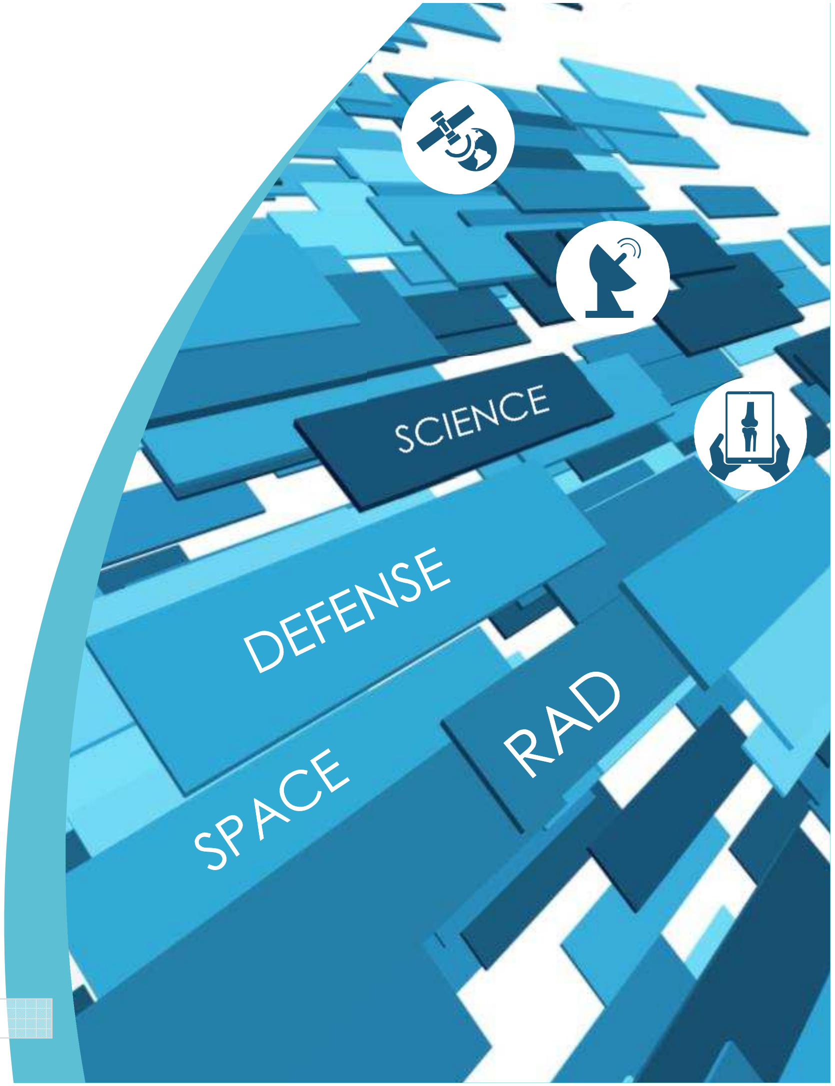
THALES

Work function of dispenser cathodes and life prediction model

VDE-ITG CONFERENCE BAD-HONNEF 5-6/09/2018
L1. 1-2

JEAN-MICHEL ROQUAIS



OUTLINE

- Presentation of Thales AVS FR in Vélizy France
- Impregnated cathode description
- Characterization of cathodes (physical and chemical)
- Model of dispenser cathodes
- Model vs. Experimental results

TAVS in Vélizy France

- **Design and production of Traveling Wave Tubes, klystrons, gyrotrons, generators, space amplifiers, defense transmitters, energy storage…**

