented in the document “HTR-E-02/03-D-2-D-1 : Recuperator of technical survey” (Ref.2).

Recent progress on thermal hydraulics of headers and maldistribution performed by studies and inlet feeding mock-up tests have clearly shown the necessity to modify the cylindrical header geometry in “Z” flow configuration by adopting a none constant section all over the module height to obtain an “homogeneous velocity field”. This arrangement is necessary to avoid the flow maldistribution in the recuperator, but introduce a penalty to respect space requirements.

A another way is to use a “U” flow configuration which allows to keep easier the same static pressure between inlet and outlet header all over the height (gravitational and functional effect are non preponderant). With this configuration, the maldistribution of flowrate could be eliminated.

It is a relevant factor beside space requirements to be checked into the layout proposals performed by the manufacturers.

4.3.4 Reliability of the manufacturer

4.3.4.1 INGERSOLL RAND

INGERSOLL RAND has evolved into a diversified multinational manufacturer of industrial and commercial equipment’s and components.

INGERSOLL RAND has been contacted to validate the “standard” INGERSOLL RAND Energy Systems (IRES) unit-cell recuperator based on its own improved technology (figure 3).

4.3.4.2 NORDON

NORDON Cryogenie was founded in 1986 by NORDON, 97 % owned by Groupe Fives Lille, acquired TRANE's technology and production site in France for the design and manufacture of brazed aluminium plate fin heat exchangers.

NORDON manufactures plate fin heat exchangers for various industries including gas separation and oil industry.

4.3.4.3 MHI

MITSUBISHI HEAVY INDUSTRIES Ltd is a great Japanese multinational company, which is also a manufacturer of a plate fin heat exchangers.

4.3.4.4 HEATRIC

By 1999, HEATRIC has supplied over 400 PCHE’s on over 80 major project worldwide, both in gas processing and petrochemical markets, and consequently has a great experience of this product.

4.3.5 Reliability of the product

The reliability of the product in operation of each manufacturer is presented in the table 3.

The crucial point to be checked in priority is the transition of the exchanger core with attachments headers in thermal transients conditions for each design concept.

4.3.6 Cost

The weight balance tendency attached at each concept is brought in the table 3.

The PCHE and PFHE costs have to be evaluated by each manufacturer.

5. Conclusion

An analysis and a synthesis of each technology versus objective criterions, suitable to the HTR direct cycle application could be summarised as follows.

The new core concept of PCHE proposed by HEATRIC has a thermal hydraulic design with perfect counter flow and “U” flow configuration from secondary side, which is more favourable to meet required efficiency (95 %).

HEATRIC has already manufactured many PCHE in austenitic stainless steel by diffusion bonding and some in nickel alloys.

HEATRIC concept is able to withstand pressure difference in operation, PFHE concepts appears limited to accommodate this difference between low and high pressure sides.

This concept is more robust compared with PFHE, like INGERSOLL RAND and MHI, but it is also slightly heavier and probably more expensive.

The leaktighness level required between both sides is a weak point of INGERSOLL RAND concept.

NORDON has only a great experience for welding and brazing process of aluminium and could be a candidate manufacturer for austenitic stainless steel and nickel alloy exchanger by leading an adapted development program and validation tests.

The weak point of all concepts is the thermomechanical behaviour in thermal transients of the exchange core with attachments headers.

Table 1

Degree of maturity of the technology and technical risk

	HEATRIC	INGERSOLL RAND	NORDON	MHI	Comments
Manufacturing					
♦ experience	Austenitic stainless steel (mock-up in 304 L) Nickel alloys	Inconel 625 Austenitic stainless steel	Aluminium Austenitic stainless steel (1)	Austenitic stainless steel (304 SS) Nickel alloys (Hastelloy XR)	(1) Short experience, only a small product manufactured
♦ main manufacture sequence	Bonding process	Brazing and welding by plasma (rings)	Brazing	Brazing	
♦ leaktightness required (1.33 10^{-7} Pa.m^3/s)	Acceptable	To be improved (2)	Acceptable	Acceptable	(2) Not acceptable for a “standard” product, leaktightness could be improved by a double laser weld of the plate lips on the perimeter (to be checked)

