Effusive-flow characterization of arbitrary size and geometry target/vapor transport systems: radioactive ion beam applications

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The principal factors that severely limit intensities of short-lived radioactive ion beams produced by the Isotope Separator On-Line (ISOL) technique are time delays due to diffusion of radioactive species from solid or liquid target materials and their effusive-flow transport to the ion source. Although diffusion times can be reduced by proper design of short diffusion length, highly refractory targets, effusive-flow times are more difficult to assess. After diffusion from the target material, the species must travel through the target material and vapor transport system to the ion source. The time required for effusive-flow transport to the ion source depends on the conduction path, chemical reactions between the species and target material and materials of construction as well as the physical size and geometry of the' transport system. We have developed a fast-valve (1 ms closing time) for introducing gaseous or vapor-state species into the target/vapor transport/ion source/system that permits measurement of effusive-flow times for any gaseous or vaporous species (chemically active or chemically inactive) through any vapor transport system, independent of size and geometry. Characteristic times are determined from the exponential decay of the momentum analyzed ion beam intensity for the species during effusive-flow through the vapor transport system under evaluation. This report describes the effusive-flow apparatus and presents characteristic time spectra and characteristic effusive-flow time data for noble gases flowing through both serial and parallel-flow target reservoir systems.

I. INTRODUCTION

The ISOL technique is a very efficient method for producing short-lived isotopes for research at radioactive ion beam (RIB) facilities such as the Holifield Radioactive Ion Beam Facility (HRIBF) [1]. After being created in the matrix of a solid or liquid target, the short-lived species must diffuse from the target material and then be transported in gaseous or vapor form through a transport system to an ion source where a fraction of the species are ionized and accelerated. The principal means whereby short half-life radioactive species are lost between initial formation and utilization are attributable to delay times required for the diffusion and effusive-flow processes to take place in relation to the lifetime of the isotope of interest. Thus, both processes must be minimized if useful beam intensities of interesting isotopes are to be realized. We have developed a simple and versatile experimental method for measuring effusive-flow times of gaseous or vaporous materials through arbitrary geometry target/vapor transport systems. The system utilizes a fast-valve (0.1 ms closing time) for interrupting the gaseous or vapor flow through the target/vapor transport/ion source/system that permits measurement of effusive-flow times for any gaseous or (chemically active or chemically inactive) through any vapor transport system, independent of size and geometry. In this report, we demonstrate the viability of the technique and present experimentally measured effusive-flow time spectra for two different target/vapor transport systems with and without Reticulated-Vitreous-Carbon Foam (RVCF) material in each target material reservoir. The experimental setup can be used to characterize present and future target/vapor transport systems. The ultimate objective of these developments will be to use them as tools for optimally designing vapor transport systems for RIB applications so as to reduce the times required for transport of a given short-lived species to the ion 'source to values as low as practically achievable and thereby increase the intensities of short-lived RIBs at ISOL-based facilities.

II. THE EFFUSIVE-FLOW FORMULA

For an ideal gas in a tube of radius, a, and length, l, at low pressure, p, the steady-state flow rate, dN/dt, for particles of average velocity, v, flowing through a tube under a density gradient along the tube, dn/dz, is given by [2]:

$$
\begin{aligned}
dN/dt &= -\{2\pi a^3/3\}v\, dn/dz \approx -\{2\pi a^3/3\}vn/l \\
&= -\{2\pi a^3/3\}vp/k_B Tl = -\{2\pi a^3/3k_B T\}v\, dp/dz
\end{aligned}
\tag{1}
$$

where n is the particle density; v is the Maxwellian velocity defined below; and k_B is Boltzmann's constant.

