PLASMA – Value Add for Metallurgical Refining in VID-Processes

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The VIM/VIDP process is widely used for melting high-value charge materials, refining and alloying under vacuum or protective atmosphere, and finally for casting under defined environmental conditions. The equipment is suitable and dedicated for manufacturing high-end grades, especially in the aerospace industry. Besides these well-defined and specified alloy manufacturing routes, where the VIM/VIDP process acts as the starting point of triple melting, there is a field of potential use of vacuum melting for grades with medium quality requirements. For this market segment, ALD's preferred technical approach is the VID as the primary melting and refining tool. While refining and alloying in VID is done under the same conditions as in the VIM/VIDP process, the ingot casting itself is performed under inert-gas shrouding. Due to the easy furnace-body accessibility, even liquid charging is possible. In these production routes, the VID is well integrated and is a valuable tool for fine-trimming quality requirements. However, this solution experiences some metallurgical restrictions – for example, managing slag is difficult. In this paper it will be shown how plasma processes accelerate the kinetics of gas/melt interface reactions, and how the integration of thermal plasma sources opens the field of opportunities for performing additional metallurgical refining treatments in VID. By this means, refining steps usually performed prior to or after the VID process could be integrated directly into the VID, allowing for higher quality or for reducing the number of additional melting and refining processes. Furthermore, due to the nature of thermal plasma processes, in-situ gas alloying (e.g. nitrogenization) becomes very effective. With additional features, even direct iron ore reduction by hydrogen could be performed in this equipment, combining the best of both worlds – the global melt-bath movement by electromagnetic forces from induction, and the enhanced interface activation by plasma.

KEYWORDS: VACUUM INDUCTION MELTING, VID, PLASMA, NITROGEN, DEGASSING, SLAG

INTRODUCTION:

Vacuum induction melting (VIM) is the workhorse process for melting reactive and high-value alloys – nickel- and cobalt-base superalloys, specialty and tool steels – under vacuum or a controlled inert atmosphere. Melting under vacuum removes dissolved hydrogen and, to a controllable extent, nitrogen, strips volatile trace elements, and allows tight compositional control that cannot be achieved in air melting [1,2].

Two closely related equipment families build on this base process. In the first, a VIM crucible furnace melts and refines the heat, which is then cast into electrodes or ingots for downstream remelting by Electroslag Remelting (ESR) or Vacuum Arc Remelting (VAR). This VIM–ESR/VAR (or VIM–ESR–VAR) "triple-melt" route is the qualified production path for rotating and other critical aerospace components, where each remelting step further improves segregation control and inclusion cleanliness [3]. In the second family, Vacuum Induction Degassing (VID) furnaces integrate melting, alloying and refining in a single, compact vessel a cost-effective alternative to a separate LF/VD line, and available at capacities from about 1 to 30 metric tons [1].

Beside the well-defined, tightly specified triple-melt routes for premium aerospace grades, there is a broad market segment of alloys with medium quality requirements – tool steels, high-speed steels, heat-resistant austenitic/martensitic grades and general-purpose Ni/Co-base alloys – for which a full triple-melt pedigree is not economically justified. For this segment, ALD's preferred technical approach is to use the VID furnace itself

as the primary melting and refining tool. In this production route, refining and alloying inside the VID furnace are carried out under essentially the same vacuum/protective-atmosphere conditions as in a VIM/VIDP furnace; only the final ingot casting step is performed under inert-gas shrouding rather than under high vacuum – a compromise that retains most of the metallurgical benefit of vacuum processing while reducing capital cost and cycle time relative to a separate degassing/casting line [1].

Because the furnace body is easily accessible, even liquid charging is possible, in addition to the usual solid charge. This flexibility, combined with the option of oxygen lancing for enhanced carbon removal in the "VID Oxy" variant, makes the VID a well-integrated and valuable tool for fine-trimming quality requirements at the end of a heat [1]. However, because heat is generated by electromagnetic induction into the liquid metal itself, this solution experiences characteristic metallurgical restrictions, most notably that managing slag – its temperature, fluidity and reactivity – is difficult.

Metallurgical Limitations of Induction Heating

Induction heating works by coupling an alternating electromagnetic field to a conductive load; eddy currents are induced within the skin depth of the liquid metal, and the resulting Lorentz forces simultaneously heat and stir the melt. The slag layer floating on the melt is a poor electrical conductor and therefore couples only weakly, if at all, to the induction field – it can only be heated indirectly, by conduction and radiation from the metal beneath it. As a consequence, the slag tends to run colder and more viscous than a metallurgically optimal slag, which limits its ability to participate in reactions that require a hot, fluid, chemically reactive slag – desulfurization, deoxidation, and inclusion absorption among them.

