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(Version B)

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«HTR-E - RECUPERATOR TECHNICAL SURVEY»

(VERSION B)

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Résumé

Résumé : Ce document présente le déliverable 13 du WP 'Recuperator' du projet HTR-E. Il présente des fabricants de récupérateurs de chaleur ainsi que leur technologie.

Abstract :
This documents presents the deliverable 13 of the WP Recuperator of the HTR-E project. It presents recuperator manufacturers and their technology.

Revision	Date	Modifications
A	November 2002	First issue
B	July 2003	Final issue

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List of notations

GT-MHR	: Gas Turbine Modular Helium Reactor	
HTR	: High Temperature Reactor	
HTR-E	: Acronym for the European project on high temperature reactor components and systems	
HTGR-GT	: High Temperature Gas Reactor Gas Turbine	
c_p	: calorific capacity	J/kg K
d_h	: hydraulic diameter	m
L	: length	m
u	: velocity	m/s
ΔP	: pressure difference	Pa
x	: offset length of the fins	
H	: height of the fins	
w	: pitch of the fins	

Greek letters

μ	: dynamic viscosity	Pa.s
ρ	: density	kg/m^3
λ	: thermal conductivity	W/m/K

Dimensionless numbers

Nu	: Nusselt number	$Nu = \frac{\alpha\, d_h}{\lambda}$
Pr	: Prandtl number	$Pr = \frac{\mu\, Cp}{\lambda}$
f	: Friction coefficient	$f = \frac{\Delta P}{4\,\rho \frac{u^2}{2} \frac{L}{d_h}}$
Re	: Reynolds number	$Re = \frac{\rho\, u\, d_h}{\mu}$

List of tables

List of articles concerning technology studied abroad

Ref 2, 2000, Jaeri, Plate fin heat exchangers

Ref 3, 2001, Jaeri, Ultra Fine Offset fin heat exchangers

Ref 4, 2001, Jaeri, Ultra Fine Offset fin heat exchangers

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1 INTRODUCTION

1.1 Objective

The objective of this document named " Recuperator " is to establish a list of potential recuperator manufacturers. Different technologies are proposed and each concept is analysed (as far as it was possible) . The stress is put on the basic concept (i.e. type of the technology), typical applications of the concept, reliability of the manufacturers. Concerning the technology, criteria as such technological risk, thermal and hydraulic performances, compactness, are dealt. To carry out this task, different sources of information have been used : articles, phone or mail contacts and meetings. In the same way, it is a list of potential manufacturers but some of them can certainly not respond to GTMHR specifications because they are more specialised in an other range of working conditions (for example for micro turbines applications). Nevertheless, it may be interesting to investigate a large range of manufacturers who could modify their product to respect HTR specifications.
This document may be split into 2 parts : the first one is more dedicated to compact heat exchangers and it is written by CEA, the second one is the FZJ's contribution and it concerns tubular heat exchangers. The FZJ's study is issued from the former German nuclear project and the Japanese HTTR..

1.2 Recuperator working conditions

The table 1.1 reminds the typical thermal and hydraulic steady state working conditions. The values are extracted from "HTR-E-Recuperator, specifications of typical operating conditions for HTR" written by Framatome ANP [1].

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 (instead of 0.03 Mpa in Framatome's document)
ΔP between the high and low pressure sides	4.5 MPa

Table 1.1 : GT-MHR typical steady state working conditions

The figure 1.2 reminds the principle of the high temperature gas cooled reactor. It is extracted from the same source than the previous one.

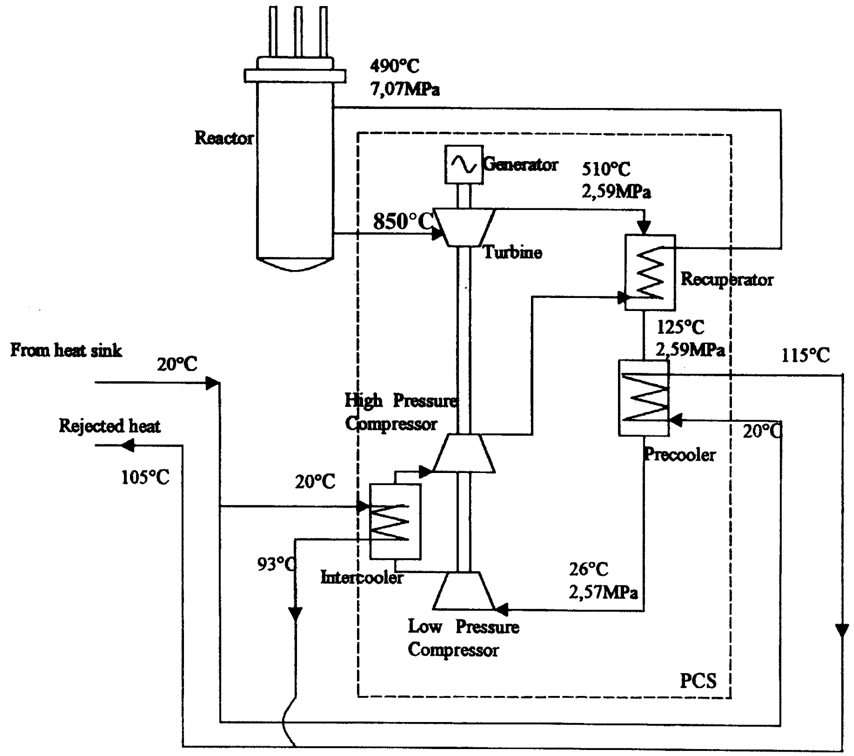


Figure 1.2 : HTR principle

2 JAERI

For the HTGR-GT, Jaeri has carried out several studies to develop a recuperator. The HTGR-GT characteristics are very closed to the GT-MHR ones.

Parameter	Unit	Hot side –Low pressure	Cold side – High pressure
Heat duty	MW	497	
Flow rate	kg/s	248	
Inlet Temperature	°C	520	114
Outlet Temperature	°C	134	500
Inlet pressure	MPa	2.61	7.2
Pressure Drop	MPa	0.0261	0.072

Table 2.1 : HTGR-GT design requirement

2.1 Basic concept

In literature, several articles are available which describe what they've done :

JAERI [2000] : " Feasibility Design study of Compact Heat Exchanger for HTGR Gas Turbine Systems " [2]
S. ISHIYAMA, Y. MUTO, M. KASABA, T. KANETA

This section is only a paper study, which allows by a parametric way to estimate the best geometric design to fit to the HTGR-GT specifications. A plate fin heat exchanger was studied and the most suitable geometry for the fins is the following one :

Parameter	Unit	Hot side –Low pressure	Cold side – High pressure
Thickness	mm	0.15	0.1
Height	mm	1.5	1.0
Pitch	mm	1.5	1.0

Table 2.2 : Ultra fine offset fin geometry

By using this geometry for the recuperator, they proposed the following modules arrangement:

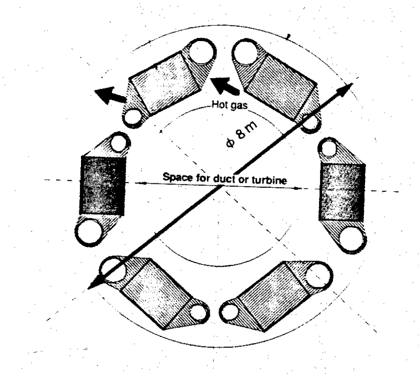


Figure 2.3 : Modules arrangement

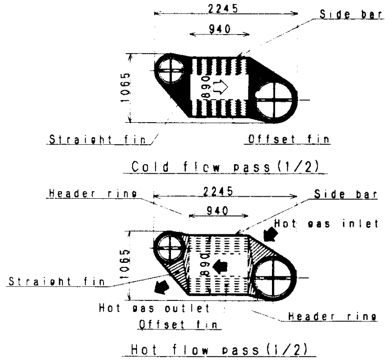


Figure 2.4 : Detail of the plates

	Hot side –Low pressure	Cold side – High pressure
Thermal requirement	OK , efficiency = 0.95	
Pressure drop (%)	1.42 (instead of 1)	0.38 (instead of 1)
Reference	Jaeri	
Status	paper design[1]	
Nb of units	6	
Position	horizontal	
Max dim. (m)	4.9 (Height)	
Heat transfer length (m)	0.94	
Volume[3] (m^3)	70	
Weight[4] (tons)		
Dh HP (mm)	0.9	
Dh LP (mm)	1.35	
Effectiveness	95 %	
Pressure drop	< 1 % (HP), > 1 % (BP)	
Heat duty (MW)	497	
Capacity (MW/m^3)	7.1 20 (considering only heat transfer surface)	
Reliability[5]	to be proved	
Manufacturing	to be proved	

Table 2.5 : Resulting design specifications and comments

[1] recuperators at lower pressure existing
[2] recuperators at lower pressure or lower temperature existing
[3] volume including distribution zones and headers but excluding piping
[4] mass of the recuperator without pipings
[5] for steady state conditions

JAERI [2001 a] : " Development of the Compact Heat Exchanger for the HTGR, (1) Fabrication of the Ultra Fine Offset Fin " [3]
S. ISHIYAMA, Y. MUTO, M.TANIHIRA, K. OGATA, Y.KAMITO, T.IGARI

A mock up has been designed and tested. The mock up is manufactured by Mitsubishi. The main goals are to check the feasibility of this technology and the thermal and hydraulic performances. This mock up is a cross flow type.
The geometrical characteristics of the plate and fin heat exchanger are the following ones :

Parameter	Unit	
Core dimensions	mm	200*200*200
fin dimension		
Thickness	mm	0.15
Height	mm	1.5
Pitch	mm	1.42

Table 2.6 : Mock up specifications

No thermal results

JAERI [2001 b] : " Development of the Compact Heat Exchanger for the HTGR, (2) Heat Transfer and Fluid Characteristics Test " [4]
S. ISHIYAMA, Y. MUTO, K. OGATA, Y.KAMITO

A second mock up has been manufactured and thermal and hydraulics tests were carried out with air flow.
Experimental results are compared to Wieting Formula [5].