Table 2

Thermal and hydraulic performances and compactness

			HEATRIC (new concept)	INGERSOLL RAND	NORDON	MHI	Comments
Thermal capacity		MWth	625	625	625	625	
Thermal effectiveness			0.95	0.95	0.95	0.95	
Pressure losses							
♦ low pressure side		MPa	0.03	0.03	0.03	0.03	
♦ high pressure side		MPa	0.07	0.07	0.07	0.07	(1) To be defined by the manufacturers.
Type			PCHE	PFHE	PFHE	PFHE	
Thermal and hydraulic design			Counter flow area	Cross (Note 1) and counter flow area	Cross (Note 1) and counter flow area	Counter flow area	(2) Another project application (600 MWth), order of magnitude, for example.
Number of modules			(1)	(1)	(1)	(1)	(3) Manufacturer capability in aluminium, in austenitic stainless steel, to be defined.
Heat duty		MWth/module	(1)	(1)	(1)	(1)	
Fluid			He/He	He/He	He/He	He/He	
Fin pitch		mm	-	0.5	1.6	1.1	**Note 1 :** Could affect the required thermal efficiency (95 %).
Fin thickness		mm	-	0.08	0.2 at 0.5	0.2	
Thickness of plate		mm	1	0.46	0.8 at 2.5	0.5	
Fin height		mm	-	-	3.53 at 9.63	1.3	**Note 2 :** Pack height limitation (200 mm) due to furnace capability.
Core size capability :	Width	mm	788 (2)	432 (2)	1 300 (3)	880 (2)	
	Length	mm	1 120 (2)	711 (2)	7 820 (3)	970 (2)	
	Height	mm	3 342 (2)	2 583 (2)	2 000 (3)	5 190 (Note 2)	
Core capacity		$MWth/m^3$	25 (2)	65 (2)	-	24 (2)	
Weight		Tons	more than 100 (2)	approx. 50 (2)	-	less than 100 (2)	

Table 3

Reliability of the product in operation

	HEATRIC (new concept)	INGERSOLL RAND	NORDON	MHI	Comments
Behaviour in operation :					
♦ normal conditions					
ΔP : 45 bars	Acceptable	To be improved (1)	Acceptable	To be checked	(1) To validate (by burst testing) features needed to achieve durability at specified conditions.
ΔT : 20 °C	Acceptable	Acceptable	Acceptable	"	
♦ accidental conditions (over pressure)	Capability (very high pressure)	To be improved (1)	Capability up to 140 bar	To be checked	
♦ thermal transients conditions	To be improved (2)	To be improved (2)	To be improved (2)	To be improved (2)	(2) Transition of the core with attachments headers has to be checked for each design concept.

