HIGH INTENSITY SLAG RESISTANCE FURNACE DESIGN

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ABSTRACT

Intensity of electric slag melting/reduction furnaces has progressed in generations from roughly 100 kW/m^2 hearth area in the 1960's, up to 300-400 kW/m^2 today, through a series of technological advances. Using FeNi smelting furnaces as an example they have developed from:

1. immersed electrodes (~100 kW/m^2), to
2. brush arc (~200 kW/m^2), and
3. shielded arc (~300-400 kW/m^2), often involving extensive use of copper coolers and complex mechanical tensioning devices to maintain good copper to refractory contact.

Development work is taking place at Elkem on 4th generation high intensity resistance designs (500-1000 kW/m^2), incorporating nearly 100% copper bodies, pressure vessel standards, unique electrode and cooling system designs. Furnaces up to 1.5 MW have been constructed and pilot furnaces up to 10 MW are now being designed.

INTRODUCTION

The desire for higher productivity, minimum capital cost, and improved thermal efficiency has over time, lead to increasingly larger and intensive furnace designs.

Within the FeNi industry there has been a transition from immersed electrodes, to brush arc and hence to shielded arc, with steadily increasing energy intensity. With these developments, has come the change from the original high thermal conductivity brick often with shell film cooling, to the use of imbedded copper fingers, plates, waffles or other advanced coolers designed to produce furnace freeze linings. This has allowed for further increases in smelting intensity without excessive risk of furnace vessel failure. Equipment of this type is available from a number of designers: Bateman, Hatch, Luvata, MacRae Technologies, TENOVA PYROMET, SMS Demag and producers: Falcon Foundry, KME, Thos Begbie, etc. [1-9].

With the integration of copper structures into what was originally a refractory lined steel shell, the need for tensioning devices of various types has become apparent. With improved tensioning comes less penetration of the refractory joints by liquids, improved cooler to refractory contact, better cooling efficiency, and the possibility for further increases in energy intensity [10].

These developments in FeNi furnaces can be characterised as typical of the first 3 generations of slag furnaces and roughly sorted by energy intensity as show in Table 1.

Table 1 – Energy intensity of slag resistance furnaces by generation

Furnace Generation	Energy Intensity [11] (kW/m^2 of hearth area)	Typical Characteristics
1	~100	Immersed electrodes, shell film cooling
2	~200	Brush arc and plate or waffle coolers
3	300-400	Shielded arc with finger, plate or waffle coolers
4 (under development)	500-1000	Immersed electrodes used to date See Table 3 for details.

ELKEM MULTI-PURPOSE FURNACE® (EMPF), 3rd GENERATION SLAG FURNACE DESIGN

Elkem started the development of the Elkem Multi-Purpose Furnace® in the early 1980's. These furnaces used an immersed electrode configuration, i.e. using only bath power or true slag resistance heating. Elkem is fully aware of the use and benefits of arc power (shielded arc) as patented in 1973 with respect to FeNi smelting [12] and it is generally assumed that additional power can be added to the EMPF with arc power as required.

In addition to a number of large laboratory scale furnaces, three pilot installations were built and operated on different raw materials both for meltdown (slag production) and reduction (metal production). These furnaces had inner diameters 1.5, 1.7 and 2.0 meters. During the same period six commercial installations were built, between 1.8 and 10 MVA [13].

The largest pilot furnace (2 m) was installed at Mefos in Luleå, Sweden with an available 5 MVA transformer. Test campaigns were run with furnace loads up to 4.8 MW and Elkem has defined, based on these tests, that the main criteria for dimensioning of slag resistance furnaces was not related to hearth load, but to the slag volume, e.g. kW of bath power/m^3 of slag bath or reaction zone, as shown in Table 2.

Table 2 – Energy intensity of Elkem Multi-Purpose Furnace®’s

Intensity	Reaction or Slag Zone (kW of bath power/m^3)
Normal	100 – 400
High	500 – 1500
Ultra High	1500 – 5000

EMPF Potentials
- Optimized Process Conditions
- Increased Operational Control
- Increased Thermal Efficiency
- Reduced Infrastructure Cost
- Allow New Process Routes
- Increased Productivity
- Reduced Operational Cost

Elkem Multi-Purpose Furnace®’s are characterised by advanced electrode seal designs, gas tight bodies and roofs, fully cooled slag zones using plate coolers (normally of steel design) to generate a freeze lining. Energy intensities are typically from 300-400 kW/m^2 of hearth area or approximately 300-1000 kW/m^3 of slag volume, thus making these 3rd generation furnaces of high intensity. See Figures 1a, b and c for more details [14].