Parameter	Unit	specification
core dimensions	mm	100*100*100
fin dimension		
Thickness	mm	0.2
Height (H)	mm	1.2
Pitch (w)	mm	1.6
Offset length (x)	mm	5.0
Hydraulic diameter	mm	1.17
plate dimension		
Thickness	mm	0.5
Stage number		29 (BP) / 28 (HP)

Table 2.7 : Geometrical characteristics of the plate and fin heat exchanger

The flow pattern is a cross flow type and the experimental tests led to the following results :

$$Nu = 0.0976\, Re^{0.693}\, Pr^{1/3} \left[x/dh\right]^{-0.162} \left[w/H\right]^{-0.184}$$

$$f = 0.924\, Re^{-0.402} \left[x/dh\right]^{-0.384} \left[w/H\right]^{-0.092} Re^{-0.402}$$

Nu : Nusselt number
Pr : Prandtl number
Re : Reynolds number
dh : hydraulic diameter

f : friction coefficient

These previous correlations gave results which are 10 to 13% and 0 to 27% lower than Wieting formula for the heat transfer coefficient and for the pressure drop.

If we use these correlations to HTR application, i.e. :

Re around 1000
ρ : 2.1 kg/m3
μ : 3.1 e-5 Pa.s

We get : $Nu = 7.56$, $f = 0.032$ (then the pressure drop is 0.0145 MPa/m).

2.2 Thermal and hydraulic design

Regarding the 2nd and the 3rd articles, it seems that Jaeri and Mitsubishi can provide ultra fine offset heat exchangers which can fit to HTGR-GT specifications. The experimental tests confirmed the expected results (10 to 13% and 0 to 27% lower than Wieting formula [5] for the heat transfer coefficient and for the pressure drop).
The main question is about flow distribution for the full scale recuperator as well as between the different plates than between the channels in the same plate. The recuperator is 5 m high so the shape of the header must be carefully designed . Moreover the detail of the channels on figure 2.4 shows very restricted fluid flow area near the headers on both sides, this will probably cause high pressure drop and even flow mal distribution in certain areas (even dead zones are visible on hot gas side just behind the cold fluid headers).

2.3 Manufacturer reliability

The previous manufacturer was the company Ishikawajima-Harima whose main activity was expertise in steam boilers and nuclear engineering. The 2 manufactured mocks up were provided by Mitsubishi Heavy Industry.

Internet advertisement :

" Mitsubishi Heavy Industries, Ltd. (MHI) is one of the world's leading manufacturers of heavy machinery.

With a vast amount of practical experience and a level of technological capability, Mitsubishi has been engaging in nuclear business for more than three decades. since commencing research into and development of nuclear power generation in the 1950s, Mitsubishi has taken part in the design, manufacture and construction of a large number of very successful PWR power plants.

Mitsubishi is the only organization to produce such a large range of supplies for nuclear power generation, including Architectural Engineering, Nuclear Steam Supply System, Turbine Generator Systems, Electrical Systems, I & C Systems, and Nuclear Fuel and also the Balance of Plant.

These achievements encourage us to improve still further reliability and economy. Mitsubishi is enthusiastically developing a new generation of nuclear power plants such as the APWR, the fast breeder reactor, the high temperature gas cooled reactor and the nuclear fusion reactor. As a comprehensive nuclear plant manufacturer, we are also engaged in the supply of fuel cycle-related equipment and the implementation of R & D programs.”

2.4 Status of development

- Paper design
- Mocks up tested in HTGR-GT working conditions

3 ALLIED SIGNAL

Using the same concept than the previous one i.e. plate and fins heat exchangers, Allied Signal proposed a solution to General Atomics with 6 modules in parallel. The units are located in an annulus space which the inner diameter is 3.56 m and the outer diameter is 7.47 m. The characteristics given in this chapter are extracted from General Atomics internal report [6].

3.1 Basic concept

Figures 3.1 et 3.2 show the modules arrangement in the vessel.

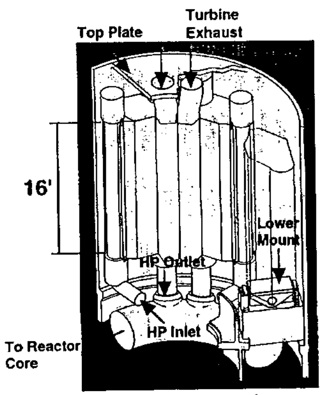


Figure 3.1 : 2 modules out of 6

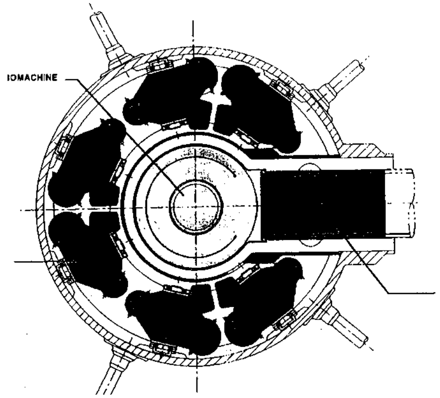


Figure 3.2 : Recuperator arrangement within vessel

This configuration leads to short heat exchange length but very high apparatus. The final stack of the recuperator is around 4.91 m which implies that the recuperator modules will be formed from a number of separately brazed units which will be welded together due to braze furnace size limitations. With such important frontal area, we may have around 1000 channels in parallel to feed in the same way.

Figures 3.3 and 3.4 show details of the plates.

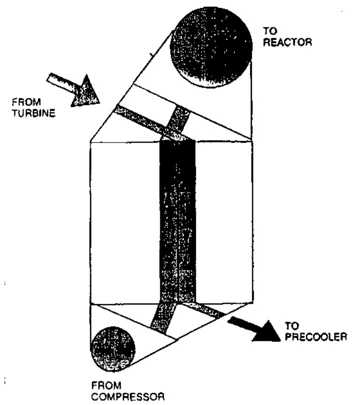


Figure 3.3 : Fluid distribution

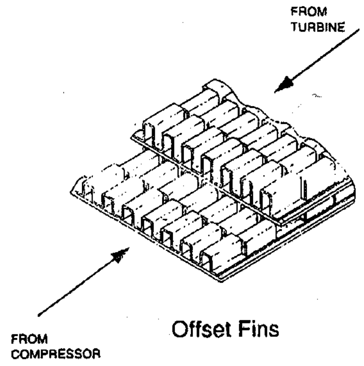


Figure 3.4 : Offset fins

There are 3 distinct areas : triangular entry and exit sections in which fluids circulate in cross way and the central zone where the main heat transfer occurs with counter current fluids. The distribution and collecting areas are made with plain fins whereas the central zone is made with offset fins which dimensions are given the table 3.5.

	Hot side –Low pressure	Cold side – High pressure
Thermal requirement	efficiency ≥ 0.95	
Pressure drop (MPa)	0.03	0.07
Reference	A.S.	
Status	paper design[1]	
Nb of units	6	
Position	horizontal	
Max dim. (m)	4.91 (Height)	
Heat transfer length (m)	1.2	
Volume[3] (m^3)	92	
Weight[4] (tons)	120	
Dh HP (mm)	0.95	
Dh LP (mm)	1.14	
Heat duty (MW)	600	
Capacity (MW/m^3)	6.5	
Reliability[5]	to be proved	
Manufacturing	to be proved	

Table 3.5 : Resulting design specifications and comments

[1] recuperators at lower pressure existing
[2] recuperators at lower pressure or lower temperature existing
[3] volume including distribution zones and headers but excluding piping
[4] mass of the recuperator without pipings
[5] for steady state conditions

The volume is an estimation and it should be confirmed by AS if further informations are required.

3.2 Thermal and hydraulic design

This solution is quite similar to Jaeri's one : same number of units, offset fins on both side with larger size on BP, the stack height is the same i.e. 4.9 m. So these solutions lead to important frontal area with fluids flow kept laminar to respect allowed pressure drops on both side. The main trouble is about flow distribution for the full scale recuperator. The recuperator is 5 m high so the shape of the header must be carefully designed .

3.3 Manufacturer reliability

These plate–fin heat exchangers are already used in several programs which have produced recuperators for propulsion and gas-turbine engines. In the existing applications (especially with propulsion engines), the recuperators are exposed to many more start / stop and low-load / high-load cycles than in the GT-MHR application.
But considering the size of the plates, the higher differential pressure and the requested efficiency, additional tests should be carried out.

3.4 Status of development

- Paper design
- Recuperators for gas turbine already operating but with much lower pressure difference (less than 1 Mpa)

4 INGERSOLL- RAND

For many years, Ingersoll-Rand has been a leading manufacturer of industrial equipment. Over the years Ingersoll-Rand has evolved into a diversified, multinational manufacturer of industrial and commercial equipment and components. The company's product lines include air compressors, architectural hardware products, automotive parts and components, construction equipment, golf cars and utility vehicles, tools, and transport temperature control systems. The company focuses on four market sectors: security and safety, infrastructure, industrial solutions and climate control.

Web site extract :
" Concerning co-generation systems, originally IR Energy Systems planned to find and adapt an existing recuperator to work with the PowerWorks engine. Considering all the recuperators currently available, IR Energy Systems purchased and tested each manufacturer's technology and design, but they all failed some significant criteria. In every instance, the PowerWorks specifications called for significant improvements in existing recuperator efficiency, durability, size, or cost. Since there was no practical way to overcome all of these design deficiencies in any single commercially available unit, IR Energy Systems decided to develop its own improved recuperator technology.
The PowerWorks recuperator has been engineered with the design latitude of a conventional plate-fin heat exchanger and the ability to vary the size to meet performance requirements. To

overcome the durability and fatigue problems of conventional plate-fin designs, the unique construction of the PowerWorks recuperator core provides exceptionally long life even under the harshest thermal transients. That same unique construction also gives the PowerWorks recuperator an easily variable stack height that allows the design to be readily adapted to different engines. Structurally, the design behaves more like a primary-surface type recuperator with its associated higher durability but without its inherent deficiencies. The PowerWorks recuperator has greater flexibility to fit a wider range of applications and does not suffer from "creep" problems. "

4.1 Basic concept

Figure 4.1 shows a plate stack. The shape of the HP gas side headers is very particular : they are not welded once the plates are brazed but they are made of rings. These rings are a part of the plates and aren't added after plates stacking. Special attention must certainly be turned to stress concentration in these areas.

