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450 kW Plasma Melting System

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Abstract. Plasma melting technology can be used to meet the scrap recycle needs of reactive metals, superalloys and refractory materials such as titanium, zirconium and uranium alloys. Fabrication involving these reactive metals, share the common problem of generating a large amount of scrap where both low and high density inclusions become highly prevalent. Plasma melting technology can be used for re-melting, refining and production of premium grade metal ingot. 450kW multi-torch plasma melting furnace is developed and commissioned by Laser & Plasma Technology Division for the re-melting and refining of metals and scraps under controlled environment. This paper presents the vacuum system design for 450 kW plasma melting furnace. The efficacy of vacuum system in cold condition is also tested and the results are included in the paper. The vacuum feed through design for the plasma torch handling mechanism is also discussed.

Key Words: plasma melting, torch handling mechanism, charge feeder, feed through

1. Introduction:

The application of thermal plasma technology in the melting and refining of reactive metals, superalloys and refractory materials is gaining considerable attention over the past two decades [1,2,3,4,5]. The major advantage has been the capability of thermal plasma sources to produce high power density at equally high source strengths. The conventional technology of superalloy refining consists of vacuum induction melting (VIM), vacuum arc remelting (VAR) and electroslag remelting (ESR). The VIM normally acts as a precursor to VAR or ESR by converting raw materials and scrap alloys into homogeneous alloy chemistry, by preventing the reactive alloying elements from oxidizing and to evaporate deleterious volatile elements such as Bi, Pb etc. The vacuum arc remelting converts the VIM processed electrodes into ingots having greatly improved chemical and physical homogeneity. Electroslag refining is a melting process similar to VAR except for the fact that it operates in air. Melting is through resistance heating instead of arc. With the demand for cleaner and more uniform microstructures, these methods have undergone many improvements but in the long run are increasingly felt to be costly and inadequate in terms of exact specificity of the new superalloys. The electron beam cold hearth remelting and plasma cold hearth melting (PCHM) under controlled environment are now being used and further developed as an alternative to non conventional methods. Plasma cold hearth remelting has proved to be extremely good for oxide refining and is characterized by the following distinct advantages.

- Plasma melting can be done at atmospheric pressures resulting in extremely low alloy losses.
- Plasma have better outgassing tolerance and so can handle feedstocks / charge of different types and densities.

- Water cooled copper hearth can be very easily used.
- The relatively shallow pool depth characterizes plasma melting in fine grained products.
- Refractory contamination is avoided through cold hearth / skull melting.
- Plasma melting can serve as a good premelter for further refining in VAR furnaces.

The 450 kW multi-torch plasma melter system is designed and developed for melting and consolidating of scraps of titanium, zirconium and uranium alloys. This paper presents the design of the vacuum system for plasma melting system. The schematic of a multi torch plasma melter system is shown in Figure 1.

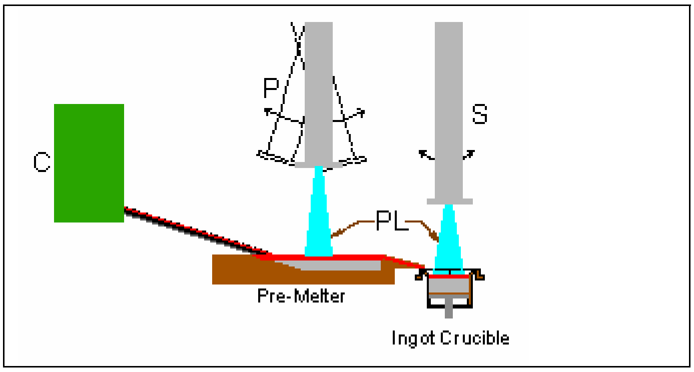


Figure 1. Schematic of the Plasma melter system; C: Charge feeder; P: Primary plasma torch (300kW); PL: Plasma Plume; S: Secondary Plasma Torch(150kW).

2. System Description:

The major subsystem of the 450 kW plasma melter system are: 1) Process chamber with dish end doors, 2) Vacuum system, 3) charge feeder, 4) Pre-melter, 5) Ingot crucible, 6) plasma torch remote handling system, 7) ingot retraction sub assembly, 8) plasma torches and 9) plasma torch power supply. The transferred arc plasma torches [6] are mounted on the torch handling mechanism after completion of the performance testing of individual components.

