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# TEMPERATURE EFFECTS ON CURRENT EMISSION IN AN ARTIFICIALLY HEATED MPD CATHODE

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## Abstract

The performance of a pulsed, multi-MW, gas-fed MPD thruster with cathode heating has been experimentally and theoretically investigated. An arc heater was used to heat 2% thoriated tungsten cathodes up to 2100 K on the tip, before each firing. The results show that the thermal conditions of the hot cathode allow a complete surface coverage of a thorium monolayer to be obtained and maintained for a time by far longer than the entire test duration. At these conditions, a diffuse, not erosive thermionic emission with Schottky effect from the cathode tip is compatible with the measurements of temperature, current density and surface electric field carried out so far. A study on the application of a pulsed MPD thruster with cathode heating in a LEO-GEO transfer mission of a large vehicle has indicated that a thoriated cathode with a surface in the order of 100 cm$^2$, heated at 2100-2200 K, is capable of providing a diffuse, not erosive field-enhanced thermionic emission of the arc current for the entire mission time, provided the electrode undergoes a preliminary flashing at about 2500 K for few minutes.

## Nomenclature

| | |
|---|---|
| $A$ | Richardson constant, A/cm$^2$ K$^2$ |
| $b$ | electromagnetic thrust coefficient, N/A$^2$ |
| $C$ | concentration, atoms/cm$^3$ |
| $D$ | diffusion coefficient, cm$^2$/s |
| dc | duty-cycle |
| $E$ | evaporation rate,atoms/cm$^2$ s |
| $F$ | electric field, V/m |
| $g$ | sea-level gravity acceleration, 9.81 m/s$^2$ |
| $h$ | Planck constant, 4.14x10$^{-4}$ eV/s |
| $I$ | current, kA |
| $I_{sp}$ | specific impulse, s |
| $j$ | current density, A/cm$^2$ |
| $k$ | Boltzmann constant, 8.63x10$^{-5}$ eV/K |
| $\dot{m}$ | mass flow rate, kg/s |
| $m_f$ | final vehicle mass, kg |
| $m_p$ | propellant mass, kg |
| $N$ | atoms per unit surface, atoms/cm$^2$ |
| $P$ | instantaneous power, W |
| $t_m$ | mission time, s |
| $T$ | temperature, K, thrust, N |
| $\gamma$ | diffusion rate, atoms/cm$^2$ s |
| $\Delta v$ | mission characteristic velocity, m/s |
| $\eta_t$ | thrust efficiency |
| $\varphi$ | work function, eV |
| $\theta$ | coverage degree |

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## Introduction

In a near-to-long term scenario, the application in space of MPD thrusters has been favourably considered for medium to high power primary missions, ranging from orbit-raising of large satellites to cargo interplanetary transfer. The high thrust density (up to $10^5$ N/m$^2$), the design simplicity, the robustness and the possibility, in principle, of using diverse propellants (gases, polymers, alkali metals) can be assumed as the most attractive features of MPD thrusters. Moreover, an high thrust efficiency (larger than 50%) for specific impulses from 2000 to 5000 s can be obtained at instantaneous operation power in the order of MWs, provided that an oculate choice of the propellant and of the thruster geometry is made[1-3]. Nevertheless, beside the high performance, a thruster lifetime long enough to meet the mission requirements must be assessed. Since the thruster operation involves high current levels (in the order of tens of kAs), the cathode depletion has proved to be the most critical occurrence limiting the thruster lifetime.

MPD cathodes are generally made of high melting temperature, low work function materials. Tungsten and tungsten alloys are extensively adopted. In a pulsed, low duty-cycle application (or during the start-up phase of a continuous operation), the cathode remains relatively cold and a spotty, highly erosive current emission takes place. On the contrary, high temperatures are generally reached during a continuous operation. In tests of MPD thrusters with thoriated tungsten cathodes, operating in a continuous mode at a power level in the order of 1 MW, temperatures higher than 3000 K on the cathode tip were observed [4]. At these temperatures, thorium, added to low the tungsten work function, completely evaporates in few minutes [5]. Although the temperature is high enough to establish a diffuse, not erosive thermionic emission also from a pure tungsten cathode, the tungsten evaporation rate is not negligible and could limit the thruster lifetime.