Figure 1

Direct GT-MHR cycle overview

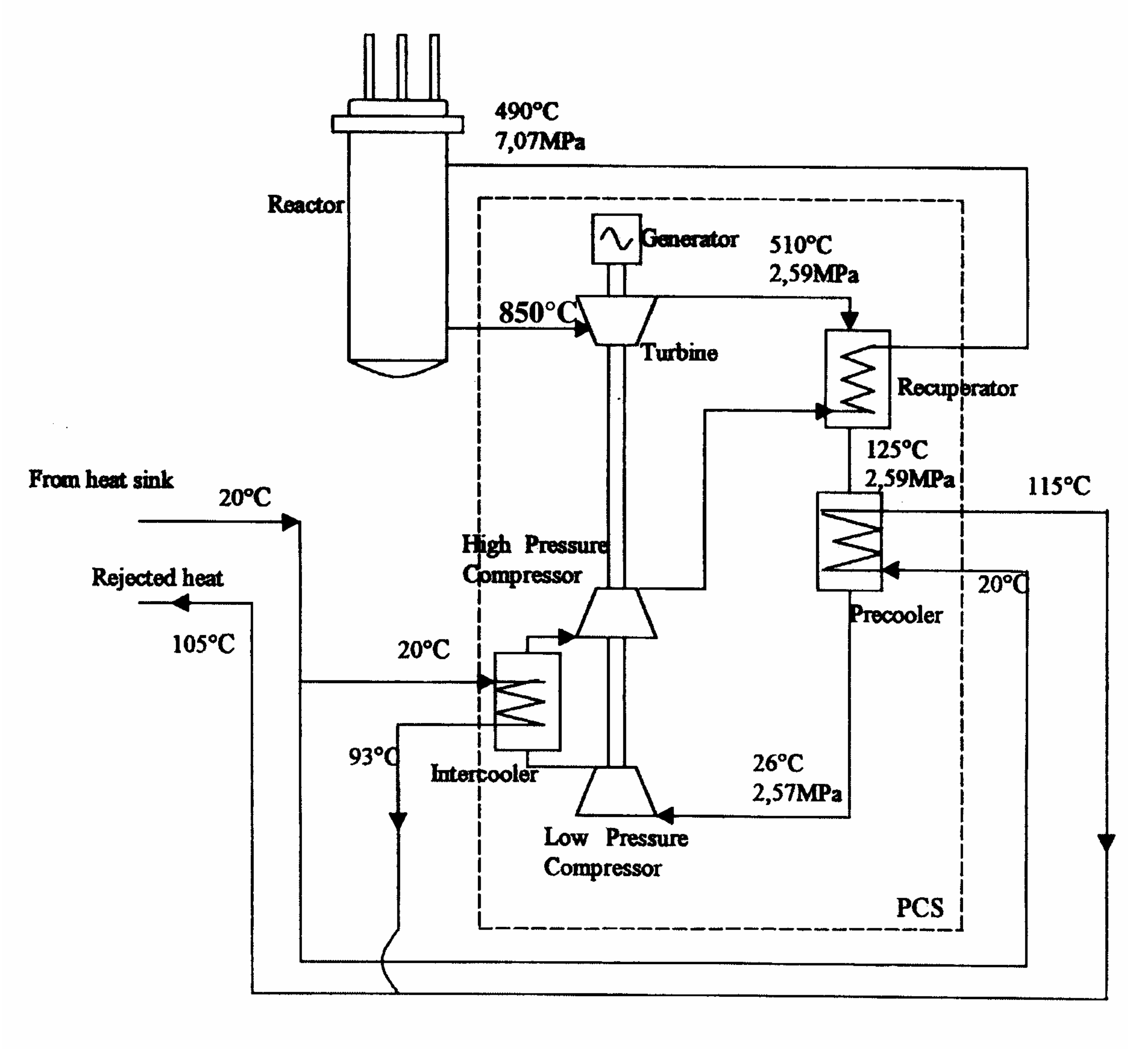


Figure 2

GT-MHR reactor module arrangement

