

Blanket concept based on FliBe and advanced ferritic steel

**Siegfried Malang
US-APEX Study Team**

**US/Japan Workshop on Power Plant Studies
and Related Advanced Technologies
San Diego, April 6-7, 2002**

Challenges for the design of FLiBe-Blankets:

a) Exceptional low thermal conductivity of FLiBe

(1 W/(m*K) compared to 15 W/(m*K) for Pb-17Li and 50 W/(m*K) for Li)

To obtain sufficiently large heat transfer, high turbulence is required.

b) Viscosity of FLiBe is really high, especially at temperatures close to the melting point.

(At of 500°C for example, the kinematic viscosity is 11.5 E-6 m²/s compared to 0.12 E-6 m²/s for water at 300°C, 15 MPa (PWR-conditions))

High velocities and/or large channel dimensions are required to obtain sufficient turbulence.

c) Breeding capabilities of FLiBe are limited, making additional neutron multiplier mandatory. Usually a region of beryllium with a thickness of 3-5 cm is arranged close to the first wall (FW). This implies the problem of beryllium swelling under neutron irradiation (10-15 vol.% at end-of-life conditions), and a large tritium inventory in the beryllium (up to some kg's) which is a safety concern.

d) The high melting point of FLiBe (459°C for (LiF)₂(BeF₂)) requires a structural material with a temperature range up to > 650°C. In addition, FLiBe is rather aggressive to a number of candidate structural materials. This requires an excess of beryllium in contact with the FLiBe in order to stabilize the fluor in the salt. This contact can be provided either inside the blanket or outside the irradiation environment.

Main characteristics of the proposed blanket concept

A) Coolant exit temperature higher than structure temperature

Self-cooled blankets have the potential to achieve coolant exit temperatures higher than the maximum interface temperature and in some cases higher than the maximum structure temperature.

The key feature of such concepts is to cool the structure with the “cold” inlet flow, and to limit heat losses from the “hot” zones to the structure by employing an additional insulator (ARIES-ST) or by low heat transfer coefficients (ARIES-AT).

In the proposed FLiBe blanket concept the coolant is routed first through channels in the structure including the FW before it is heated up further by volumetric heating in large exit channels, flowing there with low velocity.

B) Recirculation of first wall coolant

The coolant mass flow rate in a blanket element is determined by the power input and the desired temperature rise in the blanket.