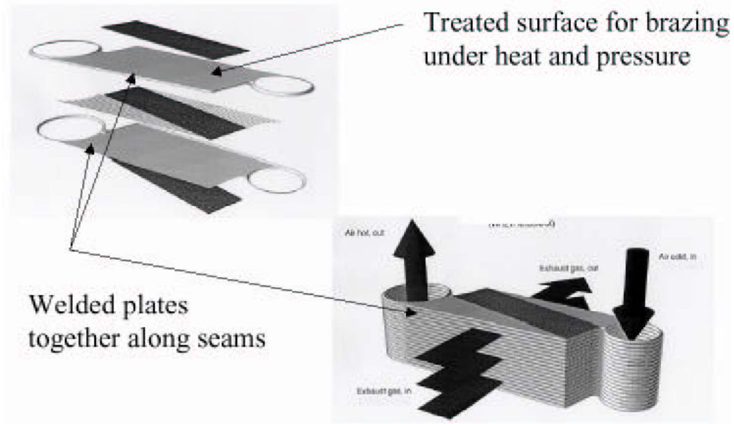


Figure 4.1 : Ingersoll-Rand plate fin exchanger

In distributing areas, fins are rectangular whereas in heat transfer zone, fins are undulated. They have the ability to manufacture very small fins such as 0.05 inch height (i.e. 1.3 mm) and 45 fins / inch (i.e. 1.8 fin / mm).
An other characteristic concerns gas seals : they do not use edge bars as conventional manufacturers but plates are brazed and welded.
Using this technology leads to heat exchangers that more wide than long and the suitable arrangement in the vessel would certainly the same than Jaeri or Allied Signal's one.

4.2 Thermal and hydraulic design

As it is said above, the general aspect of the stacking is the certainly equivalent to others plate fin H.E. manufacturers. Nevertheless, as the plate is more wide than long, we must be very careful with flow distribution not only between the plates but also inside one plate : if gas physics properties are not correctly considered it may lead to gas over feeding in some channels and sub feeding in others which is directly links to recuperator efficiency.

The shape of HP gas headers must be considered carefully as well because such angular areas may be submitted to important stress concentration.
Moreover, the cross flow area, which seem to have an important size on figure 4.1, affects the overall efficiency.

4.3 Manufacturer reliability

This plate fin H.E. has already been used for co-generation systems, but regarding GT-MHR working conditions, further investigations must be carried out.

4.4 Status development

Recuperators for gas turbine are already operating.

5 NORDON

NORDON CRYOGENIE was founded in 1986 by NORDON, 97% owned by Groupe FIVES-LILLES, acquired TRANE's technology and production site in FRANCE for the design and manufacture of brazed aluminium plate fin heat exchangers.
By building on TRANE's core technology, Nordon cryogenie has become a leader in the heat exchange industry. Nordon Cryogenie has already manufactured more than 6000 cores.
Developed half a century ago for the needs of the aircraft industry where compactness, low weight and high efficiency are features of paramount importance, aluminium plate fin heat exchangers have now established a reputation in the gas processing industry.

5.1 Basic concept

The figure 5.1 shows general view of the plate and fin heat exchangers with different constituting elements.

1 - Assembly
2 - Manifold
3 - Core
4 - Header
5 - Nozzle
6 - Width
7 - Stacking height
8 - Length
9 - Passage outlet
10 - Cap sheet
11 - Parting sheet
12 - Heat transfer fin
13 - Distribution fin
14 - Side bar
15 – End bar

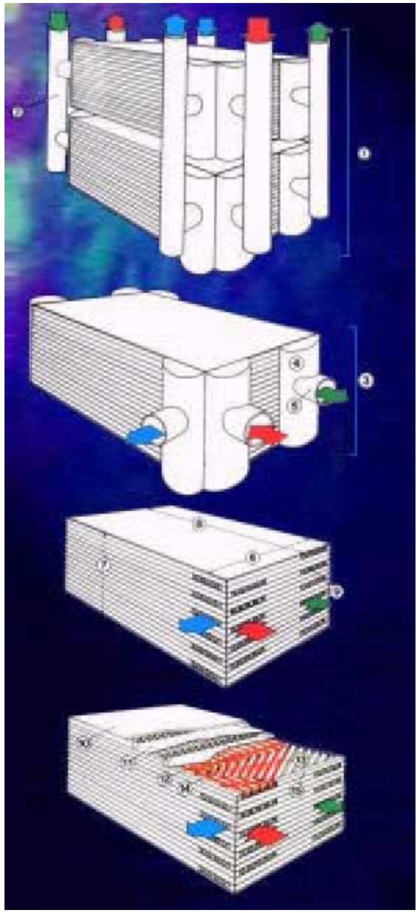


Figure 5.1 : General description of the heat exchanger

A brazed aluminium plate fin heat exchanger consists of fins (corrugated aluminium sheets) separated by parting sheets (flat plates), forming passages which are closed by bars, with openings for the inlet and outlet of fluids.

The heat exchangers are manufactured in the following way :

- The production of fins consists of passing a band of aluminium through a special press.

- Prior to stacking, fins, separating sheets and bars are degreased, acid etched, detergent washed, rinsed and oven dried. Once stacked, the assembly is then brazed.
- A brazed core is then fitted with headers and nozzles.

The table 5.2 shows typical geometrical size of heat exchangers that Nordon can manufacture.

Width	max. 1300 mm
Length	max. 7820 mm
Stacking Height	max. 2060 mm
Fin type	Straight, straight perforated, serrated
Fin height	3.53 mm, 5.10 mm, 6.35 mm 7.13 mm, 8.89 mm, 9.63 mm, 12.7 mm
Fins	More than 60 different types

Table 5.2 : Possible geometry of heat exchangers

As Nordon Cryogénie behaves the largest vacuum brazing furnaces in the world, they can provide very big modules.

5.2 Thermal and hydraulic design

Even if Nordon is more used to manufacture aluminium heat exchangers, they have already produced stainless brazed plate fin apparatus as shown on figure 5.3.

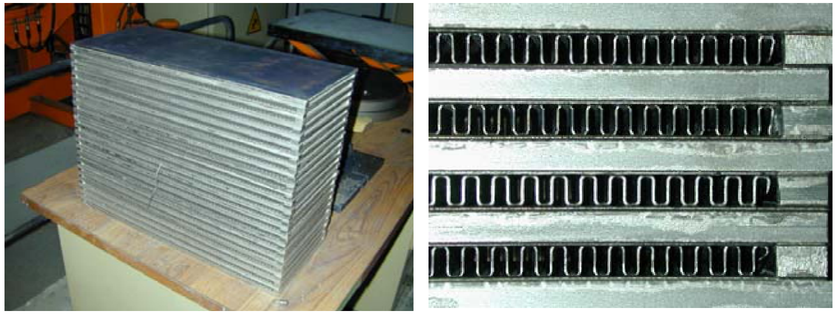


Figure 5.3 : Stainless heat exchanger (maximum temperature up to 700 °C)

So they manufactured stainless steel fins with the following size :

Fin type	Straight, serrated
Fin height	2 mm, 4 mm, 5.1 mm
Fin thickness	0.1-0.15 mm
Channel width	around 1 mm
Serrated fin length	around 3 mm

These stainless steel fins have been used to manufacture prototype but also industrial heat exchangers (1.6 m * 0.225 m * 0.125 m). Nordon has the ability to manufacture modules

which can fit to the HTR specifications as well as required fin dimensions and size of the modules.
So it is possible to manufacture channel with hydraulic diameter around or less than 1 mm and straight or serrated fins.
Considering fins with 1mm height, 0.1 mm thickness, a pitch of 1 mm and a separation sheet between channels with a thickness of 0.9 mm, it leads to compacity factor equals to 520 m^2/m^3 (reported to primary surface) and 970 m^2/m^3 (reported to developed exchange surface).

According to HTR specifications, Nordon has carried out a parametric study to estimate the volume of the thermal exchange area according to different types of fins. At first, they considered straight fins and finally serrated fins. This is only a paper study without considering their ability to manufacture these fins or not. As variables, they considered height, pitch and thickness of the fins.
At first, Nordon considered straight fins on both side which led to large volumes of the recuperator : the volume of the thermal exchange area is always over 90 m^3. In the second part of the study, they used offset fins.
As constant, they kept :

- the length of the fins (i.e. 3.175 mm),
- the thickness of the plane sheet of metal between two channels (i.e. 1 mm)
- the width of the plate (610 mm).This width cannot be increased for technical reasons linked apparently to the brazing method and the size of the furnace (to be confirmed eventually)
- the pitch of the fins on LP side (i.e.1.66 mm that is to say 600 fins/m).

Their sizing leads to determine the length and the volume of the recuperator. The number of cores is determined in such way that one module has a square shape but it may be possible to reduce the number of cores by welding several modules together. The table 5.3 presents the parametric study carried out by Nordon.

Fins on LP side	Fins on LP side		Thickness of fins LP&HP	Volume	Length	Number of cores	DP LP side	DP HP side
Height	Height	Fins/m					In thermal exchange area	
mm	mm		mm	m^3	mm		MPa	MPa
3.53	1.5	600	0.2	71	1838	106	0.0248	0.0517
		800	0.2	71	1516	128	0.0143	0.0462
2	1.2	600	0.2	58	1285	123	0.0257	0.0288
		800	0.2	52	1195	119	0.0256	0.044
		1000	0.2	51	1175	119	0.0252	0.0642
1	1	600	0.2	57	806	193	0.0252	0.0088
		800	0.2	50	739	185	0.025	0.0134
		1000	0.2	48	720	182	0.0243	0.0194
1	1	1000	0.1	43	884	133	0.0248	0.0170
3.53	2	800	0.18	69	1726	109	0.0246	0.0467

Table 5.3 : Nordon parametric study

As it was said previously, this is only a paper study but they should be able to manufacture the recuperator with the fins characteristics given in the last line of the previous table.
The mock up to be tested on GREThʼs facility in HTRE program is sized with these fins.