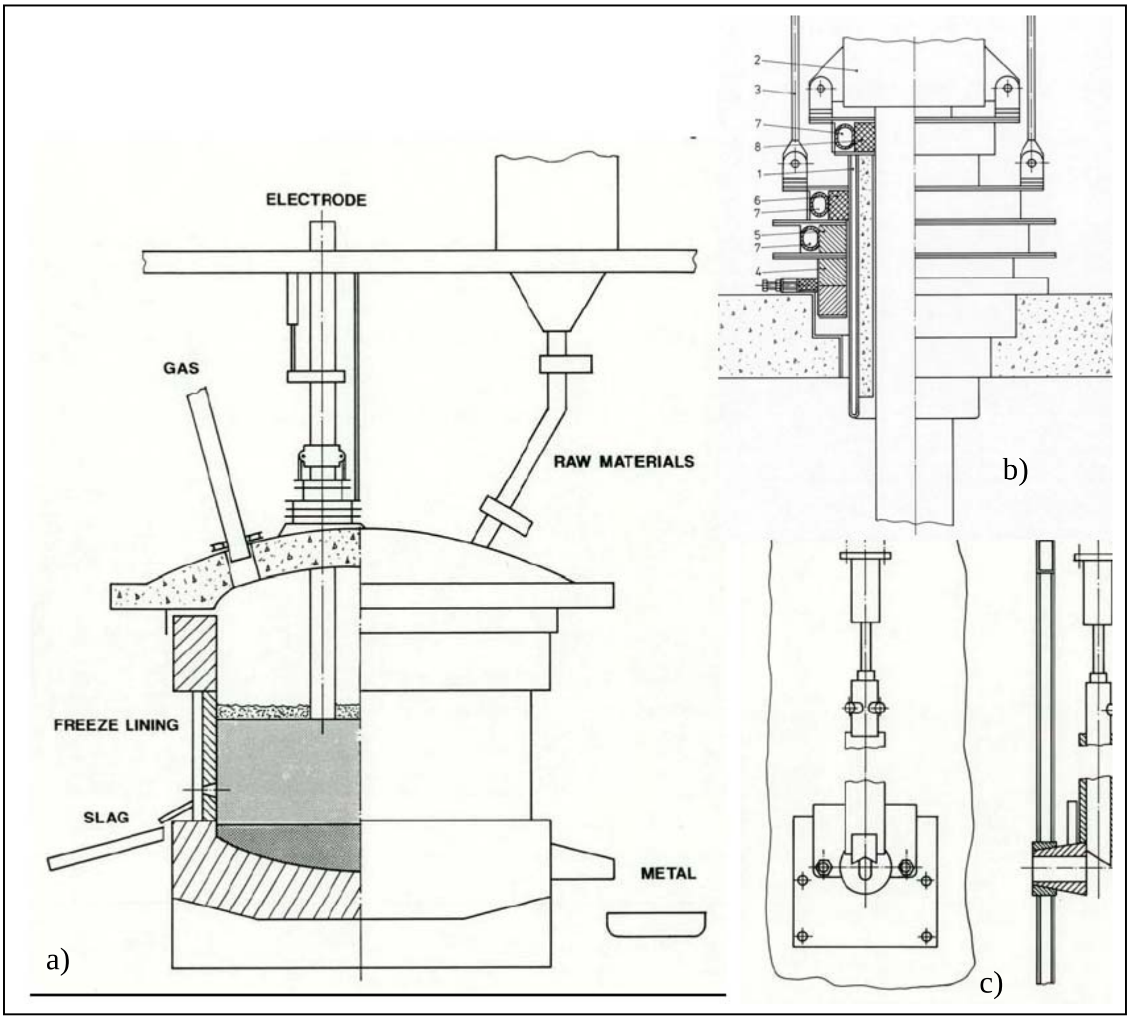

Figure 1 – Overview of some furnace details. a) Elkem Multi-Purpose Furnace®,
b) electrode seal, and c) slag flow controller [14]