The process chamber which is double walled water cooled cylindrical chamber with 1200mm ID and 2200mm length is initially evacuated to a base vacuum level of $5x10^{-6}$ mbar. The Argon / Helium gas is used as a carrier gas for the plasma torches used for melting operation. During the plasma torch operation the vacuum pumps are required to handle external gas load which may be as high as 60 lpm at atmospheric pressure for a typical process cycle duration of one hour with the process chamber pressure set between 20 to 200 mbar. The 450 kW plasma melter assembly is shown in figure 2. Figure 3 shows the photograph of the actual system at BARC.

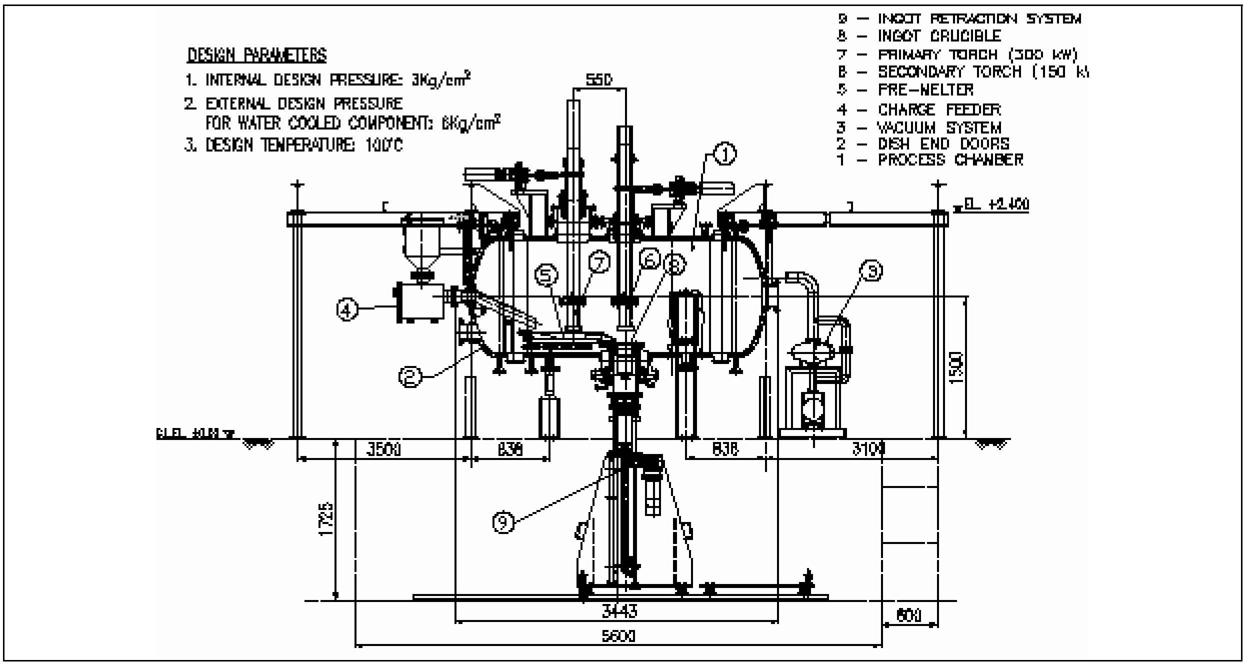


Figure 2. 450 kW Plasma Melter Assembly

Figure 3. Photograph of the 450 kW Plasma Melter System

In a typical metal cycle charge is fed into pre-evacuated process chamber maintained at pressure levels of 10^{-3} to 200 mbar from a charge storage hopper via vibratory feeder. A transferred arc plasma beam from 300 kW Primary plasma torch with sweeping motion is used to melt the charge and create a molten pool in the crucible (pre-melter). Due to the incoming charge material, the molten metal overflows through the pouring lip of the pre-melter into an ingot crucible with an inside diameter of ϕ150mm. The secondary plasma torch (150 kW) with gyroscopic motion is used to maintain the top layer of ingot in molten state while the metal flows from premelter to ingot crucible. On formation of the ingot of required length (maximum length ~ 300mm) the feed of the incoming raw material is stopped. The process chamber is isolated from the ingot crucible assembly and ingot is withdrawn by a suitable ingot retraction mechanism. A charge feeder assembly is used for the storage and supply of feed material to the pre-melter and consists of an eccentric charge storage hopper with 100 kg storing capacity and the feeder mechanism. The feed material consists of metals in the form of 5 mm thick chunklets of 10-25 mm size. The density of the feed metal is about 8-15 g/cm^3. The material is fed to the pre-melter through a vibratory feeder at a pre-determined rate. The vibratory feeder encased in a vacuum tight rectangular stainless steel casing is provided with two 100mm NB ports. The top port is connected to the storage hopper and the side port is connected to the vacuum chamber dish end door. The storage hopper top is covered with a vacuum tight lid which is closed after filling it with charge at the start of the experiment. The pre-melter is a rectangular cup in cup type crucible with outer cup made of stainless steel material and inner cup made up of forged ETP copper. The ingot crucible is copper cup encased in water cooled stainless steel casing. This functions as a mould for ingot formation by facilitating heat removal while solidification of molten metal occurs. Primary plasma torch (300 kW) and Secondary plasma torch (150 kW) are mounted on the process chamber top port via suitable vacuum feed throughs.