Consequently, in a pulsed as well as in a continuous operation, the cathode thermal condition proves to be a fundamental aspect and the cathode temperature control could be crucial for attaining a sufficiently long thruster lifetime. In fact, the temperature should be maintained high enough to allow a significant thorium coverage of the surface to reduce the work function and to allow a diffuse thermionic current emission during the entire mission, but not so high to induce a thorium evaporation rate incompatible with the lifetime requirements.

On pulsed thrusters, this objective can be achieved by adopting an artificial cathode heating technique [1,6] (to the same purpose, cathode cooling could be considered in a continuous operation).

In this paper, some results of an experimental and theoretical activity on a pulsed MPD thruster with cathode heating developed at Centrospazio are illustrated. Moreover, the effectiveness of the cathode temperature control by means of a heating technique on an MPD thruster used for a solar electric LEO to GEO transfer of a large space vehicle is discussed on the basis of the same results.

## Experimental Activity

***Experimental Apparatus.*** Experimental activities on a pulsed, multi-MW, gas-fed MPD thruster with the cathode artificially heated have been carried out at Centrospazio since 1992 [7-11].

The thruster, as shown in Fig. 1, consists of an axial, 2% thoriated tungsten cathode 20 mm in diameter and a coaxial, deoxidized copper anode, 100 mm in inner diameter, screwed on an aluminum body (anode-to-cathode radius ratio of 5). The insulators between the electrodes are made of boron nitride. The gas is injected into the discharge chamber by two separate feeding lines. The first one provides the injection at the cathode root through six orifices, the second provides the injection peripherally, towards the anode, through twelve equally spaced orifices, drilled in the bell-shaped insulator.

The cathode heater consists of a 2% thoriated tungsten electrode 3 mm in diameter placed inside the hollow cathode, with its conical edge a few mm from the cathode bottom. The cathode and the inner electrode are separated by boron nitride and alumina insulators. Before testing, the heater is evacuated and then filled with argon at 1 ata. The external surface of the cathode is heated by the electric arc ignited between the cathode itself and the inner electrode.

***Experimental Results.*** The experimental results obtained so far have shown that cathode heating has beneficial effects on thruster performance with respect to a cold operation. The hot cathode tests were performed having heated the electrode at temperatures of 2100-2300 K on the tip, before each shot. Cold and hot cathode operations with different cathode lengths and propellants have been compared in terms of electrical characteristics [9], thrust [8], plasma quantities in the cathode region [9,10], current distribution [10] and cathode surface erosion [9,10]. The most significant effects of cathode heating have proved to be a significant reduction in cathode erosion and a different current distribution on the cathode with respect to a relevant cold cathode operation.

Figs. 2 - 5 illustrate the nominal current density on four different cathode regions (as sketched in Fig. 6) with and without cathode heating, at 4 g/s of argon and 8 kA of total discharge current on a long cathode configuration (the measurement procedure is illustrated in Ref. 10). The following observations can be made:

- the current distribution appears more uniform on the hot than on the cold cathode. The hot cathode tip emits less current, whereas the other regions of the cathode, especially on the rear, are more involved in the current emission process.
- after a first phase during which the discharge is sustained by the rear cathode region, the discharge extends to the other zones more gradually in the hot cathode than in a cold electrode.
- the signals obtained with the heated cathode appear more regular and less affected by high frequency fluctuations.

Results gathered for different operating conditions are qualitatively similar to those illustrated above.

### Current Emission Regime Assessment

In thoriated tungsten cathodes, the temperature mainly affects the following phenomena [5,12-16]:

-thoria ($Th_2O$) reduction in the tungsten matrix;

-thorium (Th) diffusion towards the surface;

-thorium evaporation from the surface;

-current emission regime.