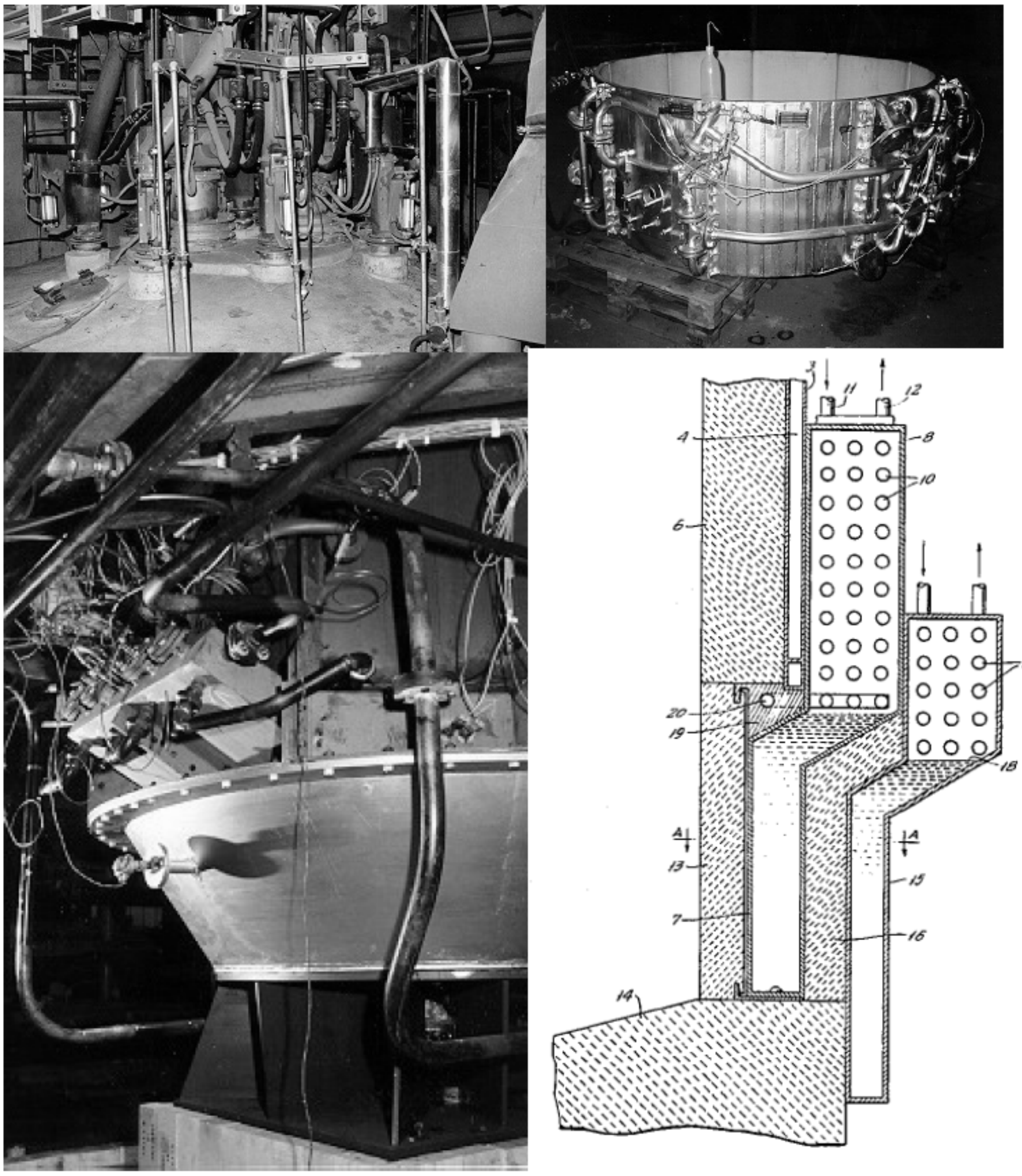

Figure 2 – Elkem Multi-Purpose Furnace®’s, showing: gas tight roof, cooled steel bath line, furnace shell with metal zone evaporative cooling, and schematic of sidewall evaporative coolers [15]

FOURTH GENERATION FURNACE DESIGNS

From the late 1990's, a new generation of Elkem Multi-Purpose Furnace®'s have been under development based on cooled copper panels. These units were operated on a regular basis during the last eight years, with smelting intensities up to 4 MW/m^3 and can be described as 4th Generation Slag Resistance Furnaces.