A second, related restriction concerns the kinetics of gas/melt interface reactions – decarburization (via [C] + [O] → CO↑ under vacuum), denitrogenization and dehydrogenation. These reactions proceed at the free surface of the melt, and their overall rate is generally governed by mass transfer of the reacting species through a boundary layer at that interface rather than by the intrinsic chemical step, a picture consistent with kinetic studies of nitrogen removal from superalloy melts during vacuum induction melting [4]. Electromagnetic (Lorentz-force-driven) bath stirring renews the bulk melt and thins this boundary layer on the scale of the whole bath, but it does not add energy or chemical reactivity at the interface itself.

Here denitrogenization deserves closer attention because it illustrates the interface bottleneck in its most stubborn form. Nitrogen leaves the melt via

$$2\,[N]_{Fe} \;\rightarrow\; (N_2) \qquad (1)$$

a combinative desorption step: two nitrogen atoms already adsorbed on the surface must meet and react at the same surface site before the resulting N_2 molecule can leave. The overall rate is therefore never purely a transport problem; it is a mixture of (i) diffusion of dissolved nitrogen from the bulk melt to the surface region and (ii) this interfacial recombination step, and which of the two dominates depends on melt cleanliness and stirring intensity [4].

Thermal Plasma as an Independent, Interface-Localized Source of Heat and Reactivity

A thermal (DC, transferred-arc) plasma torch strikes an arc between a torch cathode and the melt itself, sustained in argon or a reactive working-gas mixture. Arc-core temperatures for such torches are on the order of 10^4 K – an order-of-magnitude figure, since the exact value depends on torch design, current, gas composition and pressure – which is far above typical melt-surface temperatures of roughly 1 700–1 900 K for steels and nickel-base alloys. This gives the torch two properties that induction heating structurally cannot provide: the heat flux can be aimed at a chosen spot – including the slag cover – independently of that phase's electrical conductivity, and it arrives already carrying chemical activity rather than only thermal energy.
The chemical activity comes from gas-phase dissociation and ionization in the arc column: passing N_2, H_2 or an O_2-bearing mixture through the plasma dissociates a significant, and at sufficiently high arc temperature

essentially complete, fraction of the diatomic molecules before they reach the melt surface. The species arriving at the interface are then atomic or ionic radicals rather than the stable diatomic gas. This combination – concentrated, independently directable heat plus a chemically activated reactive species – is why thermal plasma is reported in the metallurgical literature as offering “high thermal performance, concentrated energy, significant chemical activity and controllable reaction atmospheres,” with established industrial use for melting, refining and tundish heating [5]. Because the rate-limiting adsorption/dissociation step is effectively bypassed, the interface reaction is no longer throttled the same way it is at a comparatively cold, induction-only surface; the plasma jet’s own impingement additionally intensifies local surface renewal, on top of the global stirring already provided by induction.

EXPERIMENTAL SETUP:

To test how effectively plasma treatment accelerates metallurgical interface reactions, several test heats were carried out at ALD’s in-house plasma test bench. The average batch size in these runs was about 150 kg, and the same hot-cathode plasma torch was used for all tests. All runs were performed at 1030 mbar.