The volume may be highly reduced by changing the thickness of the plane sheet separating the fluids, with 0.6 mm instead of 1 mm, the volume is reduced by a factor around 1.7.

5.3 Reliability and manufacturing

Nordon is used to manufacture huge size heat exchangers : their furnace allow brazing of core with following size : 7.8 m length, 2.05 m height and 1.3 m width. Nordon is well known all over the world, especially in the gas processing industry where aluminium heat exchangers are currently used.
Common structure can bear 110 bar inside pressure and special one up to 250 bar.
Recent development allow to manufacture stainless steel fins with small dimensions i.e. around 1 mm and such industrial heat exchangers have been sold.

5.4 Status of development

- A mock up has to be designed and tested

6 HEATRIC

Heatric is a wholly owed subsidiary of Meggitt PLC and is the only manufacturer of Printed Circuit Heat Exchangers. PCHE's were originally developed as part of a post graduate research project. Heatric was then founded in Australia in 1985. Four years later the company made it's first sales offshore, then moved to the UK to enter the North Sea market and joined the Meggitt group.
By 1999 Heatric has supplied over 400 PCHE's on over 80 major projects worldwide, both in the gas processing and petrochemical markets.

Major benefits include:

- Very compact heat exchangers
- Pressure capability in excess of 500 bar (7000 psi)
- Extreme temperatures from cryogenic up to 800°C (1500°F)
- High efficiency heat exchange

6.1 Basic concept

PCHEs are constructed from flat metal plates into which fluid flow channels are chemically milled. The chemical milling technique is similar to that employed for etching electrical printed circuits, and hence is capable of producing fluid circuits of unlimited variety and complexity. The channel may be straight or wavy.
The milled plates are then stacked and diffusion bonded together to form strong, compact, all-metal heat exchange cores (see figures below).

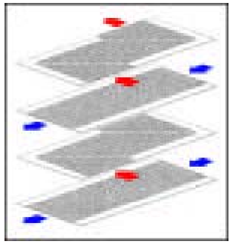


Figure 6.1 : Flow distribution

Figure 6.2 : Stack of plates before bonding

Diffusion bonding is a "solid-state joining" process entailing pressing metal surfaces together at temperatures below the melting point, thereby promoting grain growth between the surfaces. Under carefully controlled conditions, diffusion bonded joints reach parent metal strength, and stacks of milled plates are converted into solid blocks containing the fluid flow passages.

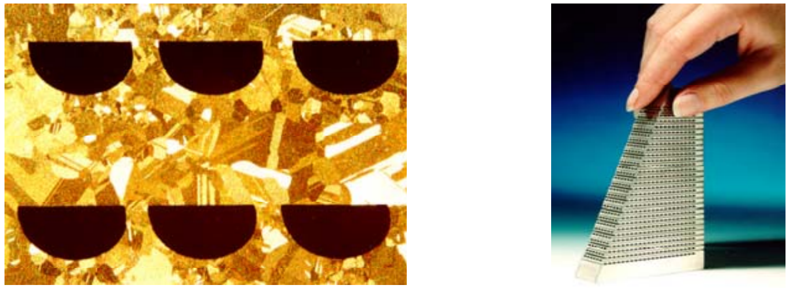


Figure 6.3 : Details of joints

The blocks are then welded together to form the complete heat exchange core for the thermal duty. Finally, fluid headers and nozzles are welded to the core in order to direct the fluids to the appropriate sets of passages.

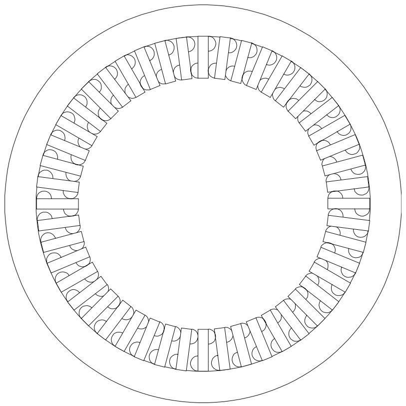
No gaskets or braze material - potential sources of leakage, fluid incompatibility and temperature limitations - are required for exchanger assembly.

Experience in extreme working conditions :

Extreme temperatures - The all-metal diffusion bonded and welded construction of PCHEs minimises design temperature constraints. Materials such as austenitic stainless steels are suitable for temperatures ranging from cryogenic to several hundred degrees Celsius.

Extreme pressures - Core design is readily tailored for containment of exceptionally high pressure. Design pressures in excess of 500 bar are feasible.

Possible arrangement of the modules :



For the GT-MHR application, the recuperator would be composed of 2 layers, each one made of 40 modules, i.e. 80 modules are necessary. Each module is less than 1 meter length.

Figure 6.4 : View of the arrangement

6.2 Thermal and hydraulic design

Like previous manufacturers, the flow type is laminar on both sides. The hydraulic diameters are less than 1 mm. On low pressure side, the channels are straight whereas on high pressure side, the channels are wavy increasing the exchange length and promoting turbulence. To respect the GT-MHR specifications, the sizing of the modules leads to a large frontal area, 80 modules with a 0.2 m width and around 3.2 m height, and a thermal exchange length of 0.64 m.

6.3 Reliability and manufacturing

Unlike other manufacturers (micro turbines ones), Heatric is more used to the combination high pressure - high temperature and to power duty over than 1MW. As it is said in introduction, they sold around 400 PCHE’s in 1999 which implies a certain experience in manufacturing. The chemical milling of the channel lets assume that the channel size remain identical from one to another. A mock up similar to 1 module is being tested by Framatome. We may wonder how it will possible to get a uniform flow distribution at first between the 2 layers and secondly in 40 modules.

6.4 Status of development

- Paper design
- A mock up (same geometry than one module) is being tested
- Units operating at high pressure (70 bars) or high temperature (650°C)

7 ACTE

ACTE (Ateliers de Construction de Thermo-Echangeurs) is a Belgian company located at Ans (Belgium). ACTE is strongly backed by an important Belgian holding company,

UNIBRA, providing the required financial support as well as an experienced team for all administrative tasks.
ACTE develops and manufactures primary surface, compact Spiral Heat Exchangers (SHE) for which the design was patented in 1996.
Data are extracted from an ASME article written by H.Antoine and L.Prieels [7] and from a meeting.

7.1 Basic concept

Description of the concept :

The heat exchanger has a cylindrical shape. It is a primary surface exchanger, it is compact and stationary. The exchange area is as high as **1600 m2/m3** and the hydraulic diameter is as small as **0.75 mm**. The heat transfer fluids enter, circulate, and exit the heat exchanger in a counter flow manner in a direction substantially parallel to the coil longitudinal axis. The flow is distributed inside the coil which includes two distributing areas and a heat transfer area like a plate heat exchanger. The high degree of turbulence created by the corrugated sheets promotes the heat transfer while considerably reducing the fouling.

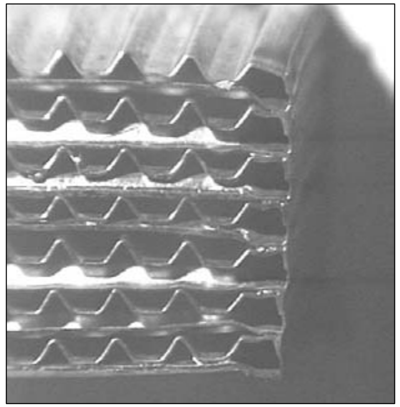


Figure 7.1 : View of the corrugations

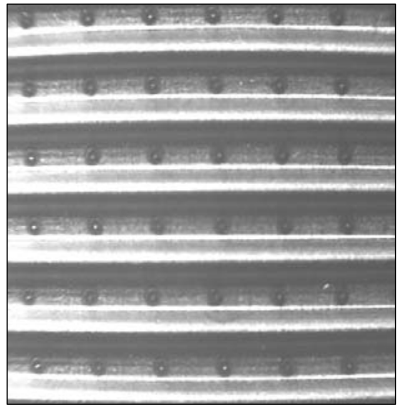


Figure 7.2 : Laser spot welding of the 2 sheets

At the moment, this technology is used for microturbine applications and covers power ranging from few kW up to 2 MW; but several recuperators installed in a battery configuration can boost power. The figures below represent a complete recuperator and fluid circulation for such an application.

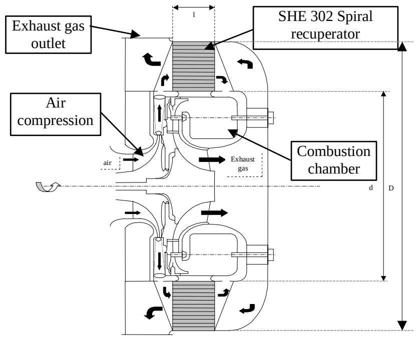


Figure 7.3 : Fluid circulation in the module   Figure 7.4 : Complete module

On the following figure, the fluid distribution is presented.

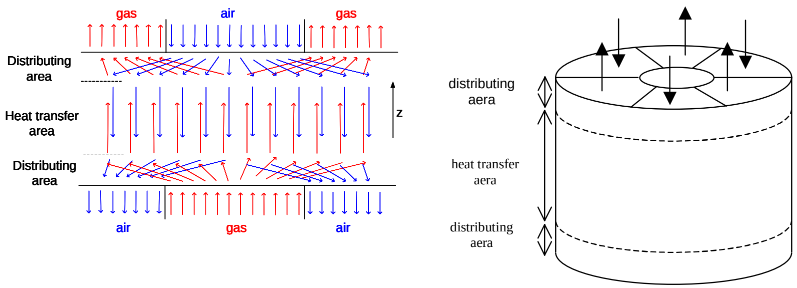


Figure 7.5 : Fluid distribution

The core is divided into 3 zones. A central counter flow zone inserted between 2 distribution zones that are adjacent to the faces. The flow in the central zone is counter flow and laminar and the geometry of the corrugations is a blend of triangular sine wave and trapezoidal shape. According to ACTE, the Shah and London ‘s correlations for this geometry fit well with the measurements. In this central zone, the air passages are predominantly sine wave, while the gas passages are predominantly trapezoidal. In the distribution zones however, the flow is parallel near the openings, cross flow inside the distribution zones an nearly counter flow at the interface of the distribution zone and central zone. By considering 3 exchangers installed in series, they estimate an equivalent effectiveness of the apparatus.