To assess the first two items, the inner cathode temperature must be known. Since this information can be hardly obtained by experiments, a numerical analysis of the cathode thermal condition was carried out for the long cathode configuration, by means of an ANSYS™ finite element model. The main numerical results are described in Refs. 11 and 17.

Limiting the discussion to the cathode tip region, for which the surface temperature is known from pyrometer measurements [9], the numerical results show that the temperature ranges from 2300 K in the heater arc attachment zone to 2100 K on the surface. Thus, an average temperature of 2200 K can be assumed in the cathode tip volume to evaluate thorium production and diffusion.

According to physical-chemical processes depending on the temperature field, thorium atoms form as a product of the reaction between tungsten and thoria compound ($ThO_2$), in the case discussed added to the tungsten matrix in a fraction of 2% in weight. Since at temperatures above 2000 K thorium reduction proceeds quite fast [12], the number of thorium atoms per unit surface N depends on the balance between the diffusion rate to the surface $\gamma$ and the evaporation rate E. Defining the coverage degree as:

$$\theta = \frac{N}{N_0}$$

(where $N_0 = 4.2 \times 10^{14}$ atoms/cm$^2$ is the thorium atoms per unit surface for a complete monolayer), the balance can be expressed by the equation [5]:

$$N_0 \frac{d\theta}{dt} = \gamma - E \qquad (1)$$

where $\theta$ ranges between 0 and 1, with the extremes corresponding to a pure tungsten surface and to a complete monolayer of thorium atoms, respectively.

The evaporation rate can be expressed as [5]:

$$E = k_d N_0 \theta$$

$k_d$ being the desorption rate, that can be expressed as [16]:

$$k_d = \frac{kT}{h} \exp\left(-\frac{7.5 - 0.1\theta}{kT}\right)$$

where the dependence of the evaporation rate from the coverage degree accounts for the repulsion among thorium atoms. For the same reason, thorium atoms can hardly accumulate on the surface, forming a multilayer ($\theta$>1), since the most external atoms are much less bounded to the surface and easily evaporate.

The diffusion rate can be expressed as:

$$\gamma = D\frac{\partial C}{\partial x}$$

where D (cm$^2$/s) is the diffusion coefficient and C is the thorium concentration (atoms/cm$^3$). The coordinate x indicates the diffusion direction.

The diffusion coefficient is the most uncertain parameter: it is not clear whether the thorium atoms migrate along the boundary of the grain or throughout the lattice. The following expressions, referring to both the mechanisms, are interpolations of experimental data[5]:

$$D = 0.66 \exp\left(-\frac{3.9}{kT}\right) \qquad \text{grain boundary diffusion}$$

$$D = 0.72 \exp\left(-\frac{5.2}{kT}\right) \qquad \text{lattice diffusion}$$

An expression for the rate of diffusion has been found by Belousova [15]. He solved the problem of finding the concentration of thorium atoms in a semi-infinitive solid as a function of time and temperature, considering an initial concentration $C_0$.

Adopting the same formalism of Ref. 5, the diffusion rate can be written as:

$$\gamma = \frac{C_0\sqrt{D}}{\sqrt{\pi t}} \qquad t \le \frac{\tau}{2}$$

$$\gamma = \frac{2DC_0}{d} exp\left(-\frac{t}{\tau}\right) \qquad t \ge \frac{\tau}{2}$$

where:

$$\tau = \frac{4d^2}{\pi^2 D}$$

and d indicates the tickness of the layer where the diffusion coefficient can be considered constant and equal to D.

This model can be applied with a good approximation also in the case of a finite body, provided d is much smaller than the other dimensions.

From an approximated solution of Eq. 1 (the dependence on θ of the evaporation rate [5] has not been considered), the time required to obtain a complete monolayer on the surface is about 90 seconds, assuming an initial decomposition of 0.3% of thoria with a temperature of 2200 K. Considering then the diffusion rate and the evaporation rate at 2100 K, a complete coverage for at least 44 hours of continuos operation can be maintained. This time is much longer than the overall running time of hot cathode tests performed so far. Thus, these results enforce the hypothesis that, during experiments with cathode heating, thorium coverage is present on the surface of the electrode tip.