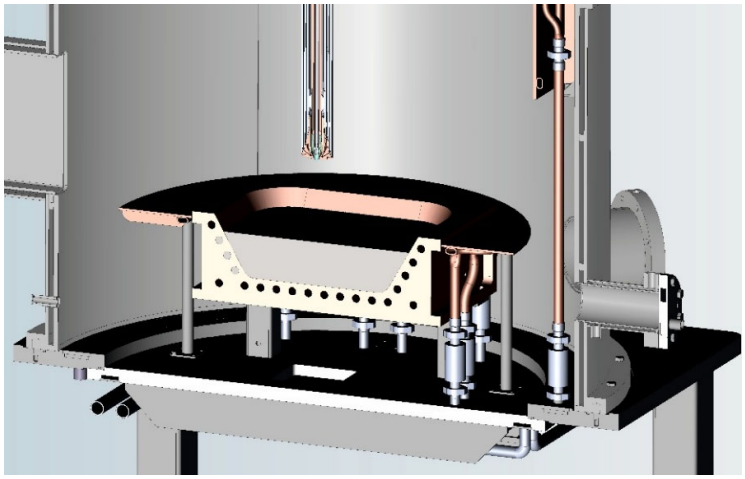

Figure 1 – Plasma Furnace

In a first step, pure ARMCO iron was used as charge material, including small additions of silicon and aluminum for deoxidation; later test runs used iron alloyed with chromium instead. The charge material was melted down in a water-cooled copper crucible under argon atmosphere, after which either nitrogen (Dia 1) was applied as plasma gas for runs where pick-up rates were to be determined, or the argon treatment was continued for de-nitrogenization tests. It is worth mentioning that pure lime was also used as a slag cover during the degassing test runs, and that the slag was found to be completely molten.

From each test ingot a middle section was sliced out of the resulting ingot and samples were taken along the height for analysis (Figure 2).

Sample Preparation

- A center slice was cut out from each ingot.
- One column per ingot was subdivided into 6–8 sub-samples.
- All samples were analyzed by REVIERLABOR (Essen, Germany).
- Nitrogen and oxygen were determined by hot-gas extraction, per ASTM E1019 (2024-08).
- Sulphur and carbon were determined by combustion analysis, per ASTM E1019 (2024-08).
- All other elements were determined by X-ray fluorescence (XRF).