The average transport time for chemically inactive radioactive particles with lifetime, $\tau_{1/2}$, to flow through a given vapor transport system can be deduced by solving the time dependent form of Eq. 1. The resulting equation is:

$$
N = N_0\, exp[-\lambda t]\, exp[-t/\tau_c]
\tag{2}
$$

where N_0 is the number of particles in the volume at time $t = 0$; and $\lambda = 0.693/\tau_{1/2}$. The characteristic time that a particle takes to go through the system, τ_c, is given by:

$$
\tau_c = \left[N_b\tau_0 \exp(-H_{ad}/k_B T) + L/v \right]
\tag{3}
$$

with

$$
v = \left(8k_B T/\pi M \right)^{1/2} .
\tag{4}
$$

Here N_b is the average number of bounces that a particle of mass M makes on the surface of the system; $\tau_0 = 3.4.10^{-15}$ s; H_{ad} is the enthalpy of adsorption, and L is the average distance traveled per particle during transit through the systems. For noble gases [3], as well as almost all of the volatile electropositive elements [4], the first term in Eq. 3 is negligible.

III. EXPERIMENTAL ARRANGEMENT

The fast closing valve system, illustrated on Fig. 1, consists of an electro-pneumatic actuator [5] that drives a shutter for interrupting gas flow of the gas or vapor of interest to the target reservoir. The valve, initially designed to close in 10 ms, has been modified so that it closes in 0.1 ms, thus, permitting measurement of transit times down to this value. To experimentally measure time spectra, the fast closing valve' system is close-coupled to the target material reservoir so as to minimize contributions to the delay function resulting from particle hold-up in the injection feed-line. The gas of interest is injected' via the gas input system through the target/vapor transport system to the Electron Beam Plasma Ion Source (EBPIS) [6] where a fraction of the species is ionized, accelerated, and mass analyzed. After establishing a *dc* current of the mass selected species, the incoming flow of gas is rapidly interrupted by actuating the fast valve, while monitoring the exponential decay of the signal. From the spectra, the time required for the signal to reach I/e of its initial value is defined as the characteristic effusive-flow time. The temperatures of the target material reservoir and vapor transfer tube are, respectively, varied by changing the current through a heater surrounding the reservoir or the resistive current flowing through the transfer tube; the magnitudes of the temperatures are measured with an optical pyrometer as well as with thermocouples. The electro-pneumatic actuator for the fast valve is thermally and electrically isolated from the target material reservoir under evaluation with an Al_2O_3 tube.

IV. EFFUSIVE-FLOW TIME MEASUREMENTS

In this study, time spectra for noble gases flowing through two different target reservoir/transport systems, with and without Reticulated-Vitreous-Carbon-Foam (RVCF), to an electron Beam Plasma Ion source (EBPIS), were measured. The two target reservoirs geometries used, shown in Fig. 2, are filled with 2-mm thick disks of RVCF of the same diameter (15 mm) and length (193 mm). A 4.3-mm annular space is provided around the RVCF in the parallel-flow system shown in Fig. 2b to change the conductance of the reservoir. The radial direction for the parallel flow arrangement of the RVCF holder is 58% open.

A. Serial-coupled system

The characteristic times for noble gas elements (He, Ne, Ar, Ќr, and Xe) flowing through the serial coupled system with and without RVCF are displayed in Fig. 3 for different temperatures. As expected, the characteristic times are shorter for lighter species. The decrease in characteristic time for noble gases with increasing temperature, T, is attributable to the fact that τ_c is proportional to $T^{-1/2}$ (see Eq. 3 and 4). The effusion-flow time of the slowest species studied (Xe) varies from 0.23 s at T = 770 $^\circ$C to 0.18 s at T = 1400 $^\circ$C in the case when the target reservoir is filled with RVCF. As noted, the RVCF does not significantly increase the effusive-flow times of the noble gases, thus, validating the importance of high permeability targets designed for RIB applications at the HRIBF [7]. The average distance traveled per particle was found to be 93 m without and 115 m with RVCF in the target material reservoir for the serial-coupled system.