Consequently, current densities in the order of 100 $A/cm^2$ , as measured in the low current case in the tip region at 2100 K (Fig. 2), result compatible with a thermionic emission regime with Schottky effect, expressed by:

$$j = AT^2 \exp(-\frac{\varphi - 3.79x10^{-5}\sqrt{F}}{kT})$$

Values of 15.5 $A/cm^2 K^2$ for the Richardson constant A and of 2.7 eV for the work function φ, relevant to the condition of a complete thorium monolayer covering the surface, were assumed, in accordance with the results of Refs. 14 and 18. The electric field at the surface F was estimated in the order of $5x10^7$ V/m, on the basis of the plasma parameter measurements [10].

As a conclusion, the theoretical and experimental study carried out so far seems to demonstrate that a thoriated tungsten cathode of an MPD thruster, with a temperature of 2100-2300 K is capable of providing current density in the order of 100 $A/cm^2$ in a field-enhanced thermionic emission regime. This diffuse emission seems to justify the cathode erosion reduction observed when operting with the electrode heated [9].

## Space Application Analysis

In this section, the effectiveness of a cathode heating technique in a pulsed MPD thruster for a space application is discussed.

The main task of a cathode heater is to guarantee a correct cathode operation for the entire mission time by establishing and maintaining thermal conditions on the cathode that promotes a diffuse, not erosive current emission. In thoriated tungsten cathodes, the heater must provide:

-a temperature high enough to obtain a sufficient thorium production from thoria reduction;

-a complete surface coverage of thorium;

-the maintenance of thorium coverage for the entire mission time.

To estimate how long the thorium coverage can be maintained as a function of the temperature, it is assumed that a coverage degree θ equal to 1 is already present on the surface. Thus, the equation:

$$E=\gamma$$

provides the minimum value of the depletion time t*, since the destruction of the monolayer begins for t >t*. Fig. 7 shows t* as a function of temperature, for both the diffusion mechanisms mentioned in the previous section and assuming an initial thorium concentration as obtained from the reduction of a half of the thoria in a layer 0.5 mm thick of a 2% thoriated cathode. These results should represent a conservative estimation of the depletion time, since a larger thorium amount should be available from the cathode volume below the layer. For temperature up to 2100-2200 K, the monolayer integrity results to be preserved for time longer than $10^7$ seconds. At temperatures higher than 2800 K the evaporation exceeds the lattice diffusion after few seconds and the grain boundary diffusion after few minutes. To accomplish a space mission, the depletion time so estimated must be at least of the same order of magnitude of the mission time.

The reduction of a sufficient ammount of thoria and the formation of a complete monolayer can be obtained by overheating (*flashing*) the cathode at the beginning of the mission. In fact, experiments on thoriated tungsten filaments [13] have shown that flashing the filament at a certain temperature and then maintaining a lower temperature for few minutes, thorium atoms, formed during flashing, migrate to and cover the surface without a significant evaporation. To obtain the initial decomposition of a half of the thoria in a 2% thoriated cathode, the flashing temperature should be around 2500 K [12].

***Reference Mission.*** As a reference mission, the low-thrust transfer from LEO to GEO of a vehicle with a final mass $m_f$ of 2000 kg is considered, with a $\Delta v$ of 6000 m/s [1]. The transfer time and the arc current are calculated on the basis of the following assumptions:

- 20 kW is the average power delivered to the thruster during the entire mission;
- the thruster operates in a pulsed, quasi-steady mode, with an instantaneous power P of 2 MW (1:100 of duty cycle dc);
- the power, the mass flow rate, the specific impulse and the thrust efficiency are constant during each pulse and mass flow losses are assumed negligible;
- the thrust is expressed by a quadratic function of the current (pure electromagnetic thrust assumption), with an electromagnetic thrust coefficient b of $2.5\times10^{-7}$ N/A$^2$.