3. Selection of Material:

The material of construction for the process chamber and vacuum plumbing line was based on the high vacuum compatibility point of view. The system is designed for base evacuation up to 5x10^{-6} mbar and the finish of the surface facing the vacuum in high vacuum range shall be buffed and polished to minimize outgassing rate. The material of construction for the plasma melter system, except for the standard pumps and motors, is AISI 304L grade stainless steel. The structural steel and standard aluminum channels are used for the fabrication of support structures and operating platforms.

4. Vacuum System Design:

The vacuum pumping module selection was based on the basic throughput load and considering the conductance of the vacuum plumbing line connecting the vacuum system to the process chamber [7, 8]. The design calculation is shown in Table 1.

Table 1. Design Calculation:

Sl	Item	Symbol	Unit	Value
1	Surface Area Exposed to vacuum	A	cm^2	6x10^5
2	Volume to be evacuated	V	Litres	5030
3	Total Degassing Load considered	Q_d	Torr.lps	9x10^{-3}
4	Total Leakage load considered	Q_L	Torr.lps	0.76x10^{-6}
5	Maximum expected Process Load	Q_P	Torr.lps	760
6	Total Throughput load due during base evacuation (Q_d + Q_L)	Q_{Tb}	Torr.lps	9x10^{-3}
7	Maximum expected throughput load during process, (Q_{Tb} + Q_P)	Q_{Tp}	Torr.lps	760.009
8	Equivalent plumbing Length for Rotary Pump	$L_{eq\text{-}rot}$	cm	160
9	Equivalent plumbing Length for Roots Pump	$L_{eq\text{-}root}$	cm	100
10	Equivalent plumbing Length for Diffusion Pump	$L_{eq\text{-}dp}$	cm	60
11	Conductance of the path in 1mbar range for rotary pump	$C_{rot\text{-}1}$	lps	8531
12	Conductance of the path in 0.001mbar range for roots pump	$C_{root\text{-}01}$	lps	13.7
13	Conductance of the path in high vacuum region	C_{dp}	lps	22303
14	Ultimate vacuum to be maintained by rotary pump alone during the process	$P_{u\text{-}p}$	Torr	15

15	Required Pumping speed of the rotary pump during the process	S_{rot}	lps	51
			m^3/hr	184
16	Ultimate vacuum to be achieved with roots pump (backed by rotary pump) during initial evacuation	$P_{u\text{-}root}$	Torr	$0.75\text{x}10^{-3}$
17	Required pumping speed of the roots pump in $1\text{x}10^{-3}$ mbar region	S_{root}	lps	97
			m^3/hr	350
18	Ultimate vacuum required to be achieved with DP during base evacuation	$P_{u\text{-}base}$	Torr	$3.75\text{x}10^{-6}$
19	Pumping Speed of the Diffusion Pump required at the mouth of the process chamber	$S_{dp\text{-}pc}$	lps	2400
20	Required minimum Pumping Speed of the Diffusion Pump (considering conductance losses due to chevron baffle and plumbing line)	S_{dp}	lps	6725

Selection of Pump:

Vacuum pump selection was done from amongst the commercially available pumps considering the following factors:

- Ultimate vacuum to be achieved
- Minimum pumping speed required in corresponding vacuum region
- Pump down time required to achieve ultimate vacuum
- Ruggedness and reliability of the pumps during the service
- Feedback regarding the maintenance and trouble free service of the pumps from various users