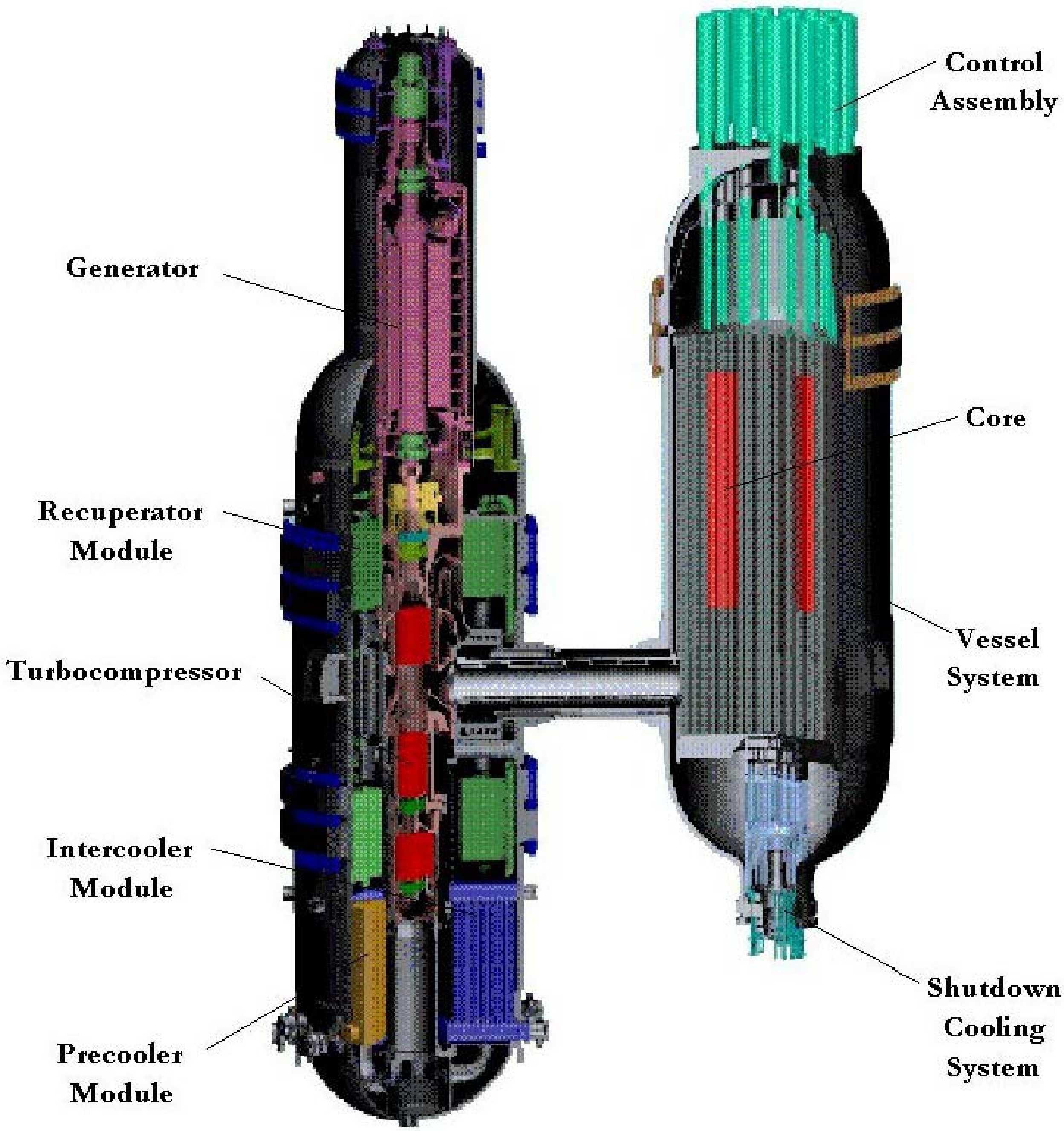


Figure 3

INGERSOLL RAND design concept