The propellant mass can be thus obtained from the rocket equation as a function of the specific impulse:

$$m_p = m_f\left(\exp\left(\frac{\Delta v}{g I_{sp}}\right) - 1\right)$$

The mass flow rate during each pulse can be expressed as a function of the specific impulse and the thrust efficiency as follows:

$$\dot{m} = \frac{2\eta_t P}{I_{sp}^2 g^2}$$

the transfer time $t_m$ is thus given by:

$$t_m = \frac{m_p}{\dot{m}}\frac{1}{dc}$$

and the current during each pulse is obtained by considering that the instantaneous thrust is:

$$T = \dot{m} g I_{sp} = b I^2$$

and thus:

$$I = \sqrt{\frac{\dot{m} g I_{sp}}{b}}$$

In Tab. 1 the results for specific impulses of 2000, 3000, and 4000 s and thrust efficiencies of 50 and 60 % are shown.

The mission time ranges from about 1 to $2.6\times10^7$ s, the current level from about 15 to 25 kA. Referring to the results shown in the previous section, these currents can be emitted in a field-enhanced thermionic regime at temperatures of 2100-2300 K from a cathode with a surface in the order of 50-100 cm$^2$, that can be approximately obtained with a cylindrical cathode 3 cm in diameter and 5-10 cm long, comparable thus to the cathodes generally adopted in MPD thruster laboratory prototypes. Moreover, the mission time appears to match with the depletion time for temperatures up to 2100-2200 K. A detailed evaluation of the power required by the heater is not immediate and beyond the scope of this discussion. It is estimated in the order of 3-5 kW during the flashing operation and the start-up phase. During the mission, the duty-cycle should be high enough to provide the maintenance of the cathode temperature without a significant contribution from the heater.

| $I_{sp}$ [s] | *2000* | *3000* | *4000* |
|---|---|---|---|
| $\eta_t$ =50% | | | |
| $\dot{m}$ [$10^{-3}$kg/s] | 5 | 2.2 | 1.25 |
| t [$10^7$s] | 1.4 | 2 | 2.6 |
| T [N] | 100 | 66.7 | 50 |
| I [kA] | 20.85 | 17 | 14.7 |
| $\eta_t$ =60% | | | |
| $\dot{m}$ [$10^{-3}$kg/s] | 6 | 2.67 | 1.5 |
| t [$10^7$s] | 1.17 | 1.67 | 2.13 |
| T [N] | 120 | 80 | 60 |
| I [kA] | 22.8 | 18.7 | 16.2 |

**Tab. 1 - Mission analysis results**

## Concluding Remarks

The theoretical and experimental results illustrated in this paper indicate that the heating of a thoriated tungsten cathode of an MPD thruster affects significantly the emission mode of the electrode. The temperatures reached on the cathode tip region, ranging from 2300 and 2100 K, proved to be high enough to allow a significant thoria reduction and a complete thorium coverage on the surface. The associated work function reduction, together with a relatively high electric field at the surface, induced by the thruster plasma, seem to allow the current to be emitted from the cathode tip in a thermionic regime with Schottky effect, for current densities in the order of 100 $A/cm^2$ , as actually measured.

The effectiveness of a cathode heater in a pulsed MPD thruster used for a primary mission, like the LEO-GEO transfer of a large vehicle has been assessed as well. The study indicates that an MPD thoriated cathode of standard dimension, heated at temperatures in the order of 2100-2200 K is capable of providing a diffuse, not erosive field-enhanced thermionic emission of the arc current for the entire mission time, provided the electrode undergoes a preliminary flashing at about 2500 K for few minutes.

As a conclusion, cathode heating, or more in general, cathode temperature control seems to be a promising technique in view of the MPD thruster application in space.