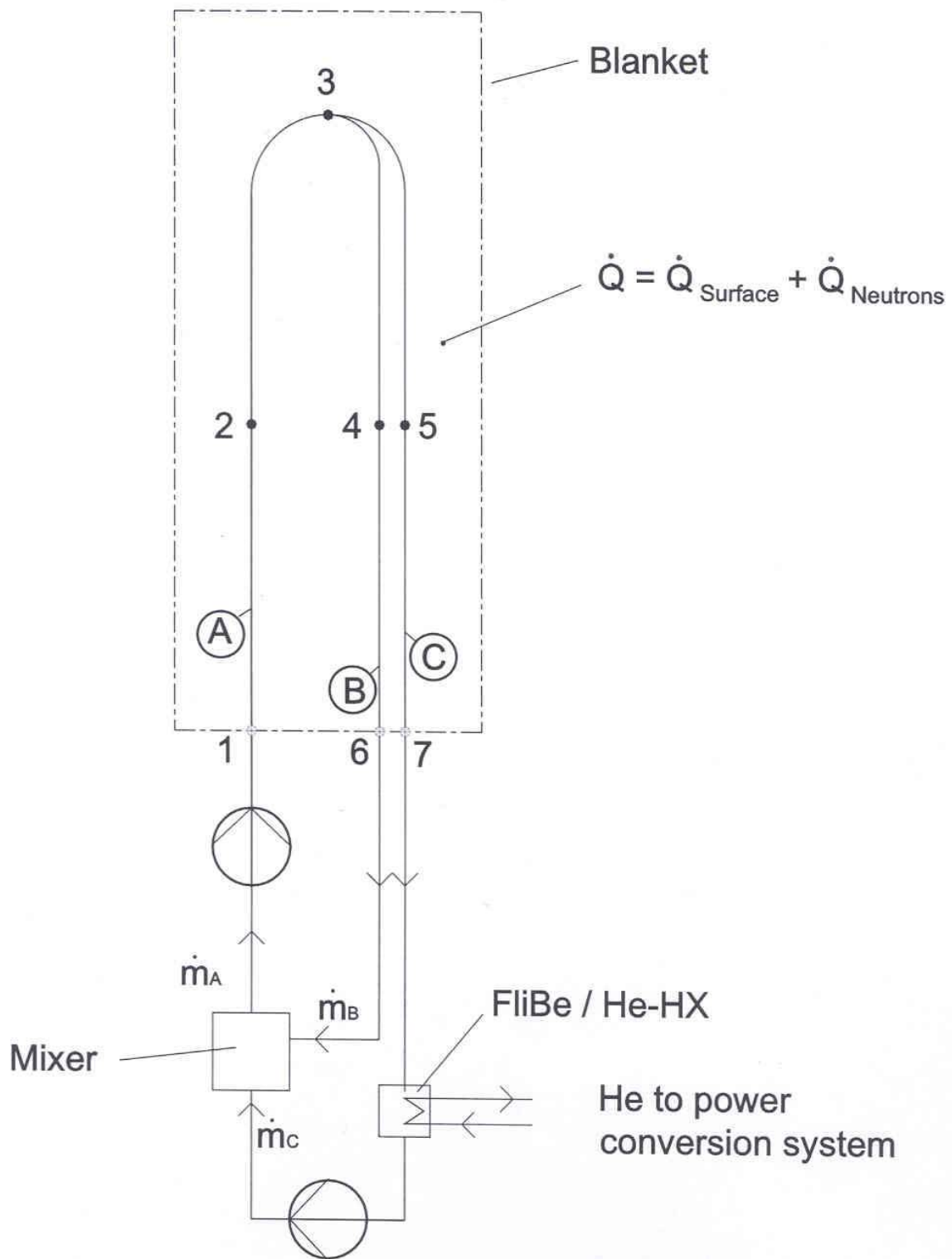
With FLiBe as coolant, and an exit temperature of 700 C or higher, this relatively low mass flow rate leads either to low heat transfer coefficients in the FW cooling channels (low velocity) or excessive high pressure drop (small channels).

Furthermore, an inlet temperature close to the melting point is accompanied by very high viscosity, resulting in increased pressure drop.

A decisive improvement can be achieved if the flow rate in the FW cooling channels is made substantially larger than in the exit ducts, and the excess flow is recirculated through bypass channels.

This bypass flow is mixed outside the blanket with the “cold” flow from the power conversion system, increasing in this way the coolant inlet temperature at the FW cooling channels.