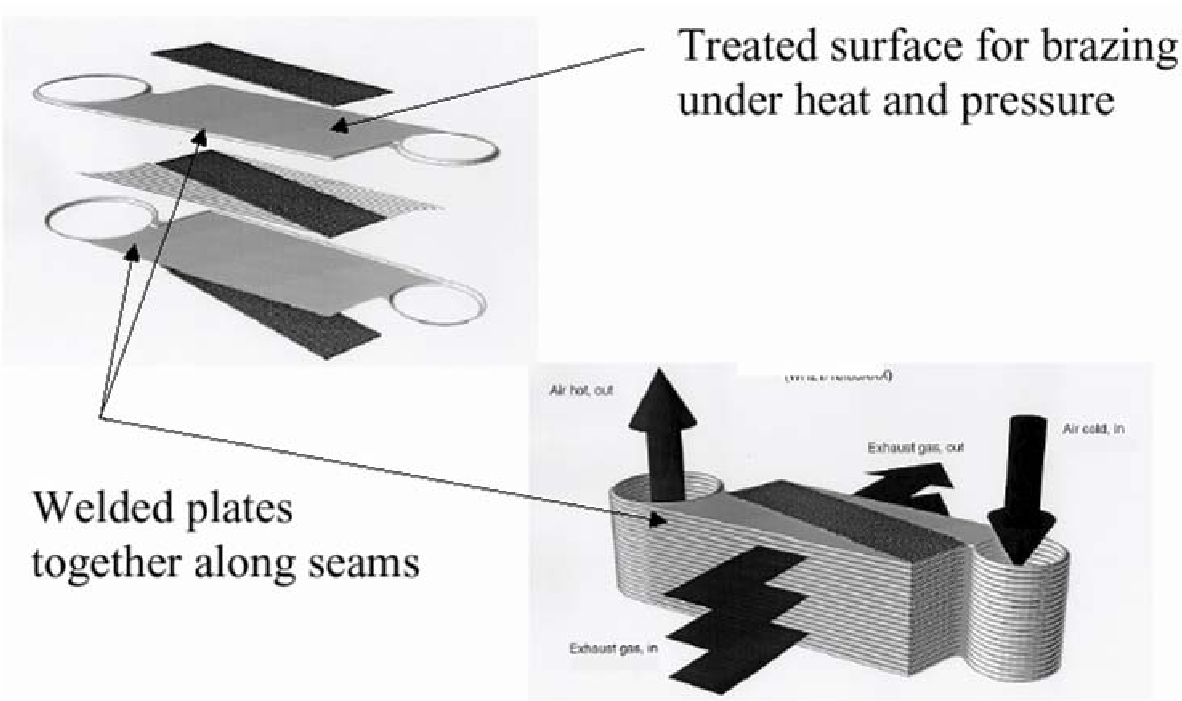
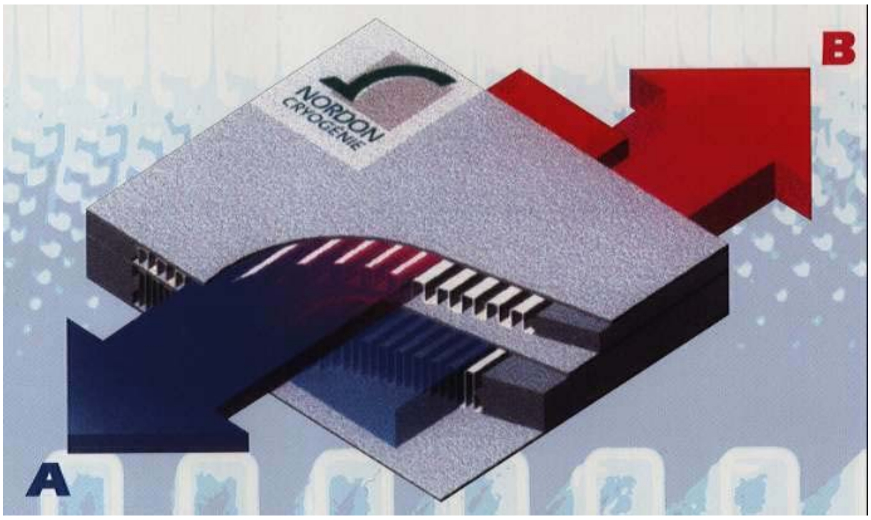
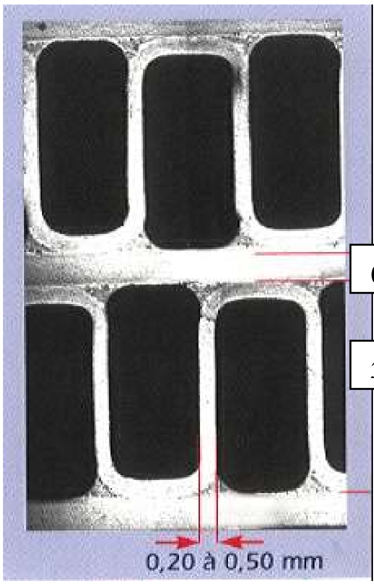