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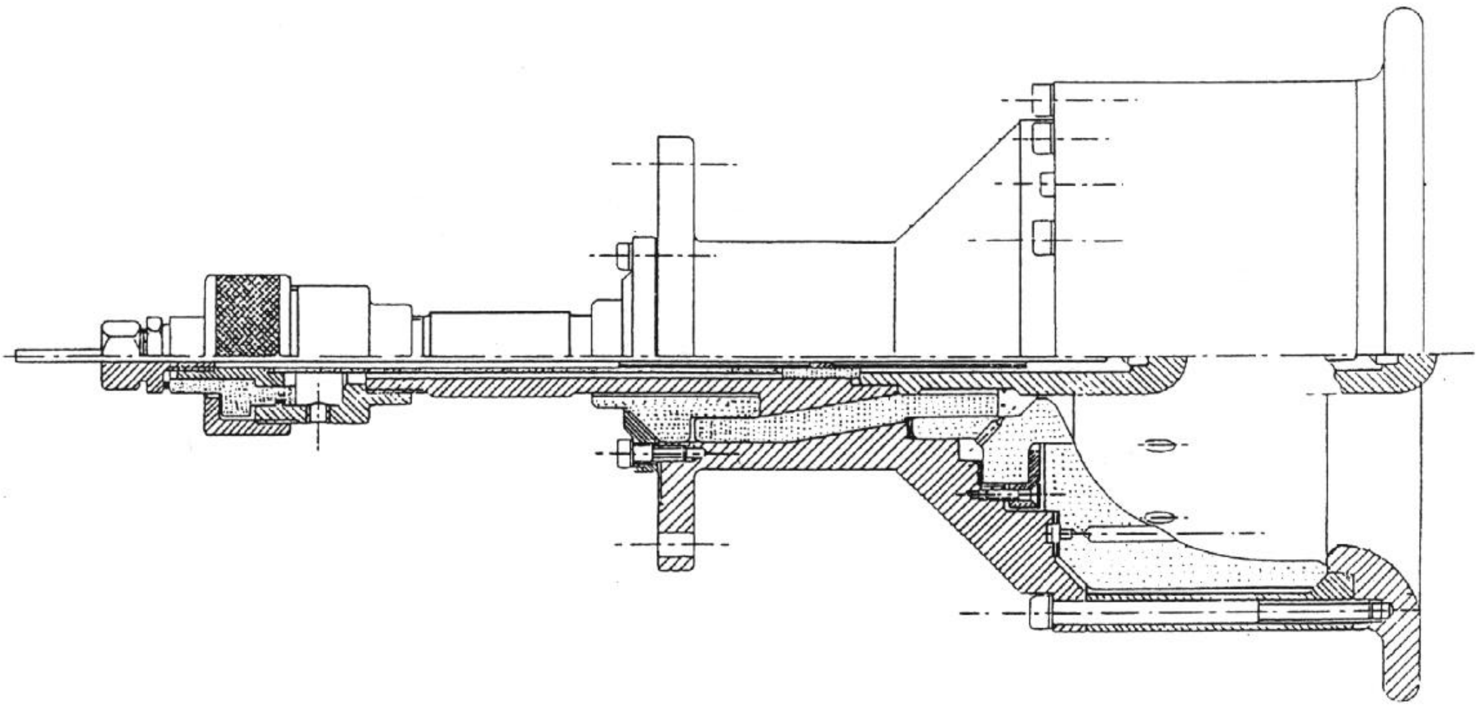