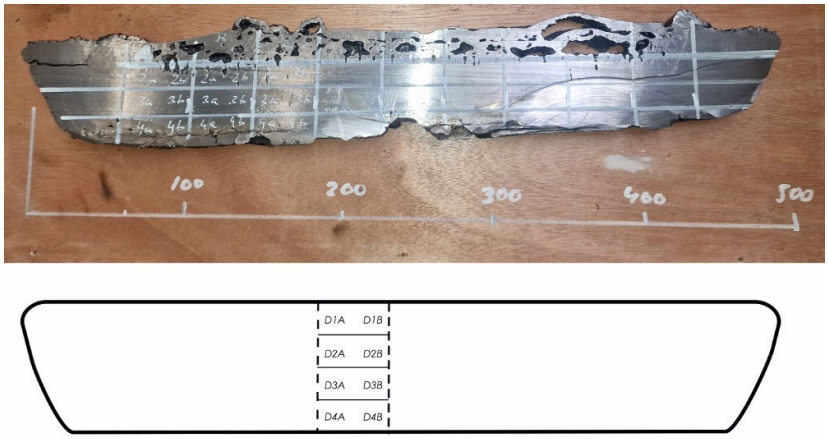

Figure 2 – Sampling

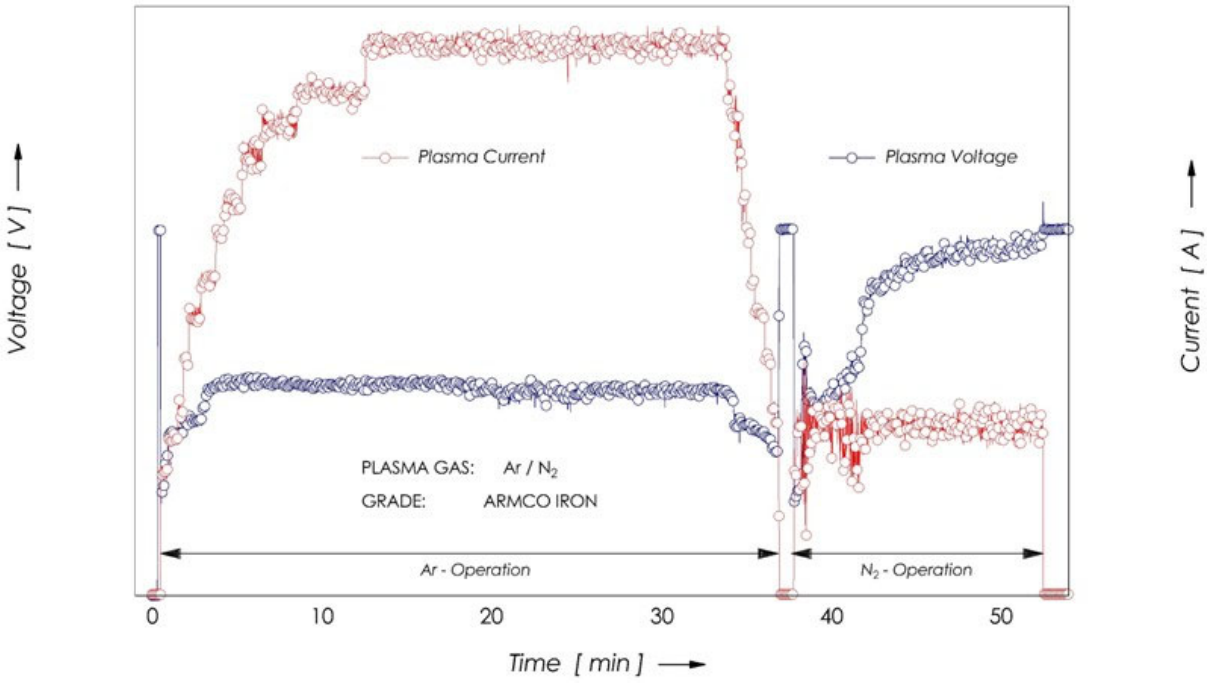

Diagram 1 – Nitrogenization run

RESULTS:

As a typical example, analysis results for nitrogenization runs at different nitrogen treatment times are shown in Diagram 2. Interestingly, nitrogen content over ingot height for 10 min of nitrogen-plasma treatment is very close to that for 80 min. Furthermore, in both runs nitrogen saturation was achieved at the liquid/gas interface, indicating a very fast interface reaction. This conclusion about saturation at the melt/gas interface is also supported by the observation of constant formation of gas bubbles at the melt surface once a critical run time was reached.

The transition from argon to nitrogen operation is also visible in the plasma's electrical characteristics (Dia 1): once nitrogen is introduced, plasma voltage rises to a distinctly higher plateau than during argon-only

operation, consistent with the additional energy required to dissociate the diatomic N_2 molecule in the arc column, as discussed in the Thermal Plasma section.

Quantitatively, nitrogen content within about 10 mm of the melt/gas interface reaches roughly 310–320 ppm mass for both treatment times – close to the plotted solubility limit of nitrogen in liquid iron at 1600 °C, 1 atm N_2 shown in Diagram 2. Content then falls off with depth, reaching the background level of the charge material (roughly 30–40 ppm) by about 50–70 mm – again essentially independent of whether the plasma was applied for 10 min or 80 min.