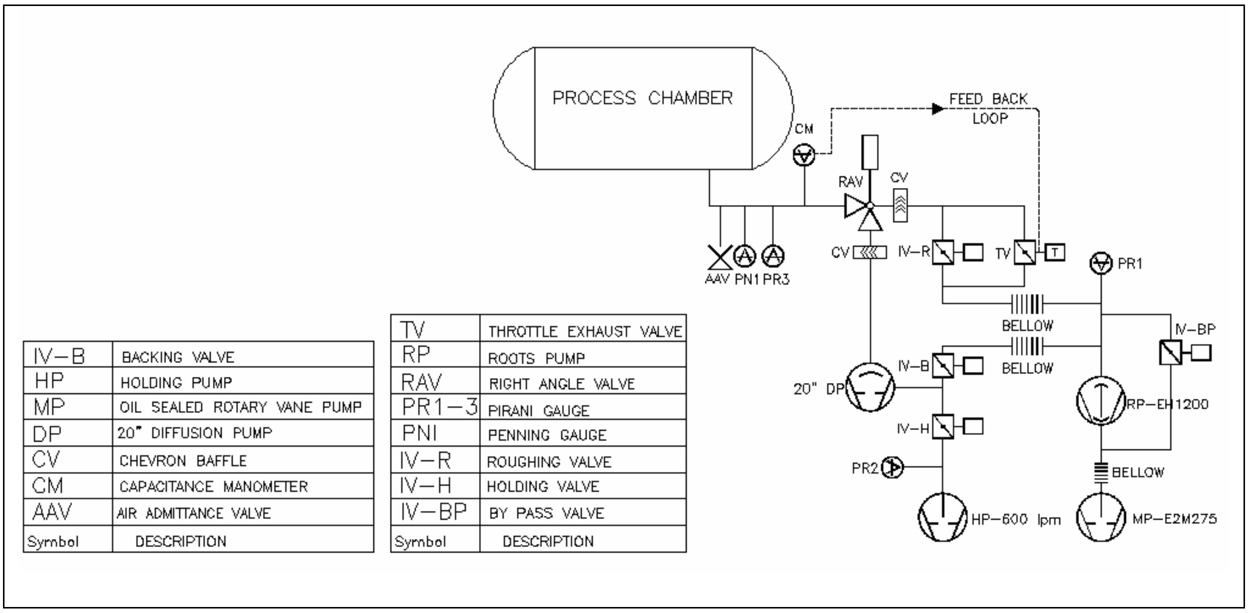
The pumping system worked out considering the above factors is given in Table 2 and Table 3. The schematic layout of the plasma melter vacuum system is shown in figure 4.

Table 2. Pumping systems worked out

Sl No.	Pressure level in mbar	Suitable vacuum pump	Ultimate vacuum to be achieved	Required pumping speed	Nearest match available from the commercially available pumps
1.	$1000 - 1\text{x}10^{-1}$	Rotary pump	$1\text{x}10^{-2}$ mbar	184 m^3/hr	E2M275
2.	$1\text{x}10^{-1} - 1\text{x}10^{-3}$	Roots pump	$1\text{x}10^{-3}$ mbar	350 m^3/hr	EH1200, MB1200
3.	$1\text{x}10^{-3} - 1\text{x}10^{-6}$	Diffusion pump	$5\text{x}10^{-6}$ mbar	6725 lps	20" Diffusion Pump (indigenous make)

Table 3. Pumping module selected for the vacuum system of 450 kW plasma melter system:

Sl No	Pump	Make	Model	Maxm. Pumping speed	Pumping speed at the mouth of the pump	Pumping speed at the mouth of process chamber
1	Rotary Pump	Edwards	E2M275	255 m^3/hr	250 m^3/hr at 10 mbar	248 m^3/hr at 10 mbar
2	Roots Pump	Edwards	EH1200	1020 m^3/hr	400 m^3/hr at $1\text{x}10^{-3}$ mbar	44 m^3/hr at $1\text{x}10^{-3}$ mbar
3	Diffusion Pump	Precise Vacuum	20" DP	12000 lps	12000 lps	3950 lps



Symbol	DESCRIPTION
IV–B	BACKING VALVE
HP	HOLDING PUMP
MP	OIL SEALED ROTARY VANE PUMP
DP	20" DIFFUSION PUMP
CV	CHEVRON BAFFLE
CM	CAPACITANCE MANOMETER
AAV	AIR ADMITTANCE VALVE

Symbol	DESCRIPTION
TV	THROTTLE EXHAUST VALVE
RP	ROOTS PUMP
RAV	RIGHT ANGLE VALVE
PR1–3	PIRANI GAUGE
PNI	PENNING GAUGE
IV–R	ROUGHING VALVE
IV–H	HOLDING VALVE
IV–BP	BY PASS VALVE

Figure 4. Schematic of the Vacuum System Layout for Plasma melter system

5. Plasma Torch Handling Mechanism:

The primary plasma torch sweeps (with a sweep rate of 0 – 300 mm/s) over premelter in a direction along the axis of vessel from feed point to pouring lip thus covering distance of 550 mm. The torch also has facility to move in vertical direction (with a speed of 0 – 10 mm/s), which is required as while striking the arc the tip is about 30 mm from top of molten pool which is increased gradually to 400 mm on achieving a stable arc.