Fig. 1 Experimental apparatus

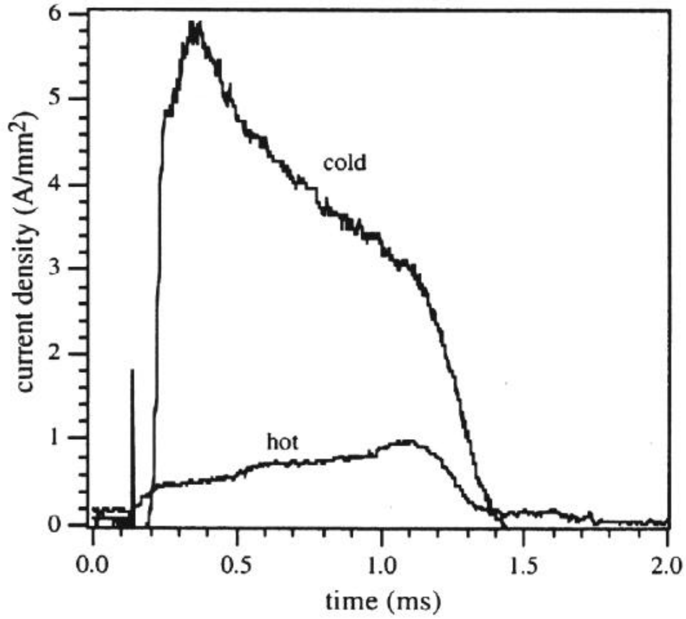


Fig. 2 Current density on the 1C zone (cathode tip) with and without cathode heating