B. Parallel-coupled system

Figure 4 shows the characteristic times for noble gases flowing through the parallel-coupled system with and without RVCF. The effusion-flow time of the slowest species studied (Xe) varies from 0.30 s at T = 770 °C to 0.225 s at T = 1400 °C in the case when the target-material reservoir is filled with RVCF. As was the case for the serial-coupled system, the effusive-flow times are shorter at higher temperatures and scale with temperature according to $T^{-1/2}$. Therefore, the effusive-flow times are longer for the parallel-flow geometry than for the serial-flow geometry. This fact is explainable because of the larger diameter reservoir (larger surface area) in comparison to the reservoir for the serial-flow case. Since both geometries have the same exit aperture, the capture probability for particles entering the transfer tube is less for the parallel-flow system. As noted, the presence of RVCF slightly decreases the characteristic flow times for the gases in this configuration. This is attributable to the flow of gas into the annular region where the resistance to flow is reduced. The average distance traveled per particle was found to be 152 m with and 166 m without RVCF in the target material reservoir for the parallel-coupled system.

Figure 5 clearly shows that the characteristic effusive-flow times for noble gases are proportional to $M^{1/2}$. Thus, according to the Eqs. 3 and 4, for these gases the sticking times on the walls of the transport system and target surfaces are negligible.

V. DISCUSSIONS/FUTURE STUDIES

These studies show that the RVCF does not significantly affect effusive-flow times in either the serial-flow or parallel-flow transport systems, thus validating the attributes of highly permeable targets designed for use at the HRIBF [7]. By measuring the characteristic effusive-flow time of a reactive gas such as N for which the sticking times on Ta metal [4] are not negligible, as is the

case for the noble gases, in principle, N_b can be determined from a plot of τ_c vs. $M^{1/2}$ at fixed temperature since H_{ad} of Eq. 3 is known. Once N_b is known, then a given target/vapor transport system can be completely characterized, independent of species, size and geometry of the vapor transport system, provided that the enthalpies for adsorption are known for the species of interest, since the average distance traveled per particle, L, and the average number of bounces, N_b, are known. The ultimate objective of these investigations is to develop a technique for designing an optimum target/vapor transport system that minimizes effusive-flow times to a given ion source. Figure 6a displays the conventional (low conductivity) vapor transport system used at the HRIBF while Fig. 6b displays a high vacuum conductivity scenario proposed for future use at the facility.

AKNOWLEDGMENTS

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Figure Captions

Figure 1: Schematic drawing of the fast closing valve, gas-input system mounted on the target/ion source chamber.

Figure 2: a) The serial-flow target material reservoir; b) The parallel-flow target material reservoir .

Figure 3: Characteristic effusive-flow time, τ_c, versus temperature, T, for noble gases flowing through the serial-coupled, target material reservoir with (open symbols) and without RVCF material (solid symbols).

Figure 4: Characteristic effusive-flow time, τ_c, versus temperature, T, for noble gases flowing through the parallel-coupled, target material reservoir with and without RVCF material.

Figure 5: Measured characteristic effusive-flow time, τ_c, for noble gases versus $(M)^{1/2}$. Experiment: $\bullet$; Theory ——; Temperature $\sim$ 1000°C.