7.2 Thermal and hydraulic design

The hydraulic diameters are the following ones :

	Air side	Gas side
Distribution area	0.76	1.57
Central area	0.72	1.03

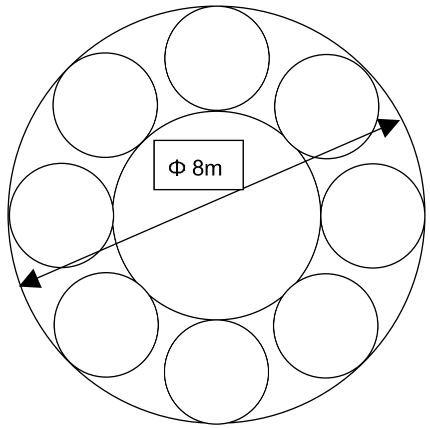
The hydraulic diameters size allows to get a compactness of 1600 m^2/m^3 in the central zone. Considering the same geometries for the GTMHR application, it is possible to estimate roughly the total volume without headers : with a Nusselt number equals to 4 on both sides, it leads to a total volume of 34.6 m^3 i.e. a compactness equals to 17.3 MW/m^3. This results doesn’t include headers but with this technology headers are located at the top and at the bottom of the recuperator (see figure 7.5) and so they are less disturbing than those located along heat exchangers.

Concerning pressure losses, we have no information but we may estimate the friction coefficient around 15 / Re for a hexagonal channel and the following parameters :

hydraulic diameter : 0.72 mm
Re around 1000
ρ : 2.1 kg/m3
μ : 3.1 e-5 Pa.s

it leads to a pressure loss of 0.37 bar /m.

Possible arrangement :
Considering 2 layers of 8 modules (each with a diameter of 2m) , it is possible to have a volume of 50 m^3 only with a one meter length heat exchanger. This volume is larger than useful one as it was shown previously (34.6 m^3 are necessary to fulfil the duty with a compactness of 1600 m^2/m^3 and a Nusselt number of 4 on both sides).



Further information and investigation are necessary to complete this proposal.

7.3 Reliability and manufacturing

Compared to finned surface, primary heat exchange surfaces are more interesting in the way they are more effective. So the total weight is smaller , the manufacturing costs are less expensive because the whole process is automated and doesn't need brazing metal. Moreover, it is a 100% laser welded recuperator which is certainly more safe than a traditional brazing technique from a "tightness point of view". The spiral pattern is very interesting in the way they just have to increase the number of turns during coiling to fit to the desired power.
The whole automated process allow accuracy, identical pieces and a fast production. The size of the welded spot may be modified to get a more robust structure to fit to HTR program.

The company was founded in 1998 and hence it is not very experienced in such huge research program furthermore their know how is actually more oriented to micro turbine (so with less severe working conditions). Nevertheless, the company is hold by a physicist engineer with many years of experience in gas turbines.
According to them, they have the ability to manufacture a spiral heat exchanger very quickly.

7.4 Status of development

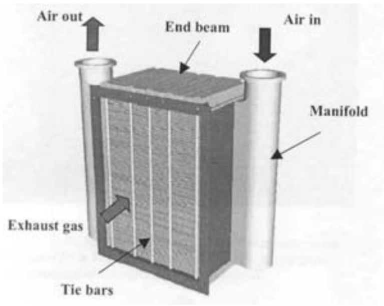
- Paper design
- Units operating for micro turbines applications

8 SVENSKA

As ACTE, Rekuperator Svenska AB owned by VOLVO Technology Transfer Corporation and Avesta Polarit has developed a completely welded recuperator for micro-gas turbine applications. The recuperator was installed in a 100 kW(e) micro-gas turbine power plant for combined electricity and heat generation. Initially, VOLVO developed hybrid vehicles equipped with a small recuperated gas turbine but without manufacturing the recuperator by themselves. The development of a micro turbine power plant for electricity and heat generation and the expensive price of the recuperator made by an American manufacturer led them to make their own heat exchanger. It is the way that Rekuperator Svenska AB was created in 1998.
Data are extracted from an ASME article written by G. Lagerström and M. Xie [8] and a presentation copy sent by Svenska.

8.1 Basic concept

The recuperator is a primary surface counter flow heat exchanger with cross corrugated duct configuration. The primary heat transfer surface plate patterns are stamped and a pair of the plates are laser welded to form an air cell. The air cells are then stacked and laser welded together to form the recuperator core which is tied between two end beams.
The following figures show the recuperator developed par RSAB and the fluid distribution in the plates.



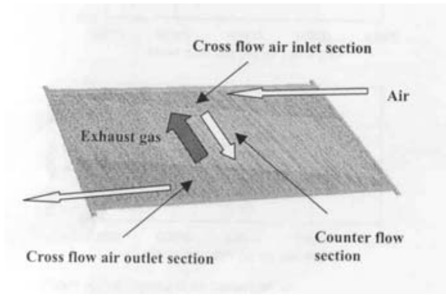


Figure 8.1 : View of the heat exchanger Figure 8.2 : Fluid circulation

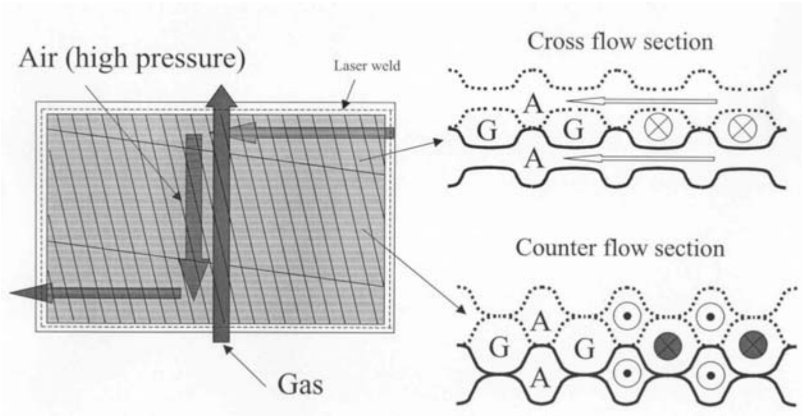


Figure 8.3 : Corrugation pattern in the recuperator.

Each air cell has three distinct sections : cross flow inlet section, counter flow section and cross flow outlet section. In the cross flow sections, the height of corrugation is lower so that a free space is formed in the assembled air cell to allow air passage. To optimise air distribution inlet and outlet section are not symmetric. To withstand the internal air pressure and to prevent "ballooning" of the air cells the heat exchanger core is clamped between two rigid end beam connected by a number of tie bars. Unlike ACTE, the plates are "only" pressed against one to another (no laser spot welding). If this technology is suitable for micro turbine applications, it may be not satisfying for HTR with 50 bars difference between channels.

8.2 thermal and hydraulic design

Recuperator developed for a 100 kW(e) micro gas turbine power plant :

Parameter	Air	Gas
Mass flow (kg/s)	0.78	
Inlet temperature (°C)	210	650
Inlet pressure (kPa)	450	110
Design requirements		
Effectiveness	89% (min)	
Total relative pressure losses	4.5% (max)	
Durability	60.000 hours / 3000 start-up cycles	

Once installed and tested, it appeared that the achieved effectiveness and total relative pressure losses were better than the design requirements (total pressure drops equals to 3.5% instead of 4.5%, and efficiency 89.1% instead of 89%). The compactness of the recuperator in the counter flow section is over 1600 m^2/m^3 and the recuperator core has 390 air cells with dimensions of 295*420*2.22 mm.

By changing the number of air cells or modifying the number of cores, they also designed a recuperator for a 300 kW(e) gas turbine power plant.

8.3 Reliability and manufacturing

As ACTE, they are using primary heat exchange surfaces which are more interesting in the way they are more effective, less heavy and less expensive (no brazing metal, automated process)
It is also a 100% laser welded recuperator which is certainly more safe than a traditional brazing technique from a "tightness point of view". But as it was said previously, plates are pressed one against another and this technology is certainly not suitable to HTR application.
Moreover it is a flat heat exchange surface so it cannot be entirely automated and the size of the plates have certainly to be modified leading to further costs.

8.4 Status of development

- Units operating for micro turbines applications

9 CAPSTONE

In the same type of products than ACTE and SVENSKA, CAPSTONE was also contacted by mail. Unfortunately, the answer was the following one : "As most of the information that you have requested below is proprietary, I cannot release it. We currently have no plans of extending the use of our recuperator to systems other than microturbines". Visiting the web site doesn't allow to extract significant pictures of geometry surfaces.

10 ALFA LAVAL VICARB

Alfa Laval is Swedish company which headquarters are located at Lund. Alfa Laval is organized in 2 divisions :

- Process Technology Division which optimise processes of customers
- Equipment Division which offers a wide range of products.

Vicarb, which was originally a French company located near Grenoble, was bought by Alfa Laval few years ago. This unit depends on both divisions.
Alfa Laval Vicarb is used to manufacture plate heat exchangers for a wide range of applications. If originally, this technology was designed for food industry, it tends now to be used for other applications such as chemical, petrochemical, districts heating and power industries since larger plates were manufactured.