The secondary plasma torch (150 kW) gyrates (with a speed of 0 – 5 rpm) over ingot crucible in a circular path of variable radius of upto 200 mm, thus covering crucible and portion of premelter pouring lip. This torch also has facility to move in vertical direction (with a speed of 0 – 10 mm/s) to vary the distance of tip of torch from 30 mm from top of molten pool to 150 mm on achieving a stable arc.

Principal operating parameters for the plasma torch handling mechanism are as under:

Primary Plasma Torch:

Z-axis Stroke Length	: 0 – 500 mm
Speed in vertical motion	: 0 – 10 mm/sec
Sweep about Y-axis	: (–) 250 mm (+) 300 mm
Total sweep over pre-melter	: 550 mm
Sweep rate	: 0 – 10 mm/sec

Secondary Plasma Torch:

Z-axis Stroke Length	: 0 – 200 mm
Speed in vertical motion	: 0 – 10 mm/sec
Gyration radius	: 0 – 200 mm
Gyration speed	: 0 – 5 rpm

The vertical motion of both torches is achieved by AC servo drives. The motion of the AC servo motor is transferred to the ball screw and nut assembly via bevel gear assembly. The horizontal / sweep motion of the primary plasma torch is achieved by DC servo drive. The rotational motion of the motor is converted in to linear to and fro motion using ball and screw arrangement. The linear to and fro motion of the ball and screw arrangement is transferred into oscillatory sweep motion of the torch by pivoting it with the torch assembly. The arrangement showing the sweep motion of the plasma torch about the spherical bush assembly is shown in figure 5. Similarly the gyroscopic motion of the secondary plasma torch is achieved by two orthogonal DC servo drives coupled to torch assembly via ball and screw assembly. The horizontal motion of both the torches is controlled by a three axes controller mounted in PLC.

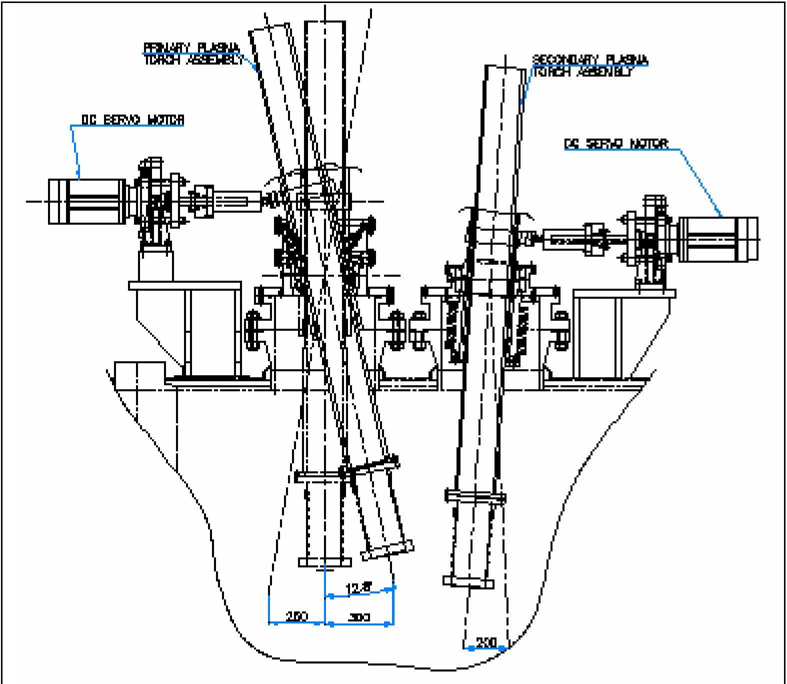


Figure 5. Plasma torch assembly in motion

6. Vacuum Feed throughs:

The ingot retraction mechanism and two numbers plasma torch assemblies are the major components piercing the high vacuum boundary.

Plasma Torch Handling Mechanism:

The primary plasma torch (300kW) and the secondary plasma torch (150kW) assemblies are mounted on 14" NB ports provided on the top of the process chamber. The plasma torch assemblies are part of the high vacuum system. The real challenge was to bring out water cooled power cables of the plasma torches (which were required to perform required sweep / gyroscopic motion at a pre-determined rate) outside the high vacuum boundary. Several schematic concepts for the plasma torch handling mechanisms and vacuum feed through were worked out. One of the vacuum feed through variants for the plasma torch is as shown in figure 6.