Figure 4

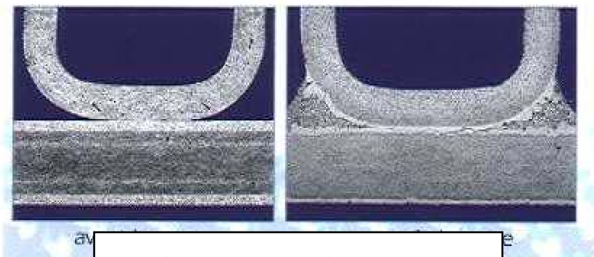
NORDON design concept



MODULE



PLATES/FINS Assembly

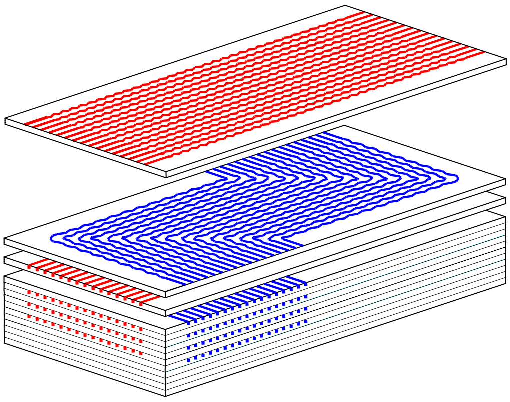


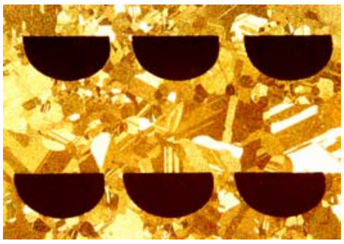
Before and after BRAZING

SERRATED FINS

Figure 5

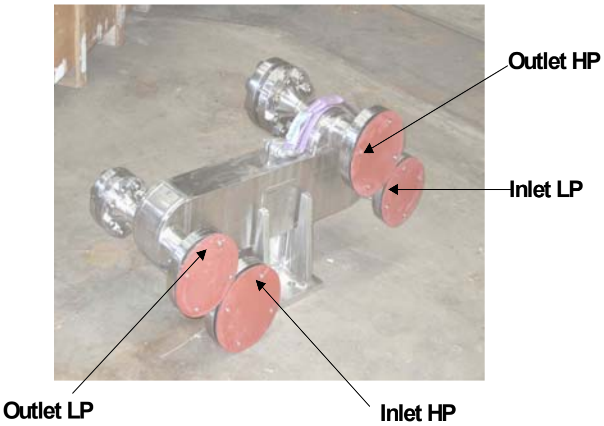
HEATRIC design concept





Section through diffusion bonded core

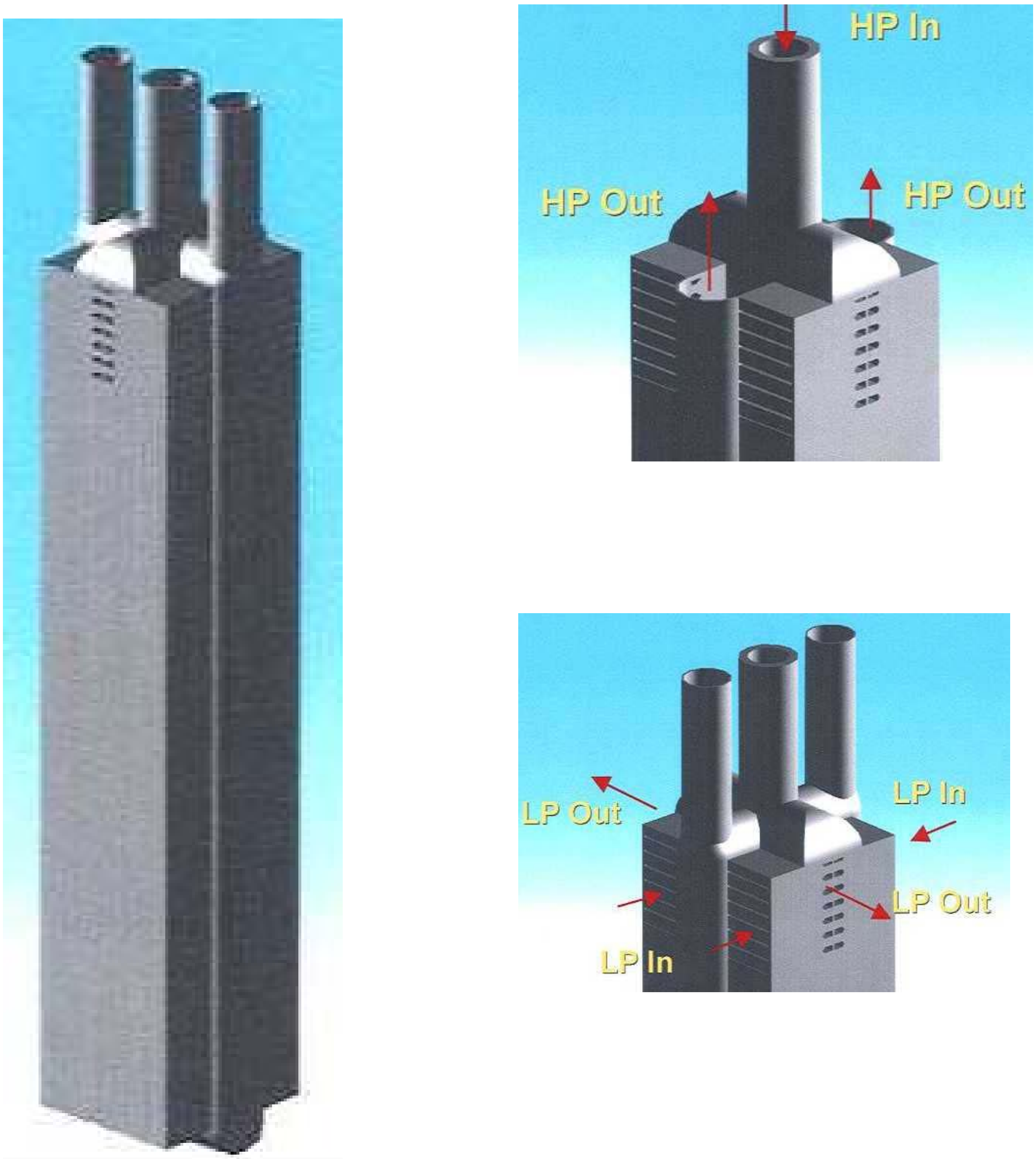
Plate stacking prior to diffusion bonding



HEATRIC mock-up

Figure 6

HEATRIC new module



Unit Module