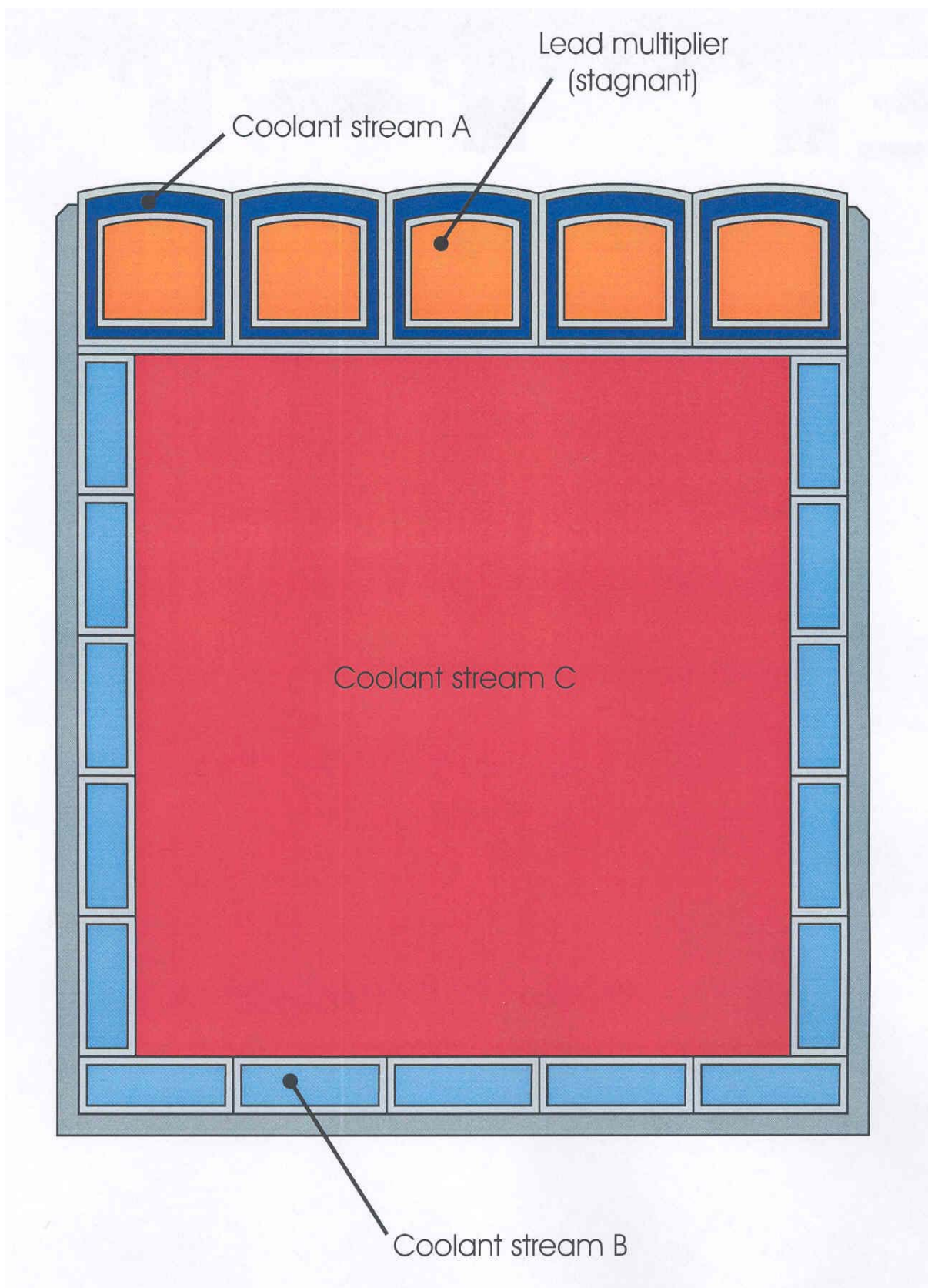
The bypass flow can be used to cool the walls of the large exit duct, enabling in this way to achieve coolant exit temperatures considerably higher than the maximum interface temperature.



C) Arrangement of neutron multiplier in the FW cooling channels

The most efficient location for the neutron multiplier is directly behind the FW. The volumetric heat generation, however, has a maximum there, making sufficient cooling a difficult task.

For these two reasons, the tubes containing the multiplier material (liquid Pb or Be pebble beds) are arranged in the FW cooling channels and are surrounded by the FW coolant, flowing with high velocity in channels with relatively small hydraulic diameter (large heat transfer coefficient!).



D) Use of lead as neutron multiplier

From a neutronics point of view, beryllium is the best neutron multiplier, characterized by a low energy threshold for (n,2n) reactions and a small neutron absorption. However, the neutron damages in Be (i.e. 55,000 appm He at a fluence of 15 MWa/m²!) may limit the lifetime of a blanket and result in large tritium inventory (some kg's) in “traps” generated by the neutrons in Be.

In a FliBe blanket a relatively thin multiplier layer behind the first wall is sufficient for achieving tritium self sufficiency. Scoping calculations performed by Mohamed Sawan indicated that either 2.5 cm of solid beryllium or 4 cm of lead are required.

For these reason lead is selected as multiplier material for the proposed blanket concept.

The beryllium required for chemical reasons (fluor control) can be located outside the neutron environment.

Boundary conditions and assumed material limits

Geometry :

- Blanket outer dimensions taken from ARIES-RS
- Cross section of an outboard first zone element
~0.3m*0.3m
- Height of outboard blanket 6.7m

Outboard wall loads :

- Average neutron wall load 5.0 MW/m²
- Maximum neutron wall load 7.5 MW/m²
- Average surface heat flux 0.67 MW/m²
- Maximum surface heat flux 1.0 MW/m²

Temperature limits :

- Minimum FLiBe temperature 500° C
- Maximum FLiBe/steel interface temp. 700° C
- Maximum steel temperature 800° C

Main Results for the reference case :