Table 3 – Primary characteristics of 4th generation slag resistance furnaces

Characteristic	Typical Values
Energy intensity	High Intensity, with bath power only used to date 500-1000 kW/m^2 or up to 1500 kW/m^3 of slag
Vessel integrity	Fully cooled slag zone, additional cooled structures wherever required to maintain integrity (e.g. metal zone, tapholes, etc.)
Electrodes	Number, type and location to match duty, often ultra-high power graphite
Pressure class	As required to match duty, either positive or negative pressure
Design tolerances	Microns not millimetres

Furnaces up to 1.5 MW have been operated and pilot furnaces from 5-10 MW are now being designed at Elkem. In 2008, an 18 MVA demonstration furnace for waste treatment was started, smelting spent aluminium pot lining [16], incorporating the bath energy intensity and cooled structures of a 4th generation design.

High energy intensity

What determines the "correct" energy intensity for a process? In the distant past this was primarily determined by the requirement to generate a freeze lining with high conductivity brick and water film cooling (~20 kW/m^2 maximum sidewall heat flux limit in practice [14]). This placed severe restrictions on the furnace designer in terms of energy intensity. Too much energy input and the slag arriving at the wall had excessive superheat, the freeze lining was lost and the refractory lining melted back. Too thin an equilibrium refractory lining thickness can lead to uncontrolled burn-outs or the whole wall structure can collapse under its own weight.

The use of cooled structures freed the designer from the need of limiting sidewall heat fluxes, as long as the coolers were within design limits. "Burn out heat fluxes" have increased with modern cooler designs, resulting in a large degree of freedom with regards to process intensity [17]. This allows one to search for the "optimum" energy density, where the process operates with the highest economic effectiveness (considering campaign length, rebuild cost, thermal efficiency, etc.).

In order to determine the correct intensity we now have a number of tools, which were not available to previous generations of metallurgists, i.e. finite element modeling (FEM) [18-20] and computational fluid dynamics (CFD) [21-23]. These tools should be utilized not only to explore the impact of energy intensity, but to examine the effect of furnace shape, electrode design, and to optimize furnace operating conditions.

Theoretical modeling is also used to verify the integrity of the furnace (thermally and structurally), when judged against actual plant data obtained from the various on-line monitoring systems. For example, temperature measurements compared with modeling results, can help to estimate remaining lining thicknesses and residual lifetime before maintenance/rebuilding must take place. Alarms can also be set based on modeling and designed to avoid specific physical limits (nucleate boiling, film boiling, copper melting, etc.).

Research has taken place that better allows boundary conditions to be estimated (e.g. heat fluxes, heat transfer coefficients, etc.) and validated models to be built [24-26]. Figure 3 and 4 show examples of furnace modeling conducted by Elkem.

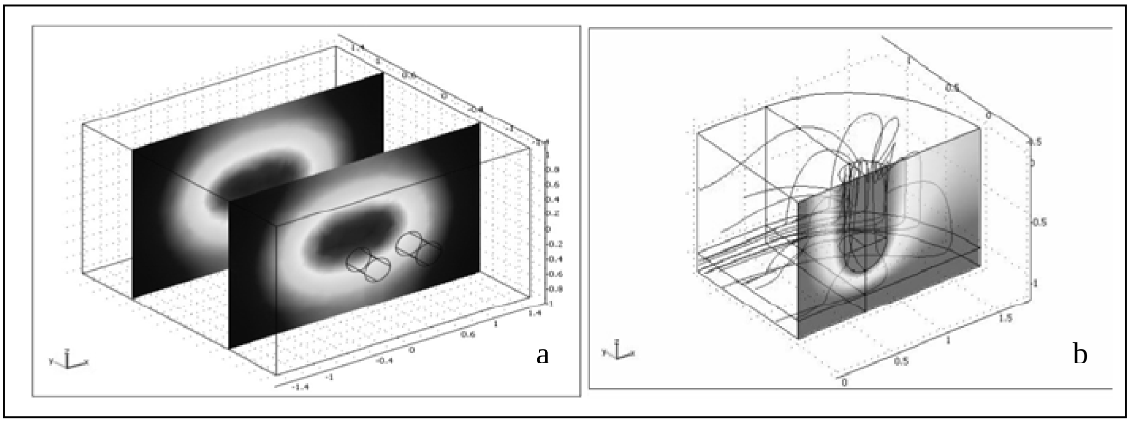

Figure 3 a and b – COMSOL® FEM modeling of current density, and current stream lines/electrical potentials [27]