The plasma torch is flange mounted on one end of a 5"NB SCH 120 seamless pipe (ϕ135mm OD x 1500mm long) and the water cooled cables are inserted in the pipe assembly. The other end of this pipe is open to atmosphere. The OD of this pipe assembly is passed through a standard reciprocating shaft seal mounted on inside diameter of a 6"NB SCH120 pipe. OD of the 6"NB pipe is provided with spherical bush assembly to facilitate sweeping motion. Two numbers of normal convolute metallic bellows were provided for isolating the spherical bush assembly both from the atmosphere and the vacuum chamber. Similar arrangement was used for the vacuum feed through of the secondary plasma torch. The vacuum feed through was fabricated, assembled and integrated with plasma melter system as per the drawing. The process chamber was evacuated with a high vacuum pumping system and pressure in the range of $5x10^{-6}$ mbar was obtained. The complete system was leak tested for a leak tightness of $1x10^{-8}$ standard cc/sec. However, the bellows of the primary plasma torch assembly showed frequent failures due to high lateral movement of the plasma torch handling mechanism during performance testing.

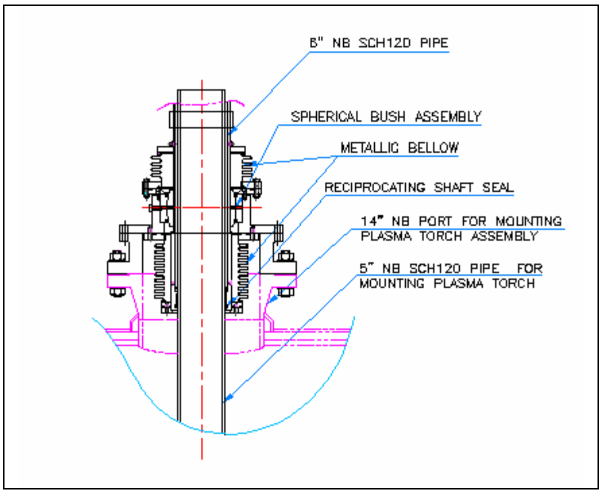


Figure 6. Vacuum feed through for plasma torch assembly with normal convolute metal bellows.

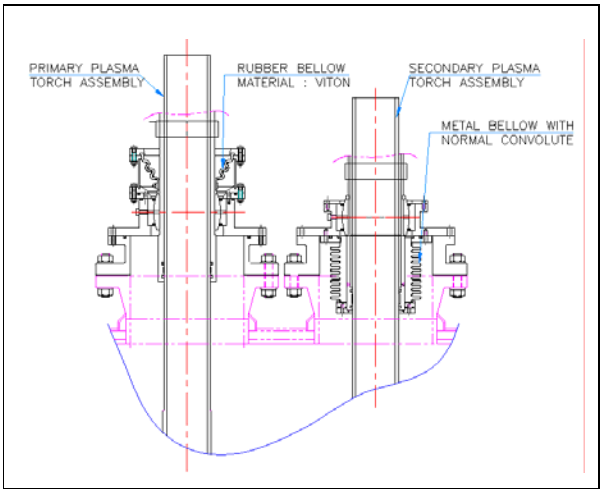


Figure 7. Vacuum feed through with rubber bellow for primary plasma torch and normal convolute metallic bellow for secondary plasma torch.

In the second iteration metallic bellows used in the primary plasma torch assembly were removed. The spherical bush was isolated form the atmosphere using tapered rubber bellows as shown in the figure 7. The vacuum feed through assembly for the primary plasma torch with rubber bellow is working fine.

Ingot Retraction Mechanism:

The ingot retraction mechanism is used for forming, cooling and removal of ingot from main chamber and consists of a ram having a water-cooled withdrawal head at the top end which acts as a bottom of the ingot crucible. The ram is capable of moving up and down to suit the rate of filling of molten metal in ingot crucible. The reciprocating shaft seal is provided for isolating the high vacuum in the vacuum chamber from atmospheric pressure. Once desired length of ingot is formed, the operation is stopped and ram is taken down to its lowest position. The solidified ingot is removed by releasing the vacuum and opening the clamps at the top of flexible joint. The up and down motion of ram is achieved by means of a rotary ball screw and guide bars with ball bushes. Figure 8 shows the detail of ingot crucible and ingot retraction mechanism.