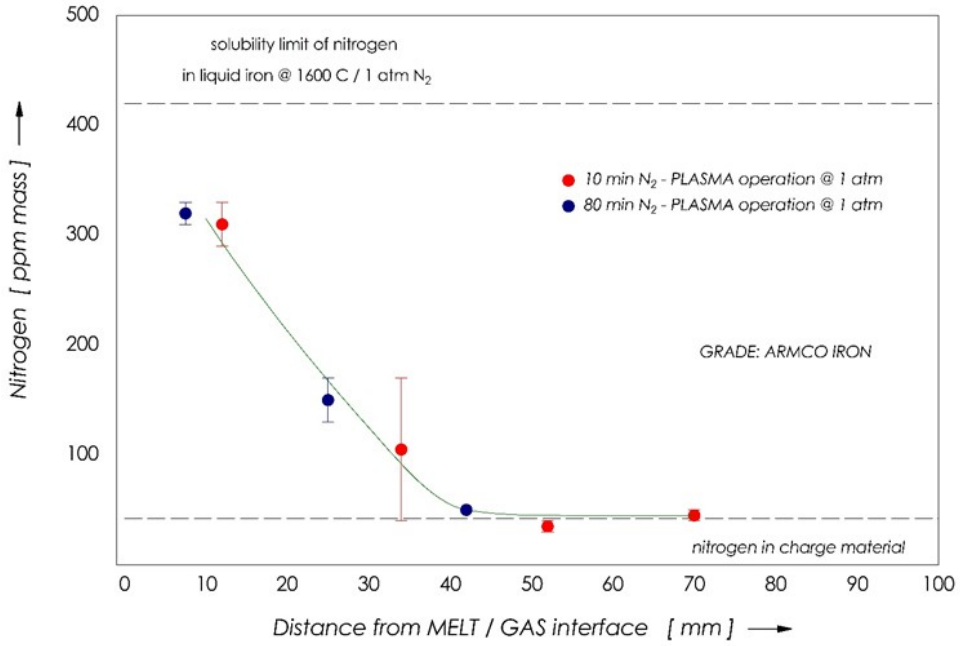

Diagram 2 – Nitrogen profile in pure ARMCO-iron

The observed decrease in nitrogen concentration over ingot height was rather surprising and may be related to temperature-dependent solubility or to limited mixing in the bulk liquid. This points to a pronounced top-to-bottom concentration gradient that persists throughout the whole run. The liquid pool depth can also be drawn from these curves: with a total ingot height of about 70–80 mm for both runs, a melt pool depth of 40–50 mm is clearly visible. In a second series of experiments, similar procedures were applied to an iron-chromium alloy (18 wt.% Cr). As chromium increases the solubility limit of nitrogen in iron, significantly higher nitrogen contents were achieved (Dia. 3). With nitrogen concentrations up to 2000 ppm wt. and much better nitrogen uniformity over ingot height, both faster in-situ alloying and better mixing in the melt pool can be claimed for this type of alloy. Subsequently, that iron-chromium ingot was used for determination of degassing rates under argon plasma. The ingot was re-melted and held under argon for 60 min. The resulting nitrogen content is shown in Diagram 3. The near-interface nitrogen content reached in Melt 3 (roughly 2000 ppm) is about six times higher than in the pure-iron runs (roughly 320 ppm), consistent with the well-established positive effect of chromium on nitrogen solubility in liquid Fe–Cr melts [6] and with the correspondingly higher solubility limit plotted in Diagram 3.

The degassing run (Melt 4) shows a less straightforward picture: rather than decreasing monotonically from the interface, nitrogen content rises from the background level near the interface to a local maximum of roughly 350–400 ppm at about 20 mm depth, before falling back toward background further down. A tentative reading is that this reflects an incomplete transition between the absorption profile inherited from the preceding melt and a new, degassing-driven profile.

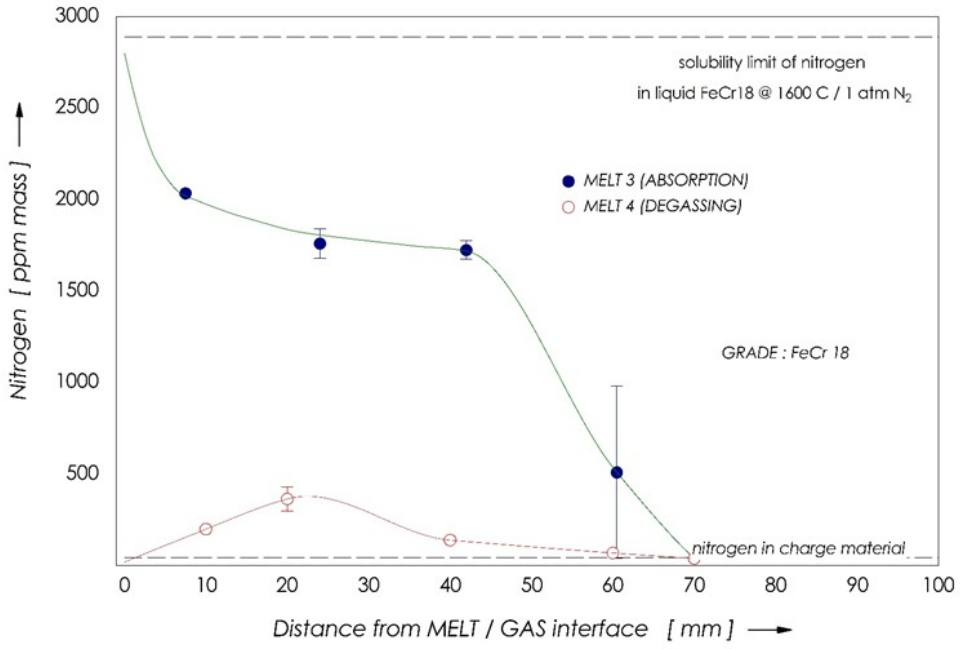

Diagram 3 – Nitrogen pick-up and degassing in iron-chromium alloy

Degassing at the interface region nonetheless appears remarkably fast, pointing toward accelerated processing whenever denitrogenization itself is the time-limiting refining step. Finally, the lime slag treatment applied during the degassing test runs also achieved a reduction in Sulphur: starting from an initial Sulphur content of about 45 ppm wt. in Melt 3, the single slag treatment in Melt 4 reduced it below the laboratory detection limit of 20 ppm wt.