10.1 Basic concept

PHE's are made of pack of corrugated plates (figure 10.1) which are pressed together. The plate size ranges from 0.02 m^2 to over 3 m^2 with conventional pressing technology (figure 10.2), but can reach up to 15 m^2 for explosion formed plates (Packinox technology). The hydraulic diameter lies between 2 and 10 mm for most common plates, but free passages and wide gap plates exist for viscous fluid applications. Typically, the number of plates is between 10 and 100, which gives 5 to 50 channels per fluid. Furthermore, the use of high quality metal and the manufacturing techniques lead plate heat exchangers to be less prone to corrosion failure than shell and tube units (Turisini et al (1997),[9]).

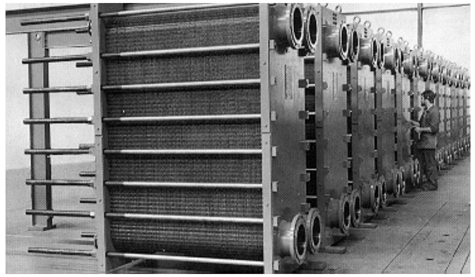


Figure 10.1 : View of plate heat exchanger

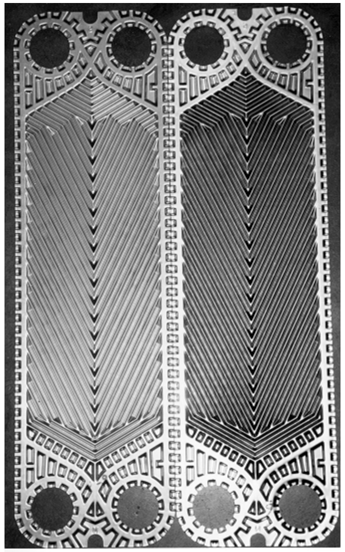


Figure 10.2 : View of corrugated plates

To insure the tightness, three technologies are available : gaskets, welding and brazing. Gasketed PHE is the most common type, and the gasket material is selected in function of the application (temperature, fluid nature ...). Temperature up to 200°C and pressure up to 25 bars can be achieved by such heat exchangers. For applications where gaskets are undesirable (high pressure and temperature or very corrosive fluids), semi-welded or totally welded heat exchangers are available (figure 10.3). The last variant is the brazed plate heat exchanger. The plate pattern is similar to conventional gasketed units, but tightness is obtained by brazing the pack of plates (figure 8). For common applications copper brazing is used, but for ammonia units nickel brazing is possible. This technology leads to inexpensive units, but the plate size is generally limited to less than 0.1 m^2. The counterpart is that the heat exchanger cannot be opened, and fouling will limit the range of application.

Figure 10.4 : Plates before brazing

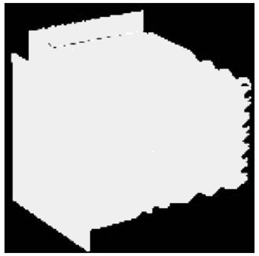


Figure 10.3 : Semi welded PHE

10.2 Thermal and hydraulic design

From technical point of view, PHE manufactured by Alfa Laval Vicarb are designed for a maximum temperature around 400°C and the allowed pressure difference between the 2 fluids is limited to 30 bars. Nevertheless, it should be possible to increase these limitations without too much R&D. This solution with plate heat exchangers must be kept in mind since they are able to corrugate plates with low height (around 0.8 mm so a hydraulic diameter of 1.6 mm). To improve pressure limitation, it may be possible to weld contact points between 2 plates. Further investigations with Alfa Laval Vicarb are required.

10.3 Reliability and manufacturing

Alfa Laval Vicarb is used to manufacture large plate heat exchangers for industries which need important exchange area. Their actual policy is mass production and applications such HTR are more considered as unit production so they need internal reflection to go further.

11 PACKINOX

Packinox S.A.is a 100% subsidiary of AREVA. Among several offices all over the world, the manufacturing centre located in Chalon sur Saône (France 71) has been contacted to get more information concerning their plate heat exchangers. Packinox is known as the world leader in large welded-plate heat exchangers for hydrocarbon industry.

11.1 Basic concept

The bundle is made of corrugated stainless steel sheets of up to 15 meters in length which are explosion formed underwater against a mould created to specification. After explosion forming and inspection, the hundreds of plates used to build a single heat exchanger are prepared for construction of the bundle. Spacers are welded to the plates and inlet/outlet inserts are added to ensure low pressure drop by distributing fluids over minimum space.

The plates are stacked alternately on the world's largest bundle welding press where automated TIG welds are performed. Headers are manually welded to the bundle block.

After passing inspections, the plate bundle is inserted into a pressure vessel. The pressure vessel is filled with fluid to ensure compression of the bundle. Alternate designs for two or more streams may call for additional thick plates and tie rods instead of a containment vessel.

Figure 11.1 et 11.2 show the different steps of fabrication and details of plates arrangement.

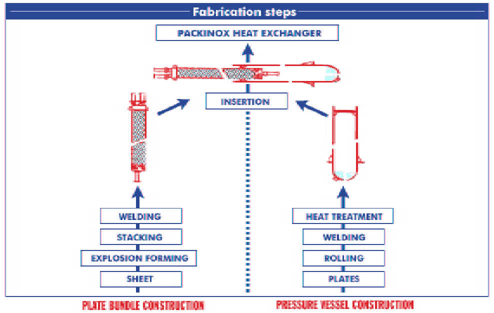


Figure 11.1 : Fabrication steps

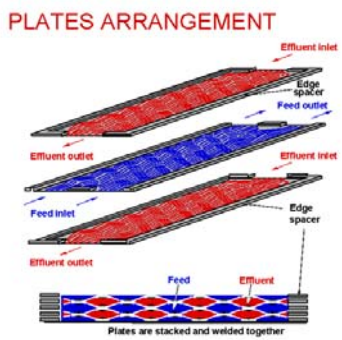


Figure 11.2 : Plates arrangement

Figure 11.3 : Packinox heat exchanger and its shell

They are used to design very large heat exchangers since the diameter of the shell can vary from 1 m to 4 m and its length from 10 m to 20 m. They are used to stainless steel (316, 321,

604 H) since typical design temperature range is 300-550°C, an application up to 650°C has already been achieved.
Concerning pressure, the pressure vessel is designed to withstand operating pressure. The vessel is filled with higher pressure fluid for compression of the bundle block. Bundles plates are exposed only to differential pressure of the flowing fluids and the maximum differential pressure is limited to 40 bars.

11.2 Thermal and hydraulic design

The thermal and hydraulic performances are directly linked to the angles of corrugations and also to the hydraulic diameter. The minimum height of the corrugations which can be manufactured by explosion forming is 2.5 mm corresponding to a hydraulic diameter of 5 mm. At first sight, this limitation is a real drawback compared to previous technologies for which the hydraulic diameter is around 1 mm. This technology is less compact since the surface area per volume is decreased.

11.3 Reliability and manufacturing

Even if Packinox is used to manufacture very large heat exchangers operating with relatively high temperature, it seems difficult to fit to HTR specifications for 2 main reasons. The first one is linked to the lack of compactness compared to other technologies and the second one is the need to have a vessel under pressure around the bundle. This vessel leads to increase the volume of the recuperator and its operating pressure must be greater than HP side pressure (i.e. 7.2 Mpa).

12 TUBULAR HEAT EXCHANGERS

This study was carried out by FZJ and it mainly deals with 2 different types of Helium-Helium heat exchangers:

- Recuperators :

In the HHT-Project the recuperators were planned by industrial firms. Some tests were made. The experiences for operating of similar recuperators were with the industrial firms.

- Intermediate Heat Exchangers :

Experience with IHX were made in the KVK (Komponenten-Versuchs-Kreislauf) for 2 different IHXs with 10 MWth . Information about operation of these IHX are presented in the following reports:

1.) IAEA-TECDOC-436: Gas-Cooled Reactors and their Applications,1987: W.Jansing, H.Breiotling, R.Candeli.: KVK and Status of the HT-Components Development, Page 407-429

2.) Nuclear Engineering and Design, Special Issue on: The HTR and Nuclear Process Heat Applications,Vol78(1984),No2, April(I): W.Maus. K.Mendte, H.Teubner,R.Exner; M.Podhorsky,F.Reuter, et al.: The He/He Heat Exchanger-Design and Semitechnical Testing, Page 195-214

12.1 Recuperators

Table 12.1 presents the main characteristics of the recuperators designed for HHT- and PBMR- project.

HHT-3x360 MW_e 1975 integrated	HHT-Demo 676 MW_e 1980 integrated	PBMR 100 MW_e former preliminary design study
3 units	2 units 1 unit= 7 elements	1 unit
1 unit Q=885 MW_{th}	1 element Q=103 MW_{th}	Q= 275 MW_{th}
543°C-178°C/178°C-494°C	493°C-153°C/105°C-464°C	572°C-143°C/104°C-558°C
25bar/62bar	25 bar/72 bar	27 bar/70 bar
Δ=0,5 bar/0,9 bar	Δ=0,9 bar/1,2 bar	Δ=0,28 bar/0,82 bar
G= 540 kg/s	G=55 kg/s	G =120 kg/s
d= 8/10 mm	d= 10/12 mm	↓***
H_{bundle}= 10,3 m	H_{bundle} = 21 m	H= m
D_a =4,93 m	D_a =1,6 m	D_a = m
D_i = 0,8 m	D_i =0,5 m	D_i = m
$V_{bundle} \approx$ 191 m^3	$V_{bundle} \approx$ 40 m^3	$V_{casette} \approx$ m^3
k_i = 1080 W/m^2grd	k_i =800 W/m^2grd	k = W/m^2grd
F_i = 16794 m^2	F_i = 3405 m^2	F = m^2
885/191 = 4,63 $MWth/m^3$	103/40 = 2,6 $MWth/m^3$	= $MWth/m^3$
16794/191 = 87 m^2/m^3	3405/40 = 85 m^2/m^3	= m^2/m^3
885000/16794 = 52 kW/m^2	103000/3405 = 30 kW/m^2	= kw/m^2

↓*** Data PBMR restricted commercial

Table 12.1 : HTT and PBMR recuperators

This table allows comparisons with future compact recuperator technologies :

- The exchanged thermal power per unit volume is relatively poor since we can reach around 25MW/ m^3 with PCHEs and PFHEs whereas tubular technology gives between 2.6 and 4.6 MW/m^3.
- So the resulting tubular heat exchanger is very large : without comparing expected efficiency, the design given in the second row of the table 12.1 would give a volume of bundle around 250 m^3 to exchange the same thermal power than GT-MHR. This solution means a third vessel only for the recuperator.
- Taking into account the required GT-MHR efficiency would increase the volume since the efficiencies in table 12.1 are lower.