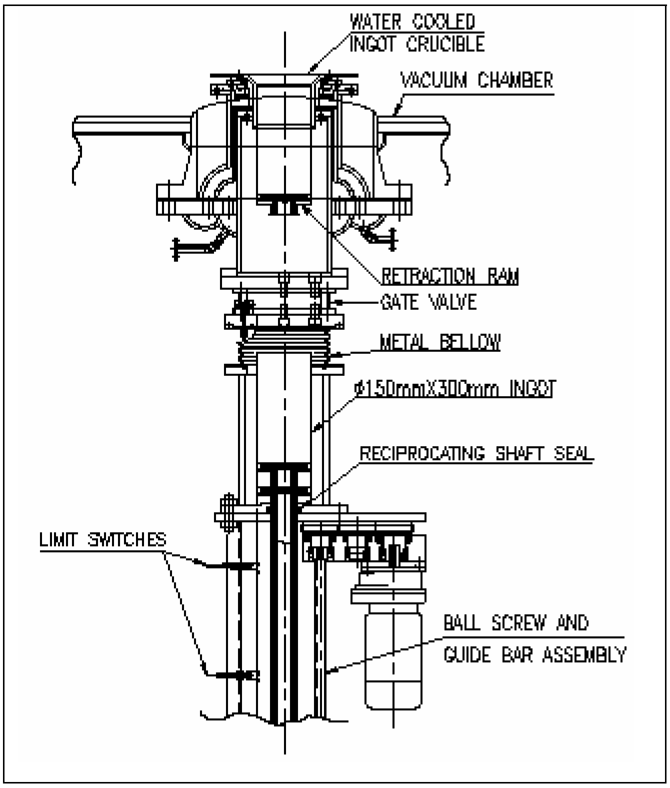


Figure 8. Ingot crucible and ingot retraction mechanism.

7. Mechanical Design and Fabrication:

The guidelines given in Boiler and Pressure vessel code ASME Section VIII Division 1 has been used for the design, fabrication, inspection and testing of the plasma melter system. The process chamber and all components subjected to thermal load due to plasma torches are provided with water cooling arrangement. The inner shell of process chamber and dish end doors are designed for an external pressure of 6kg/cm^2 (1kg/cm^2 due to vacuum and 5 kg/cm^2 due to cooling water pressure). The outer shell is designed for an internal pressure of 5 kg/cm^2. The support structures and operating platforms are designed as per good engineering practices. The fabrication of the system was subjected to various stages of inspection such as dimensional check, dye penetrant test, radiographic test, ultrasonic test, hydrostatic test, pneumatic test, leak test and vacuum test.

8. Performance test:

The plasma melter system was subjected to vacuum test and cyclic testing of the torch handling system as a part of final acceptance / performance test.

Vacuum Test:

Pump Down Time and Holding Vacuum Test:

The efficacy of the vacuum system was tested as a part of the performance testing as per the acceptance test plan. The vacuum system was integrated with the melter system. The pump down curve and holding vacuum curve was obtained for the system and were found to be as expected. The time taken to achieve 1x10^{-3}mbar in process chamber is 29 minutes which is 7 minutes higher than the theoretically estimated time. The right angle valve is opened after attaining 1x10^{-3} mbar in the process chamber and ultimate pressure of 3.6x10^{-6} mbar is attained within 55 minutes.

The right angle valve was closed after three hours of vacuum system operation and the process chamber was isolated from the vacuum system. The holding vacuum was recorded and plotted with time. The slope of pressure rise curve is large in the high vacuum region indicating the high virtual leak. The curve becomes almost flat in the rough vacuum region. Vacuum holding curve indicates that the real gross leak of the vacuum chamber is of the order of 1x10^{-2} stdd cc/sec. The pump down curve and holding curve for the plasma melter vacuum system is shown in figure 9.

Vacuum System Performance during the plasma torch operation:

The vacuum system is required to handle around 60 slm of gas during the melting operation. Performance testing of the down stream pressure controller to maintain the set pressure in the process chamber during the melting cycle was also carried out for various flow rates of Argon. The steady state vacuum achieved in the process chamber with rotary pump alone for various external gas feed rate (simulating the external gas load on the vacuum system due to plasma torch operation) is shown in figure 10. The theoretically estimated pressure was worked out as per the equation given below.

$$P_{th} = \frac{Q_v p}{S_e}$$

Where, P_{th} = Theoretically estimated pressure, mbar
Q_v = Volumetric Flow rate, lps
p = pressure at which gas is fed, mbar
S_e = Effective pumping speed of the vacuum pump, lps

It is indicated from figure 10 that the maximum difference in the theoretically estimated value of the process chamber pressure and the actual pressure measured with pirani gauge heads are less than 14%. This difference is acceptable as the accuracy of the pirani gauge heads used are within ±15%.