Reference case : $P_{\text{neutron,max}} = 7.5 \text{ MW/m}^2$

$P_{\text{surface, max}} = 1.0 \text{ MW/m}^2$

$T_{\text{FLiBe, minimum}} = 500^\circ \text{ C}$

$T_{\text{FLiBe, exit}} = 700^\circ \text{ C}$

Main Results :

- Coolant temperature at blanket inlet 580° C
- Coolant temperature at FW midplane 590° C
- Coolant temperature at blanket top 600° C
- Coolant temperature at bypass exit 605° C
- Coolant temperature at blanket exit 700° C

- Velocity at FW (midplane) 5 m/s
- Heat transfer coeff. at FW(midplane) $10,200 \text{ W/(m}^2\text{*K)}$
- Heat transfer coeff. at central duct (midplane) $665 \text{ W/(m}^2\text{*K)}$
- Maximum interface temperature
 - a) (FLiBe/steel) 700° C
 - b) (steel/multiplier) 700° C
- Maximum structure temperature 800° C

- Maximum pressure drop in FW channels 0.5 MPa
- Maximum pressure in central duct $< 0.2 \text{ MPa}$

- Pumping power for 1 outboard element 40 kW
(0.35% of thermal power)

Preliminary Nuclear Parameters

- Several iterations were performed to get reasonable TBR
- Radial build of front FS/Pb/FLiBe FW/blanket at midplane

Zone	inner radius (mm)	outer radius (mm)	thickness (mm)	volume composition
First wall	0	3	3	100% steel
FW cooling channel	3	10	7	6% steel, 94% FLiBe
Multiplier zone	10	53	43	17% steel, 13% FLiBe 70% lead
sec wall cooling channel	93	57	4	6% steel, 94% FLiBe
second wall	97	63	6	100% steel
central channel region	103	316	253	6% steel, 94 % FLiBe
back wall cooling	316	342	26	22% steel, 78% FLiBe
back wall	342	350	8	100% steel

- A 45 cm thick secondary blanket (6% FS, 94% Flibe) is used in the OB region behind the 35 cm front blanket
- Natural Li used in Flibe
- Thickness of Pb zone was varied keeping the total blanket thickness constant by changing the thickness of the central channel zone

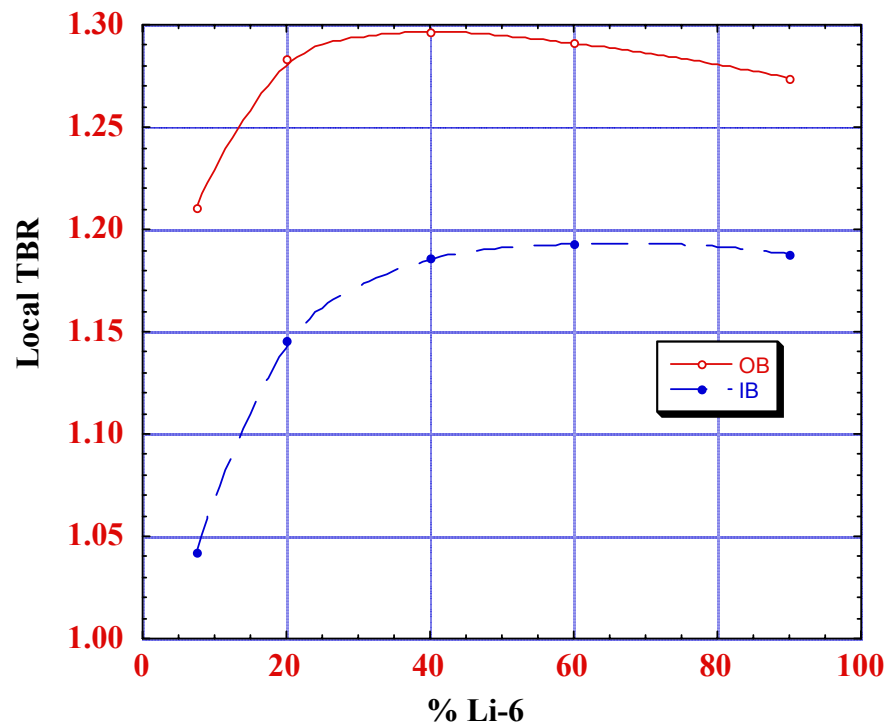
Pb Zone Thickness (mm)	Local OB TBR
3	1.130
13	1.162
23	1.181
43	1.211
63	1.226
83	1.230

- TBR is not sensitive to Pb zone thickness due to large (n,2n) threshold energy in Pb making adding Pb in back not very effective
- We considered the case with Pb zone thickness of 43 mm
- Local OB TBR 1.211 (1.042 in front blanket, 0.169 in secondary blanket). Local IB TBR 1.04. TBR can be increased by up to 10% if we enrich Li in Li-6. Cost trade-off?