12.2 Intermediate Heat Exchangers

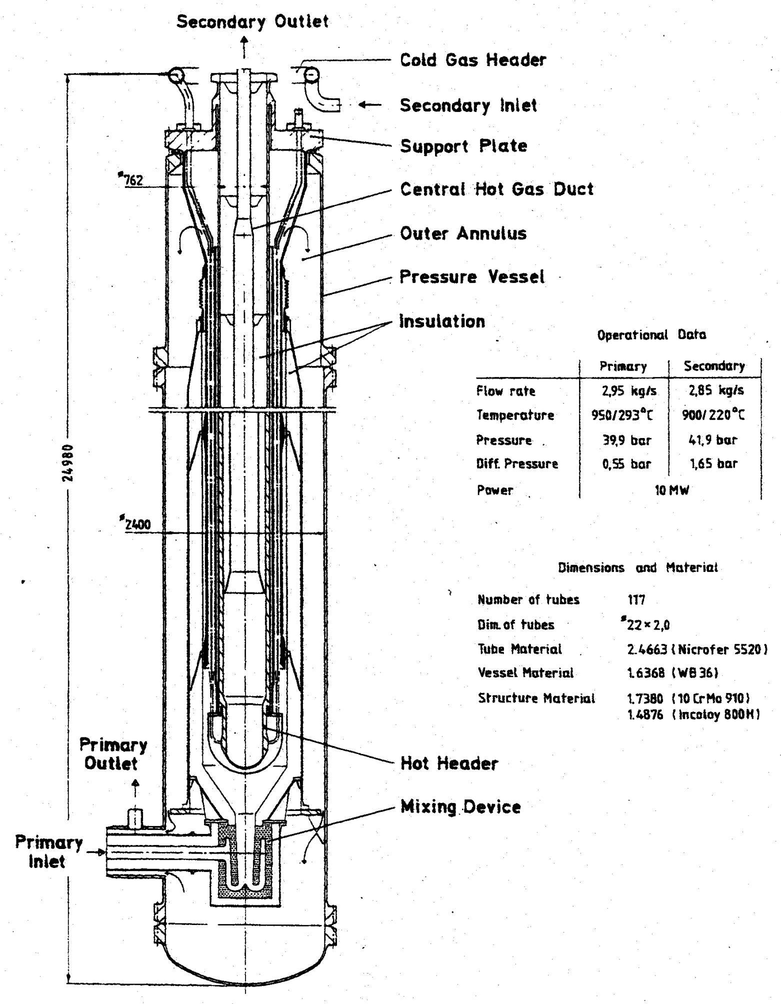
For the former German nuclear process heat project (PNP) test units for 10 MW_{th} intermediate heat exchanger (IHX) were manufactured and tested. These units were helical-coiled and U-tube flow types, which were tested in the German KVK-loop plant (Komponentenversuchskreislauf).
Also for 125 MW_{th} two IHX were planned.
Data for these IHX are taken from journal Nuclear Engineering and Design [10].

For HTTR in Japan also a 10 MWth helical-tube bundle IHX was fabricated and has been tested. As announced by JAERI [11] first tests showed secondary helium gas at 730°C via the IHX in the HTTR. Data for this IHX are taken from JAERI report No.1332 [12].

Beyond this IHX for HTTR there is a development for compact heat exchangers (CHX) in Japan for future HTR´s. It is reported [13] that a small scale diffusion welded compact heat exchanger is tested successfully.

12.2.1 German IHX

Figures 12.2 and 12.3 show respectively the German Helix IHX and U-tube IHX.



Operational Data

	Primary	Secondary
Flow rate	2,95 kg/s	2,85 kg/s
Temperature	950/293°C	900/220°C
Pressure	39,9 bar	41,9 bar
Diff. Pressure	0,55 bar	1,65 bar
Power	10 MW	

Dimensions and Material

Number of tubes	117
Dim. of tubes	⌀22 × 2,0
Tube Material	2.4663 (Nicrofer 5520)
Vessel Material	1.6368 (WB 36)
Structure Material	1.7380 (10 CrMo 910) 1.4876 (Incoloy 800H)

Figure 12.2 : German Helix IHX from project PNP

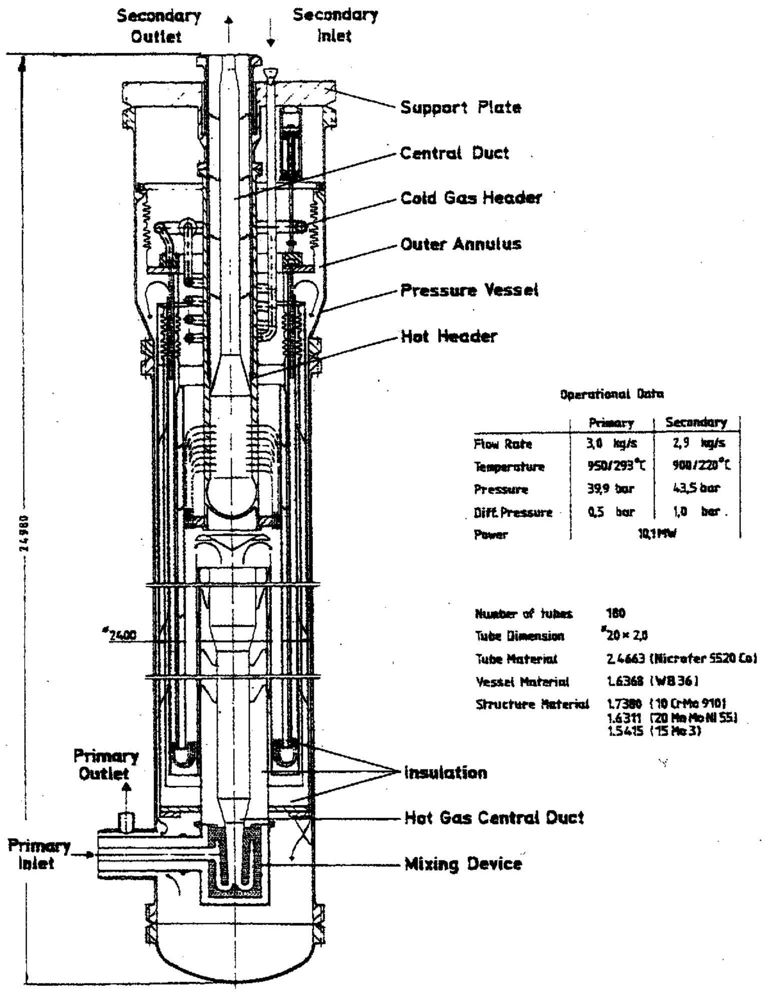


Figure 12.3 : German U-tube IHX from PNP

Table 12.4 sums up the main characteristics of the 2 German tubular heat exchangers

Helix/cross-flow Sulzer/Steinmüller		**U-tube/counter-flow Balke/Dürr**	
125 MW_{th} planned	**10 MW_{th} built&tested**	**10,1 MW_{th} built&tested**	**125 MW_{th} planned**
950°C-293°C/220°C-900°C			
39,9 bar / 41,9 bar		**39,9 bar / 43,5 bar**	
	Δ=0,55/1,65 bar	**Δ=0,5/1,0 bar**	
36,8 kg/s / 35,6 kg/s	**2,95 kg/s / 2,85 kg/s**	**3,0 kg/s / 2,9 kg/s**	**36,9 kg/s /35,6 kg/s**
d=22/18 mm		**d= 20/16 mm**	
n_{tubes}=1444	**n_{tubes}=117**	**n_{tubes}=180**	**n_{tubes}=1900**
L_{bundle} =45 m	**L_{bundle} =42,5 m**	**L =32,7 m**	**L= 32,7 m**
$D_{bundle\ a}$= 2,58 m	**$D_{bundle\ a}$=1,09 m**	**$D_{bundle\ a}$=2,03/1,66 m***	**$D_{bundle\ a}$=3,52/2,9m***
$D_{bundle\ i}$=1,21 m	**$D_{bundle\ i}$=0,88 m**	**$D_{bundle\ i}$ =1,41/1,10 m***	**$D_{bundle\ i}$=2,40/1,55m***
H_{bundle}=17,7 m		**H_a=18,47 m /H_i=16 m**	
n_{cyl}=19	**n_{cyl}=3**		
F_a= 4491 m^2 *	**F_a =344 m^2**	**F_a= 370 m^2 ***	**F_a= 3900 m^2**
k= 458 W/m^2grd *	**k=526 W/m^2grd**	**k=449 W/m^2grd ***	**k=527 W/m^2grd ***
V_{bundle}≈ 72 m^3 *	**V_{bundle}≈5,75 m^3 ***	**V_{bundle}≈ 30 m^3 ***	**V_{bundle}≈100 m^3 ***
1,73 MW_{th}/m^3	**1,74 MW_{th}/m^3**	**0,34 MW_{th}/m^3**	**1,25 MW_{th}/m^3**
62,4 m^2/m^3	**59,7 m^2/m^3**	**12,3 m^2/m^3**	**39 m^2/m^3**
28 kW/m^2	**29 kW/m^2**	**27 kW/m^2**	**32 kW/m^2**

***values are not mentioned by firms; therefore calculated approximately by FZJ**

Table 12.4 : Main characteristics of the German IHX

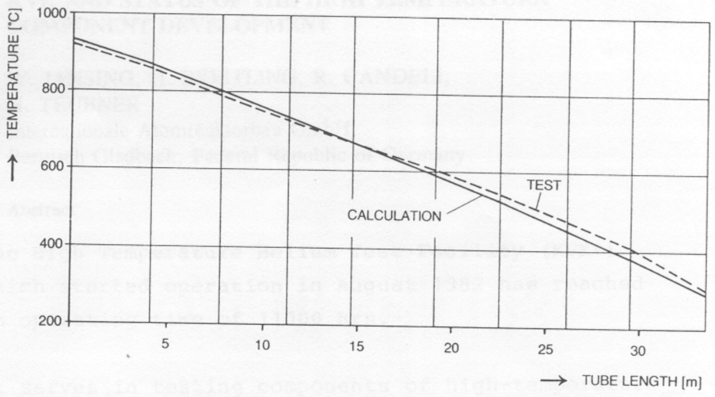
Concerning these 2 heat exchangers, we can mentioned once again the poor compactness compared to future compact recuperator technologies even if it is tricky to compare technologies at different working conditions. Nevertheless, it seems difficult to use tubular technology since we are limited in term of volume.