Figure 6: a) Standard conductivity target/vapor transport system; b) High conductivity (fast effusive-flow) target/vapor transport system.
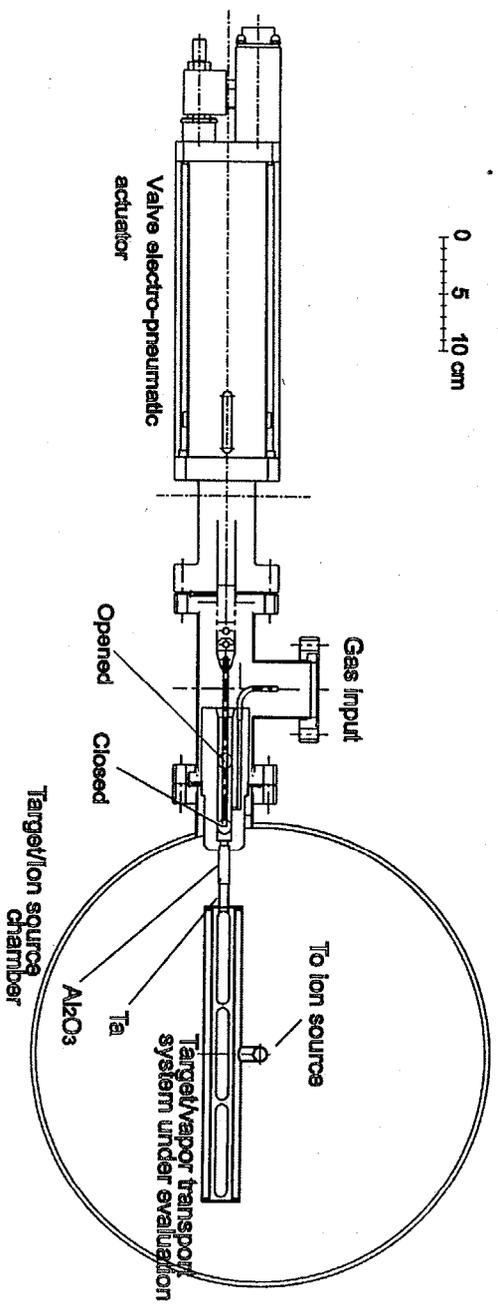
Valve electro-pneumatic
actuator

0 5 10 cm

Gas input

Opened Closed

Target/Ion source
chamber

To ion source

Al₂O₃

Ta

Target/vapor transport
system under evaluation

Figure 1
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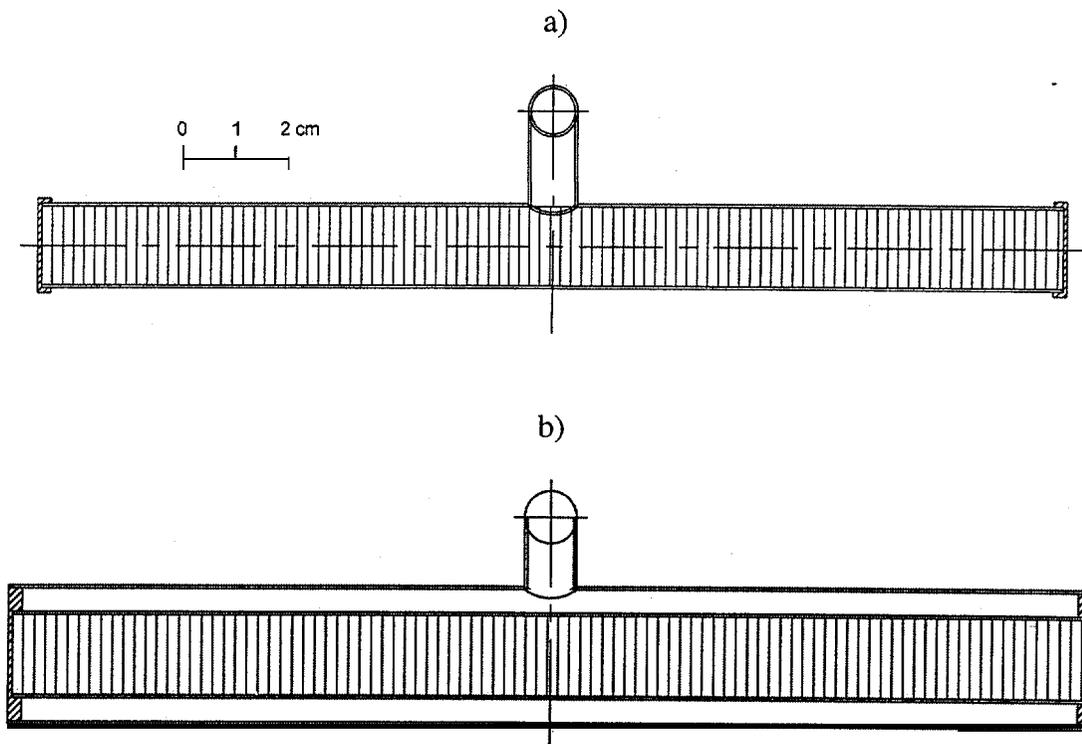
a)