- **Local OB energy multiplication 1.174 (1.070 in front blanket and 0.104 in secondary blanket)**
- **Results normalized for 5 MW/m² neutron wall loading. Heating and damage parameters scale linearly with wall loading**
- **Peak dpa and He production rates in FW are 61 dpa/FPY and 688 He appm/FPY**
- **Peak dpa and He rates at front of secondary blanket are 2 dpa/FPY and 13.3 He appm/FPY implying it can be lifetime component**

Nuclear Heating (W/cm³) in different components for 5 MW/m² neutron wall loading

	FW 3 mm 100% steel	FW cooling channel 7 mm 6% steel, 94% FLiBe	Multiplier zone 43 mm 17% steel, 13% FLiBe, 70% lead	sec wall cooling channel 4 mm 6% steel, 94% FLiBe	second wall 6 mm 100% steel	central channel region 253 mm 6% steel, 94 % FLiBe	back wall cooling 26 mm 22% steel, 78% FLiBe	back wall 8 mm 100% steel
Peak FS	34.5	33.0	23.3	20.5	21.5	24.0	5.1	3.9
Ave. FS	34.5	33.0	20.8	20.5	21.5	14.3	4.8	3.9
Peak Flibe	-	40.9	37.0	26.4	-	23.2	4.8	-
Ave. Flibe	-	40.9	31.3	26.4	-	12.6	4.5	-
Peak Pb	-	-	33.0	-	-	-	-	-
Ave. Pb	-	-	29.4	-	-	-	-	-



- We might not need enrichment
- At 40% Li-6 Local TBR is 1.297 OB and 1.193 IB

Extrapolation to different power loads :

A. Maximum neutron wall load.

Neutron wall load is mainly limited by the allowable interface temperature between structural material and multiplier.

In the reference case (7.5 MW/m² max. neutron wall load) a value of 700 C is reached.

Higher wall loads would require smaller (in toroidal direct.) multiplier tubes or higher allowable interface temperatures.

B. Maximum surface heat flux

With a heat flux of 1 MW/m² both temperature limits given are reached (FLiBe/steel < 700° C, steel < 800° C) for a FLiBe exit temperature of 700° C.

Lower heat fluxes would allow to increase the coolant exit temperature (by keeping the temperature limits of the materials) to the following values :

$q''_{\max}$	(MW/m ²)	1	0.5	0.3	0
T_{bulk} (FW exit)	(°C)	600	650	670	700
T_{exit} (blanket)	(°C)	700	800	840	900

Remark : These limits should be considered as rough estimates only. Higher allowable interface temperatures, larger heat transfer in the FW cooling channels, and a higher power fraction to the central channel would allow an increase of exit temperatures.

Conclusions and outlook :

A) Key features of the proposed blanket concept are :

- Structure cooled by the “cold” inlet flow, maximizing in this way the coolant exit temperature,
- flow rate in the FW/multiplier coolant channels considerably higher than the flow rate to the power conversion system, increasing in this way the heat transfer without excessive high pressure drop,
- use of lead as neutron multiplier.

B) All the numbers given in this memo should be considered as first estimates only, to be substantiated by detailed analyses. For the thermal-hydraulic calculations the real geometries of blanket elements (trapeze-shape, smaller cross-sections outside the midplane) should be taken into account.

C) From the material community more informations in regard to allowable temperatures and stresses, and the compatibility between steel and FLiBe as well as with lead are required. The dimensions shown in the figure are based on allowable primary stresses of ~ 100 MPa. In view of the difficulties involved in welding of advanced ferrits, an attempt has been made to avoid fusion welds in highly stressed zones. Nevertheless, the conceptual design characterized by the use of relatively thin walled tubes and sheets has to be look at by material and fabrication specialist.