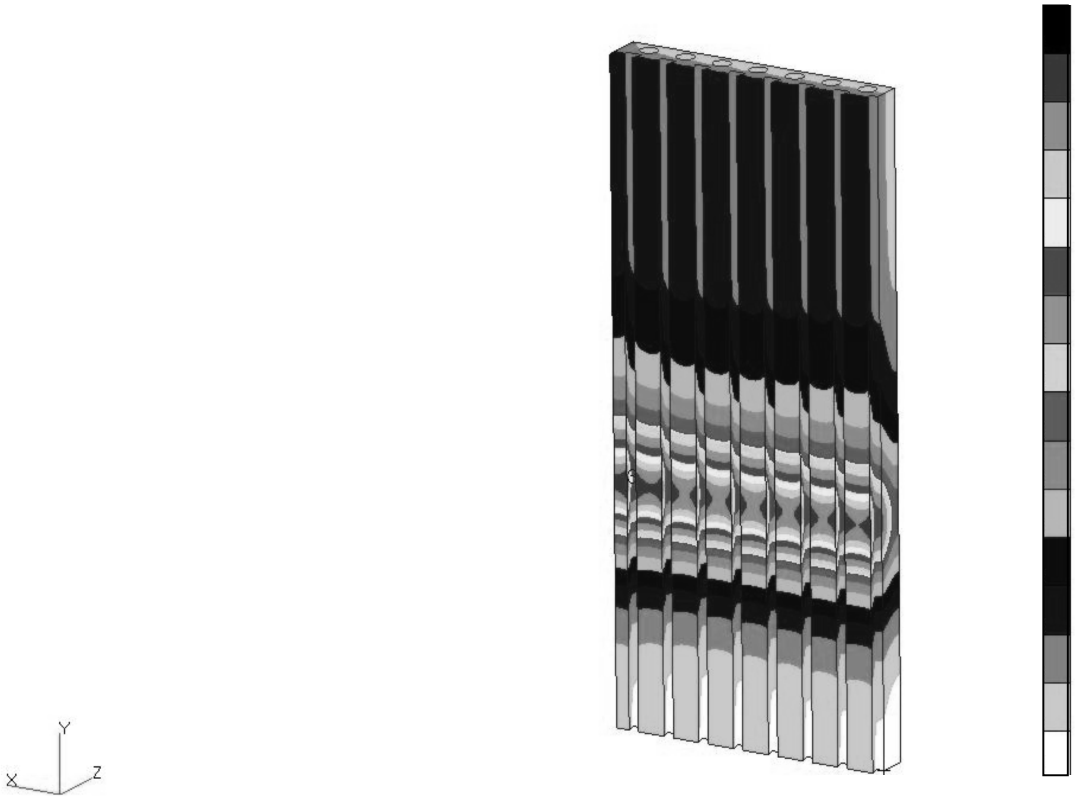

Figure 4 – Example of calculated temperatures in copper sidewall of a reactor. The sidewall is exposed to three different thermal boundaries: metal layer, slag layer and headspace

Novel furnace designs

With the use of cooled copper and steel structures, the furnace designer can explore novel designs, where the shape of the furnace is adjusted to the needs of the process. Walls need not be vertical or flat. Furnaces can now be square, rectangular, cylindrical, spherical, or conical as the designer sees fit.

Location, size, number, and depth of electrode penetration can be manipulated and the impact on heat distribution and thermal efficiency explored.

With the use of cooled structures, dimensional stability can be obtained and the designer is no longer subject to such severe constraints on joints and gaskets. Pressure tight seals can be designed and the furnace can be made to operate at elevated pressure, if suitable designs for electrode seals are implemented.

Temperature measurements and coolant flows can be monitored for individual furnace components to estimate local heat flux variations and can be integrated into an overall furnace integrity system [28-30]. Such monitoring can provide added information about the process and condition of the furnace, which increases both safety and the lifetime of the various components.

These new degree's of freedom have allowed Elkem to change its way of thinking with regards to furnace design. An evolution has taken place, moving from furnace mentality (e.g. +/- 10 mm water pressure or +/- 1 mm of clearance), to reactor mentality (e.g. design pressure of 0.X bar and +/- Y microns clearance). Customised furnace designs are now created based primarily on the requirements of the process and not on the traditional view of what a furnace "must" look like. New geometries for both furnace bodies and electrode systems have been tested.

New materials and designs for improving furnace efficiency and reliability are constantly being tested. This pertains to both thermal insulation and load bearing components.

Process control algorithms and measurement systems (especially high-temperature systems) are continuously being refined and tested. A high-temperature camera has recently been installed in one reactor to be able to observe the process; however, many challenges regarding high-temperature measurements still remain to be solved.