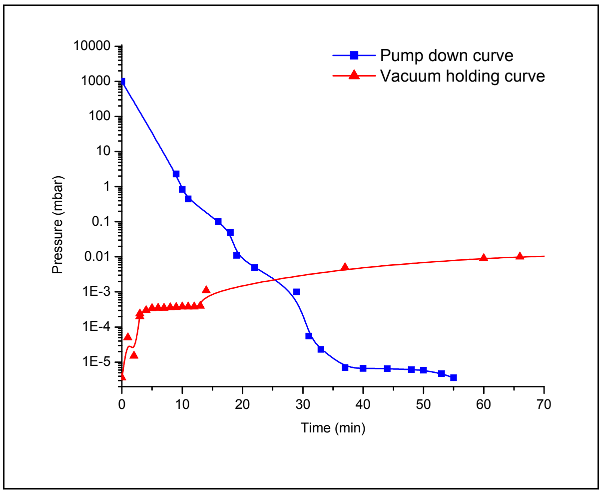


Figure 9. Pump down and Holding vacuum curve for Plasma melter vacuum system.

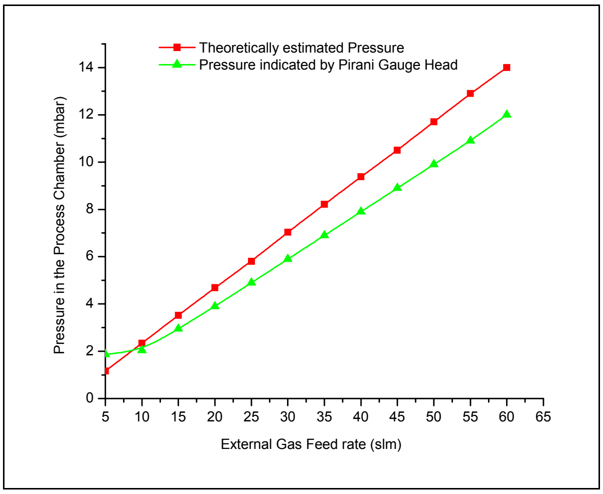


Figure 10. Process chamber pressure v/s external gas feed rate.

Plasma Torch Handling Mechanism:

A set up was prepared for the testing of the locus of the plasma torches. The locus was obtained for various set value and the same was found to be matching with the parameters set form the control panel.

The primary torch assembly with tapered rubber bellow and the secondary plasma torch assembly with normal convolute metallic bellow were subjected to 6 hours continuous cyclic testing as a part of their endurance test after successfully passing the leak tightness better than 1x10^{-7} standard cc / sec. at vacuum level of 5x10^{-6} mbar. The leak testing across the vacuum feed through assembly was carried out by Mass Spectrometer helium leak detector ASM 142 (Alcatel make) and a leak tightness of all the joints was observed to be better than 1x10^{-7} standard cc/sec. The plasma torch handling system is working fine for three consecutive years.

Ingot Retraction Mechanism:

The leak tightness across the shaft seal of the ingot retraction mechanism was tested after 6 hours continuous operation and it was observed to be better than $1x10^{-7}$ stdd cc/sec. The ingot retraction mechanism is also working fine for last three years.

9. Experimental results and discussions:

The vacuum testing of the plasma melter system was carried out with main shell and dish end jacket pressurized with cooling water. Torch handling system and vibratory charge feeder were also switched ON. The ultimate vacuum of $3.6x10^{-6}$ mbar was achieved in the process chamber. The pumping down curve and holding vacuum curve obtained during the vacuum testing of the plasma melter system are as shown in the figure 9.

The set vacuum pressure in the process chamber was tested for various flow rates of Argon. The pressure was maintained within ±2% using down stream pressure controller consisting of motorized throttle exhaust valve, capacitance manometer and programmable pressure controller.

10. Conclusion:

The plasma melter system is commissioned at BARC as per the technical specifications. The performance of the vacuum system both during the cold commissioning and during the hot operation is as per the expectations. The base vacuum of better than $5x10^{-6}$ mbar is achieved in the plasma melter process chamber with the given vacuum system. The vacuum in the range of 20 – 200 mbar is maintained in the process chamber during the melting process by rotary pump alone. The performance of vacuum system, programmable pressure controller and torch handling system is satisfactory. However, there is further scope of refinement in the torch handling mechanism in future.

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