0   1   2 cm

b)

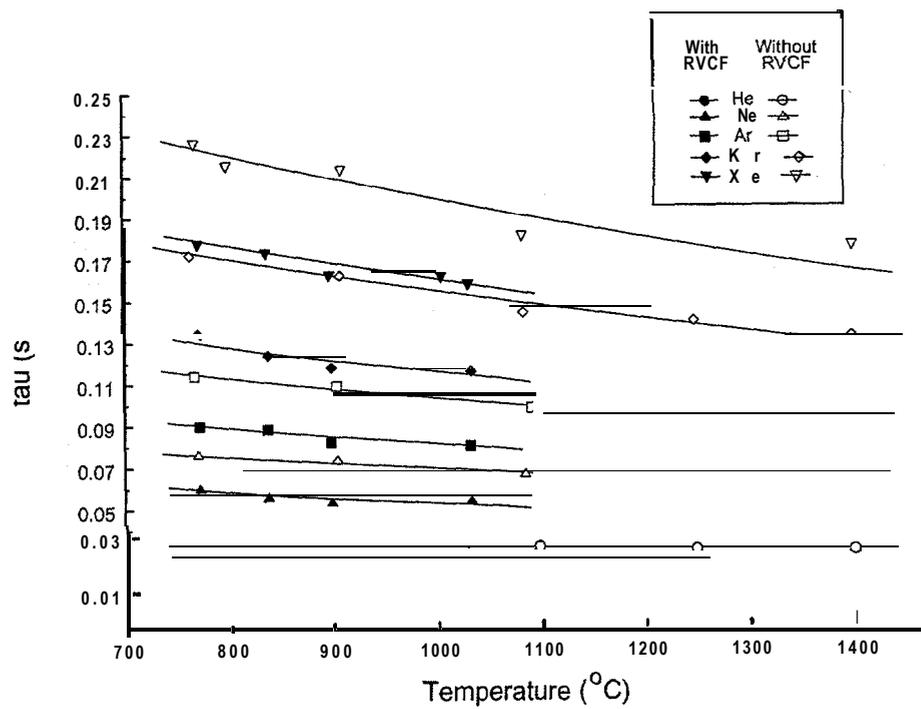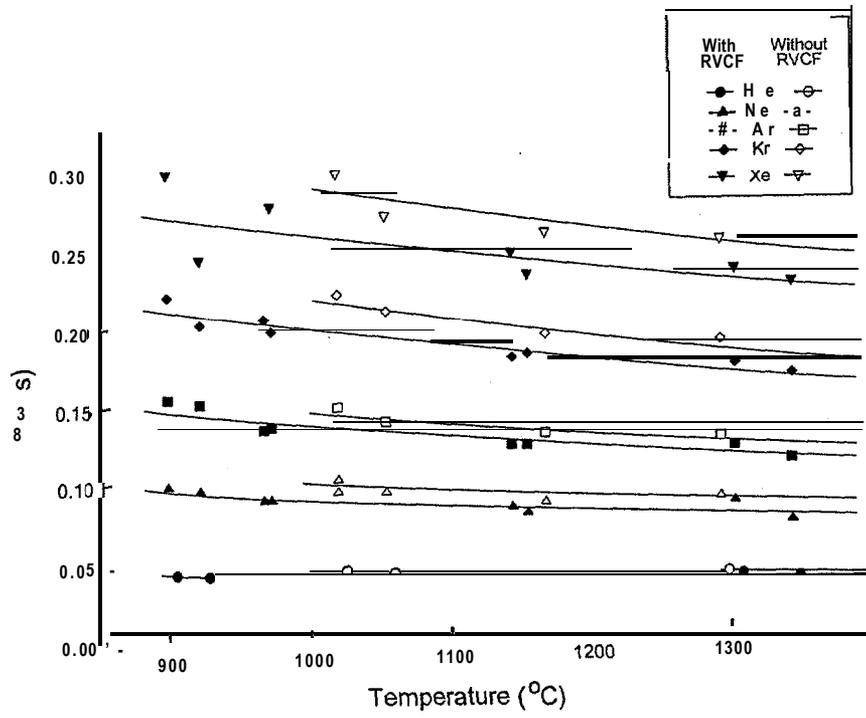Figure 2
Paper # 11.25, J.-C. Bilheux
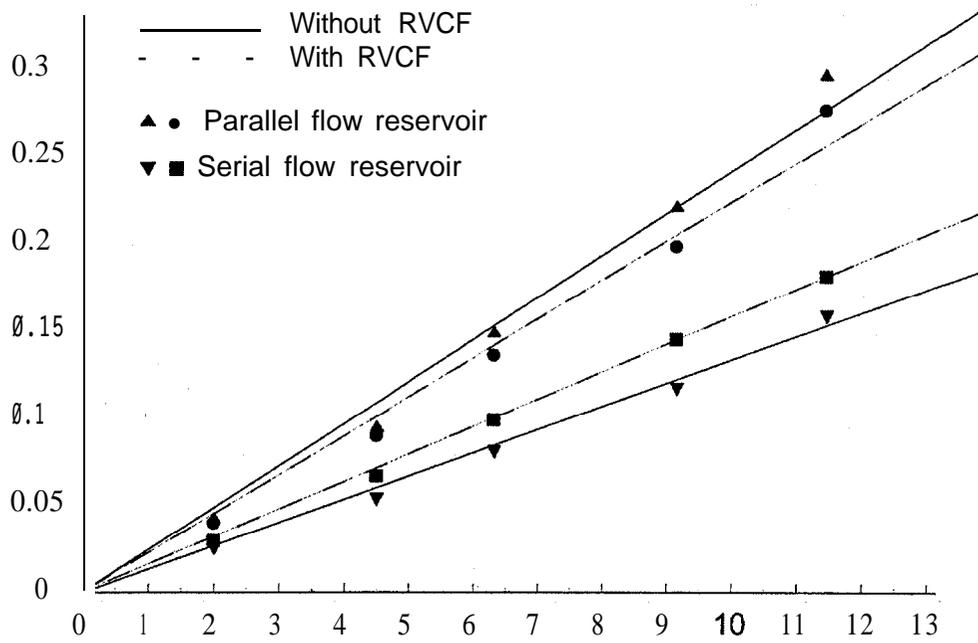
Figure 3.
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Fig 4.
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Figure 5.
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(a)