CONCLUSIONS:

Overall, these initial trials indicate that a plasma-activated interface can reach nitrogen equilibrium within minutes rather than tens of minutes, and that slag treatment becomes a viable option once a plasma heat source is in place. Furthermore, using hydrogen as the plasma gas, an in-situ iron ore reduction process can also be included; this route was previously demonstrated in a separate project with an Austrian steel institute. Taken together, the nitrogenization, degassing and slag trials point to the same underlying mechanism: once the plasma delivers already-dissociated, chemically active species directly to the melt surface, the gas/melt interface reaction is no longer the bottleneck, and the achievable rate instead becomes governed by how quickly reaction products are transported away from that interface into the bulk melt. This picture is consistent both with the fast nitrogen pick-up and degassing observed within the first tens of minutes, and with the pronounced top-to-bottom concentration gradients seen on the present, non-stirred test bench. In a production VID furnace, the additional bath-wide convection from induction stirring would be expected to reduce this gradient and shorten the time needed to homogenize the ingot, though this remains to be confirmed on a stirred, production-scale unit.

In order to convert these findings into an industrial solution, ALD has developed a VID-PLASMA furnace concept (Figure 3). In addition to standard features (e.g., charging chamber, lid swivel), a plasma torch is integrated as a movable unit, so that it can be positioned over the melt or the slag cover as required by the process step.

The VID-PLASMA furnace combines the entire refining sequence in a single vessel and a single campaign. Liquid metal can be charged directly into the furnace, after which the melt is brought to and held at the required

process temperature. The plasma torch is then positioned over the bath to treat the slag cover – a step that induction heating alone cannot address effectively – before being redirected onto the melt surface for degassing, where dissolved hydrogen and nitrogen are reduced toward equilibrium within minutes rather than the tens of minutes required by conventional practice. Once the bulk chemistry is established, a final fine-trimming step adjusts the composition, and the heat is cast under a protective inert-gas shroud. In this way, the VID-PLASMA concept integrates liquid charging, temperature control, slag treatment, degassing, fine-trimming and casting into one continuous process, offering a compact and flexible alternative to more elaborate high quality-melt production routes.

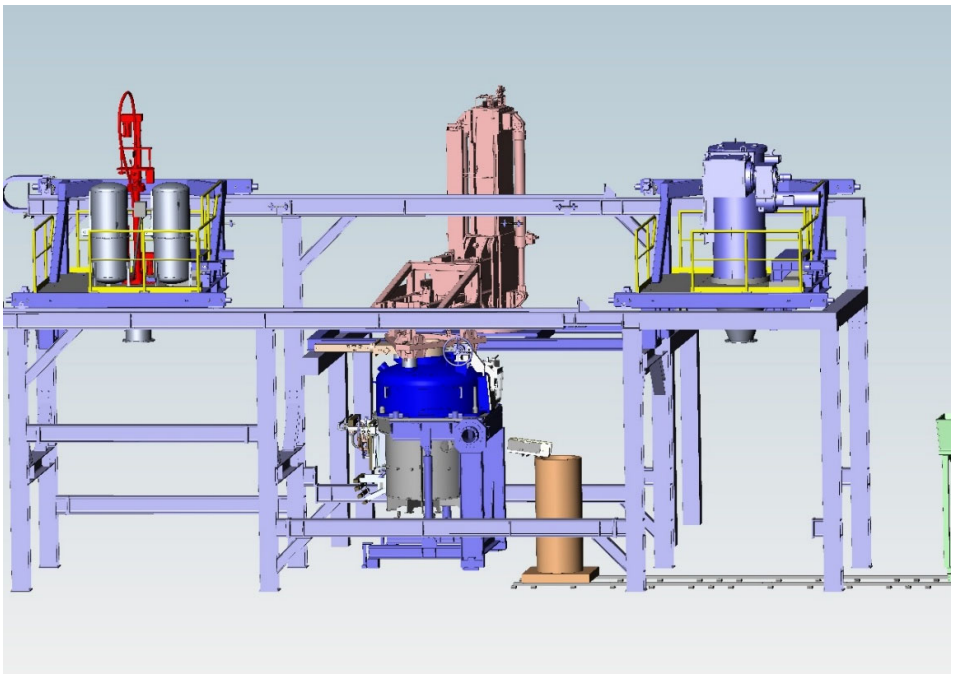

Figure 3 – ALD's VID-PLASMA furnace

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