Table 12.5 and figure 12.6 show a comparison of data between calculation and test of the U-tube helium heat exchanger.

LOAD 100 %		PRIMARY SIDE DESIGN	PRIMARY SIDE TEST	SECONDARY SIDE DESIGN	SECONDARY SIDE TEST
TEMPERATURE	[°C]				
• INLET		950	950	220	217
• OUTLET		293	306	900	894
PRESSURE	[bar]	39,9	40,0	43,6	43,3
PRESSURE DROP	[bar]	0,50	0,40	1,0	0,86
MASS FLOW RATE	[kg/s]	3,0	2,97	2,9	2,71
HELIUM VELOCITY	[m/s]	17,6	17,5	45,6	42,6
OVERALL HEAT TRANSFER COEFFICIENT	[W/m² K]	DESIGN 446		TEST 442	
HEAT TRANSFER	[MW]	10,24		9,53	

FIG. 5. COMPARISON OF DESIGN AND TEST DATA OF THE U-TUBE HELIUM HEAT EXCHANGER

Table 12.5 : Comparison between calculation and test



TEMPERATURE PROFILE OF THE U-TUBE HEAT EXCHANGER

Figure 12.6 : Comparison of temperature profile between calculation and test

12.2.2 Japanese IHX

Figure 12.7 and table 12.8 show respectively the tube IHX from HTTR and corresponding data.

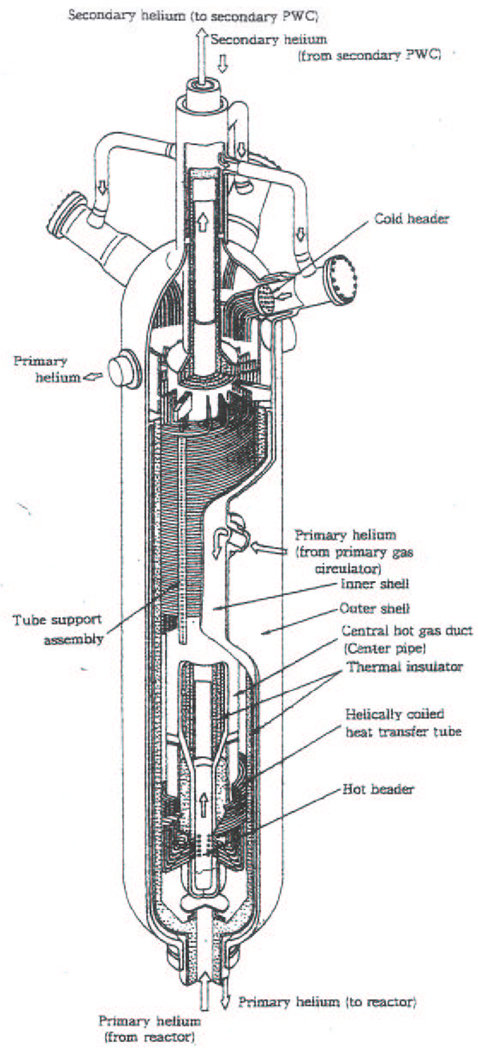


Figure 12.7 : Japanese helix-IHX from HTTR

Type	Vertical helically-coiled counter flow	
Number	1	
Maximum pressure		
Outer shell	4.8MPa	
Heat transfer tube	0.3MPa (differential pressure)	
Maximum temperature		
Outer shell	430°C	
Heat tube	955°C	
	Rated operation	High temperature test operation
Primary flow rate	15t/h	12t/h
Inlet temperature of primary helium gas	850°C	950°C
Outlet temperature of primary helium gas	390°C	390°C
Flow rate of secondary helium gas	14t/h	12t/h
Inlet temperature of secondary helium gas	300°C	300°C
Outlet temperature of secondary helium gas	775°C	860°C
Heat capacity	10MW	
Heat transfer tube		
Number	96	
Outer diameter	31.8mm	
Thickness	3.5mm	
Outer diameter of shell	2.0m	
Total height	11.0m	
Material		
Outer and inner shell	SCMV4-2NT (2¼Cr-1Mo)	
Heat transfertube	Hastelloy XR	
Hot header and hot duct	Hastelloy XR	

Figure 12.8 : Data of the Japanese helix IHX

Beside these studies with tubular heat exchangers, JAERI, department HTTR, has proposed a concavo-convex plate type compact heat exchanger (CPCHX) [13] as shown in Fig 12.9.This technology should be presented in the first part of this study but as it is for a IHX purpose, it is let in this chapter named "Japanese IHX".

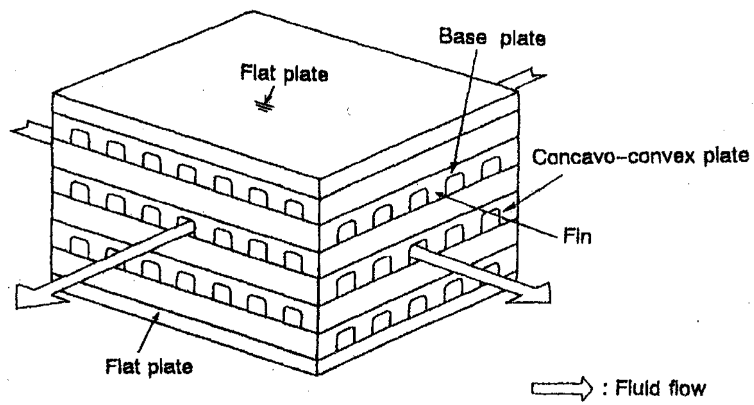


Figure 12.9 : View of the CPCHX

This compact heat exchanger consists of concavo-convex plates(CPs) welded by solid state diffusion at 1150°C, contact pressure of 44Mpa and 30 min holding time at $6x10^{-3}$ Pa vacuum.
Small –scale units of these types were made with superalloy Hastelloy XR and tested for leakage and thermal performance tests. The dimensions of these units are shown respectively in the 2 following tables.

Size	100mm (width) x200mm (length)
Number of fins	44
Height per CP	3 mm
Base plate thickn.	1.5 mm
Flow path width	1 mm
Fin thickness	1 mm
No of CP stages	3

	High Temp.-Fluid	Low Temp.-Fluid
Size	100 mm width	200 mm length
Number of fins	79 mm	39 mm
Height per CP	3 mm	3mm
Base plate thickn.	1.5 mm	1.5 mm
Flow path width	1 mm	1 mm
Fin thickness	1 mm	1 mm
No of CP stages	5	5

As a result of leakage tests (63Mpa by cold water pressure), it was confirmed that the reliability of the welding between the CP´s of the small-scale CPCHX is sufficient. A thermal performance test showed that the thermal conductance of the CPCHX was better than calculated.

13 CONCLUSION

This present paper aims to present different technological possibilities to fit to HTR specifications and to introduce potential manufacturers. Heat exchangers may be divided into 2 groups depending on their technology : primary and secondary heat exchange surface apparatus. Primary heat exchangers are made with a single corrugated sheet between 2 fluids. Generally, this sheet is very thin so it is possible to manufacture corrugations but the pressure difference between the fluids may not be high : this technology is commonly used for micro turbine applications. Among primary heat exchangers, tubular heat exchangers have also been studied by FZJ based upon the German nuclear process experience : recuperator and intermediate heat exchangers are presented. Secondary heat exchange surface heat exchangers are made of a plane separating sheet between fluids and very thin fins are located inside the channels to increase the heat exchange surface.

It may be summed up as follows :

- Primary surface heat exchanger manufacturers among whom we find ACTE, SVENSKA, CAPSTONE. As it has been shown previously, these technologies provide very high compacity factor i.e. around 1600 m2/m3 in thermal exchange area. In fact, these recuperator are designed for micro turbines applications for which pressure difference between channels is much more smaller than HTR’s one. So metal thickness can be decreased to reach this compacity factor, with higher pressure difference, metal thickness must be more important and it becomes impossible to stamp stainless steel sheet with hydraulic diameter around 1 mm. So it is clear that such technology can’t fit to HTR application. The technology developed by Heatric is considered as a primary heat exchange surface even if piece of metal between 2 adjacent passages may be assimilated to a fin. Heatric is able to manufacture channels with very small hydraulic diameter leading to high exchange coefficient with straight or wavy patterns. They are used to high pressure and temperature and the proposed design paper fits to HTR specifications. At comparable hydraulic diameter, the resulted structure is heavier than other technologies one. Plate heat exchangers were also considered. It seems possible to go further with Alfa Laval Vicarb but further investigations are necessary. In the same time, it is well known that tubular heat exchangers can fit to HTR applications since they have already been used for such applications, nevertheless this technology is not compact enough and leads to increase significantly the total volume of the recuperator.

- Secondary surface heat exchanger manufacturers among whom we find Mitsubishi (via Jaeri), Allied Signal, Ingersoll-Rand and Nordon. To reach the same performances than Heatric ones, the size of the fins has to be decreased as much as possible. The use of fins is interesting for 2 reasons : it allows to increase the secondary surface heat exchange and the Nusselt number increases when the shape of the channel is rectangular rather than square. Nevertheless, it seems that the better compacity factor is obtained with the smallest square fin dimension and it is one of the technological aspect which must be solved.

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