HEATER BUS

Re – VAPOR
TRANSPORT TUBE

0   1   2   3 cm.

LOW-DENSITY
TARGET-MATRIX

Re TARGET-HOLDER

MOUNTING
FLANGE

ANODE

ION EMISSION
APERTURE

EXTRACTION
ELECTRODE

VAPOR/GAS- INLET

To HEATER

ELECTRON EMISSION
SURFACE (CATHODE)

ION BEAM

(b)

Re – VAPOR
TRANSPORT TUBE

Re TARGET-HOLDER

LOW-DENSITY
TARGET-MATRIX

0   1   2   3 cm
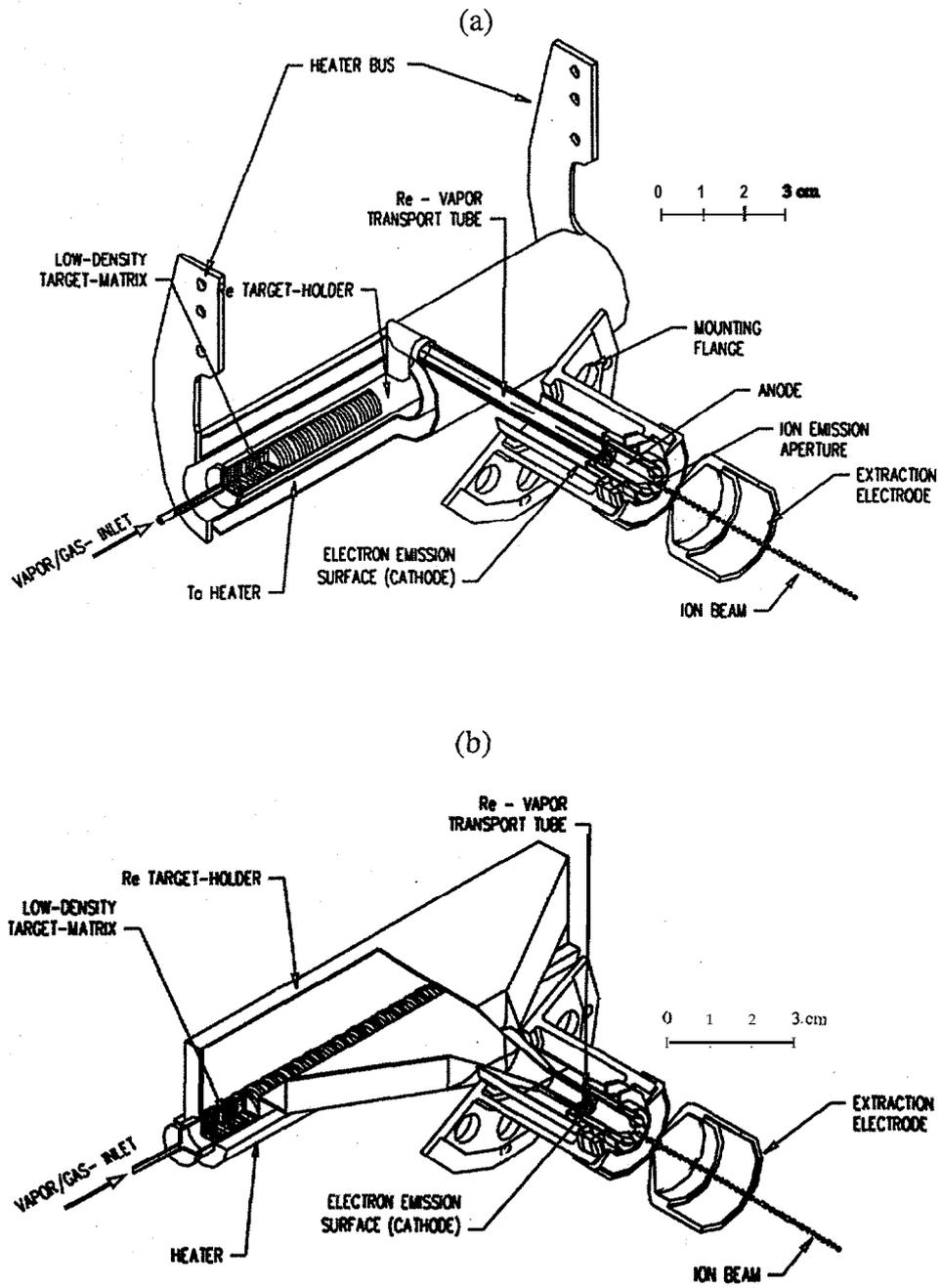
EXTRACTION
ELECTRODE

VAPOR/GAS- INLET

HEATER

ELECTRON EMISSION
SURFACE (CATHODE)

ION BEAM

Figure 6
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