4th Generation FeNi furnace design

One can speculate as to what a 4th Generation FeNi furnace design might entail. It might entail the use of 300-400 kW/m^2 of bath power and increased total energy intensity greater than 500 kW/m^2. The increased intensity would lead to a relatively small hearth area, for a given total furnace power. The largest fraction of arc power would be used and this implies relatively long arcs. To maintain stable long arcs, it will be more common for semi-covered bath operation to be the norm. The opening in the bath cover will allow the safe release of the larger volumes of reduction gases.

Most of the process energy requirement in a FeNi furnace is related to heating and melting of the charge. Slag superheat will therefore be minimised by maximising the slag-charge interfacial area, resulting in less heat transfer to the side walls. Therefore the 4th generation furnace might have sloping walls blending directly into the hearth, without the need for traditional skew bricks. Mechanical tensioning systems would be integrated into the sloping side walls to tension the hearth and prevent metal penetration and ratcheting.

Furnace charge would probably be distributed to make sure that there are good charge banks built up on the sloping walls, thus greatly reducing the chance of hot slag coming directly into contact with the copper panels, and further improving thermal efficiency.

Thus it can be imagined that a smaller, simpler and more efficient design could be accomplished by increasing intensity and no longer thinking in "straight lines".

CONCLUSION

The use of cooled structures and advanced numerical methods, now make it possible for designers to study the requirements of individual processes and tailor make the vessel for optimum performance.

Other than materials of construction, the primary limiting factor today in electric slag resistance reactor design, is the imagination of the designer. See Figure 5 for an example of an advanced conceptual design.

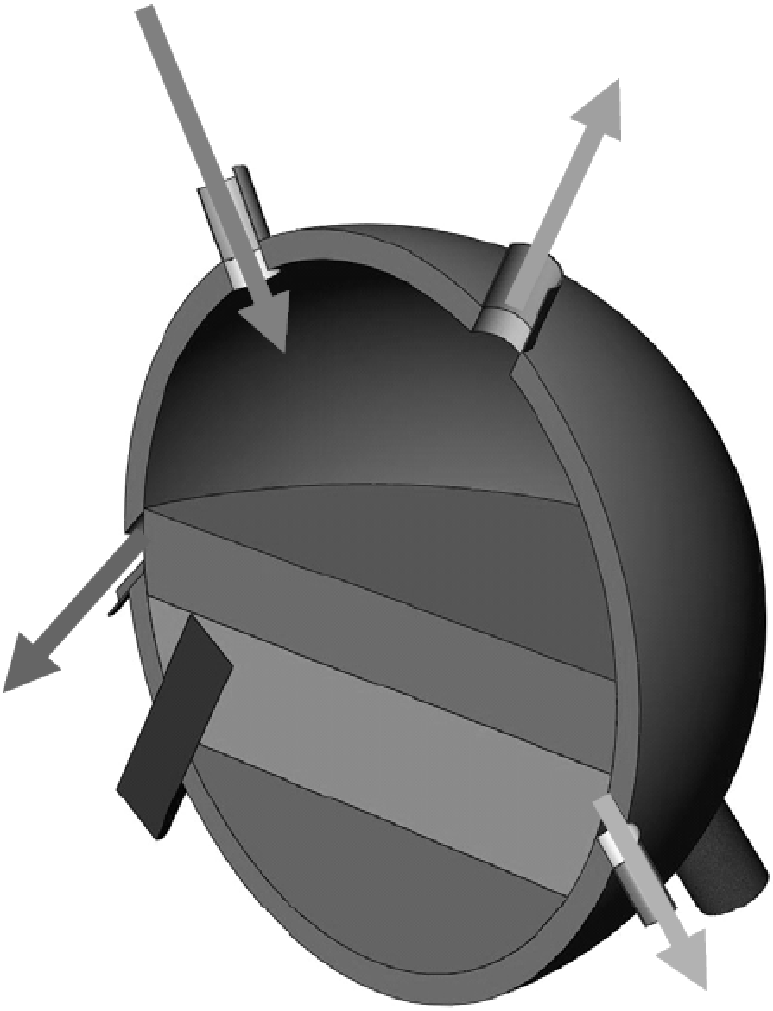

Figure 5 – Conceptual 4th generation slag resistance reactor,
with minimum possible surface to volume ratio,
for a system with floating metal [31]

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