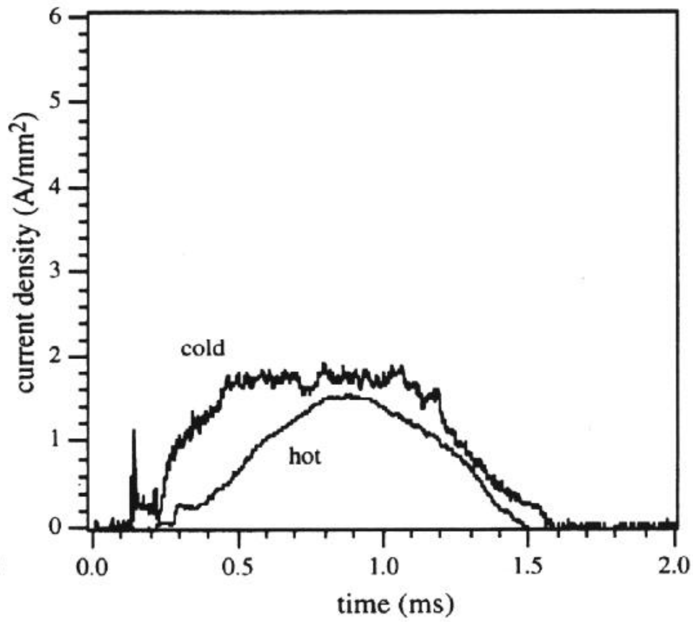


Fig. 3 Current density on the 2C zone with and without cathode heating

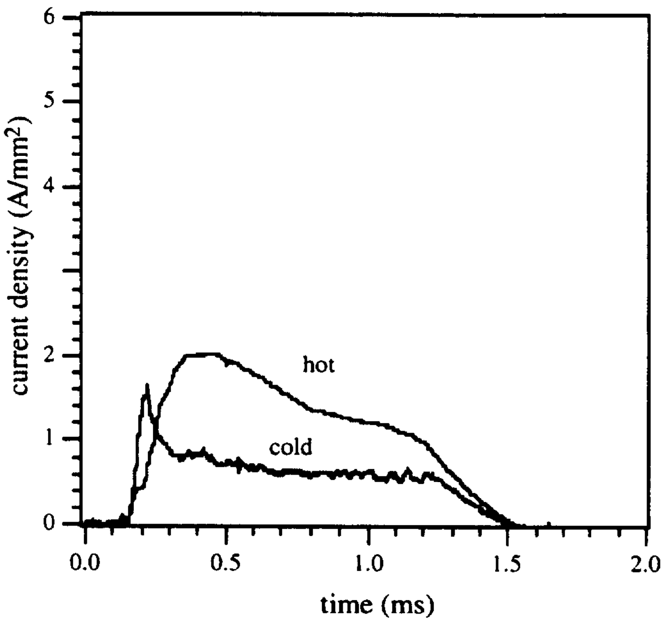


**Fig. 4 Current density on the 3C zone with and without cathode heating**

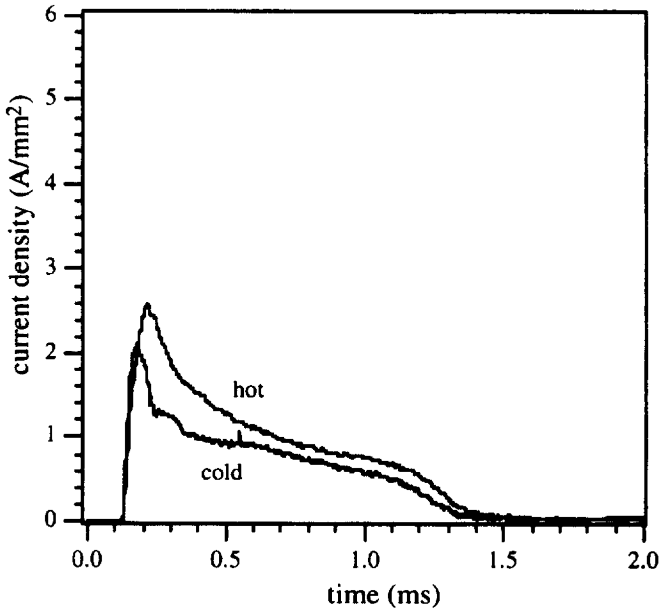


**Fig. 5 Current density on the 4C zone with and without cathode heating**

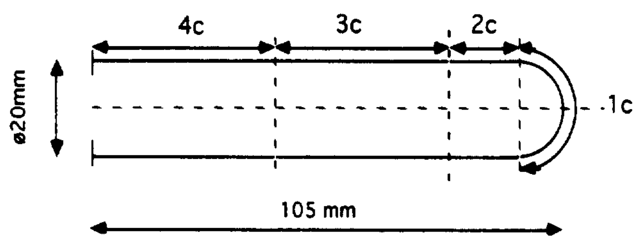


**Fig. 6 Cathode zones (see Refs. 10 and 11 for details on current density measurements)**

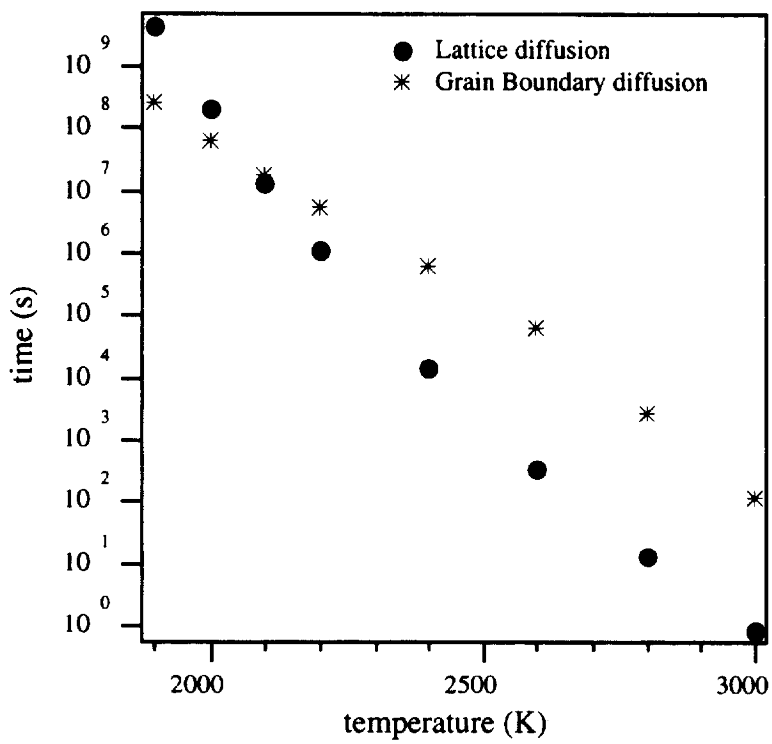


**Fig. 7 Thorium coverage depletion time vs temperature in vacuum conditions**