KLYSTRON MULTI FAISCEAUX

KLYSTRON

KLYSTRON

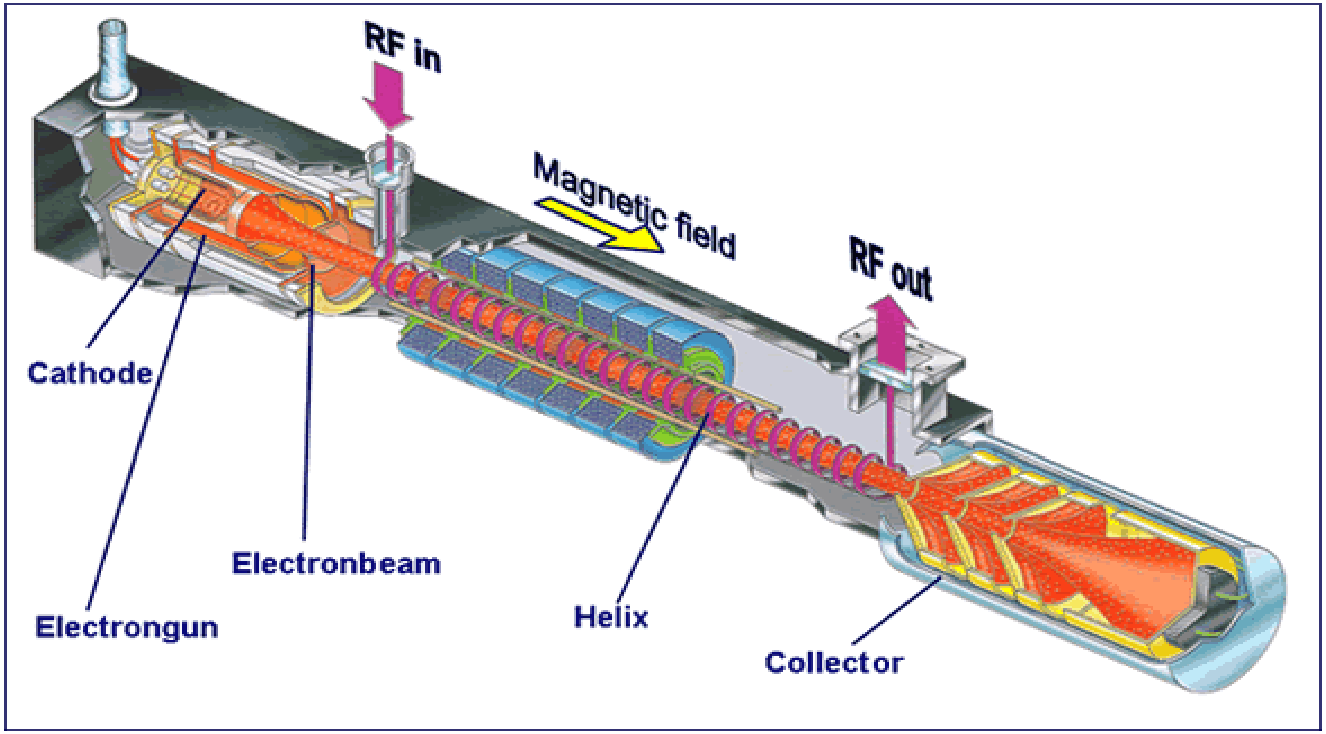
SPACE AMPLIFIER

TRANSMITTER FOR RADAR

GYROTRON

WORLD #1 FOR SPACE AND SCIENCE TUBES
EUROPEAN #1 FOR TELECOM AND DEFENSE TUBES

Cathodes in TWT's

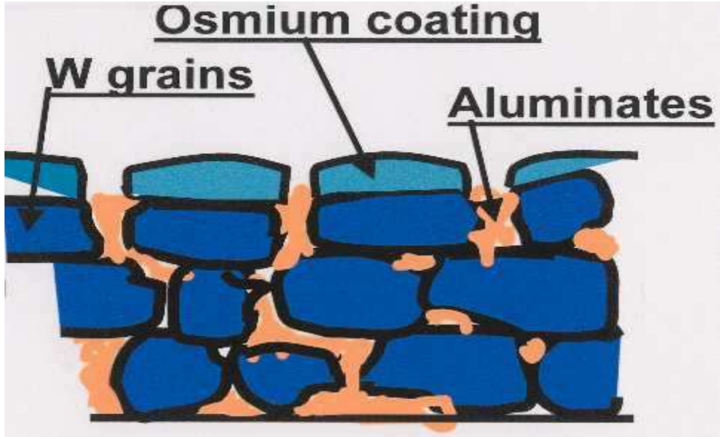


Helix TWT with impregnated cathode

Cathodes in Orbit: reliability considerations

Impregnated cathode description

Cathodes in use at TAVS:

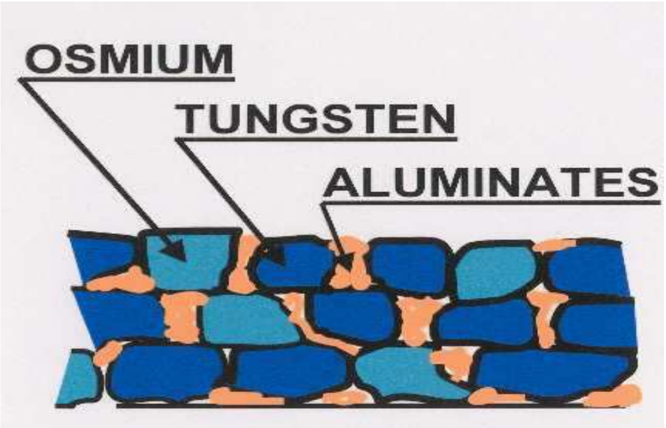


M-type cathode

Porous tungsten pellet
(porosity 18 %)
Impregnated with barium,,calcium aluminates
Osmium or Os-Ru coated (0.5 µm)

MM-Type cathode

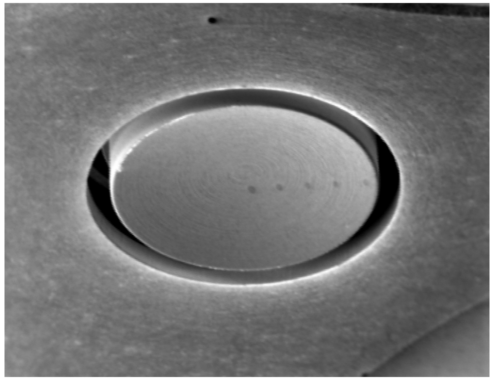
Porous tungsten-osmium pellet
Impregnated with barium, calcium aluminates

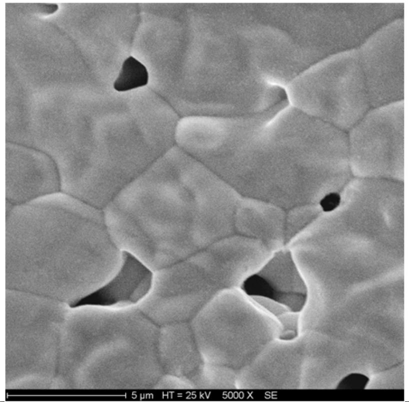


Characterization of cathodes (physical and chemical)

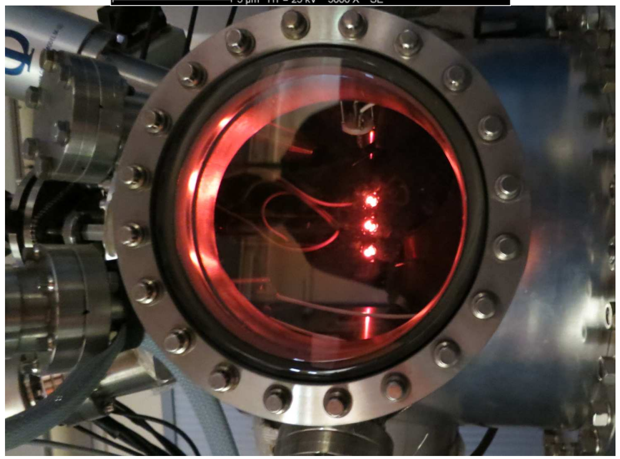
Auger spectroscopy

Phoibos spectrometer from SPECS GmbH



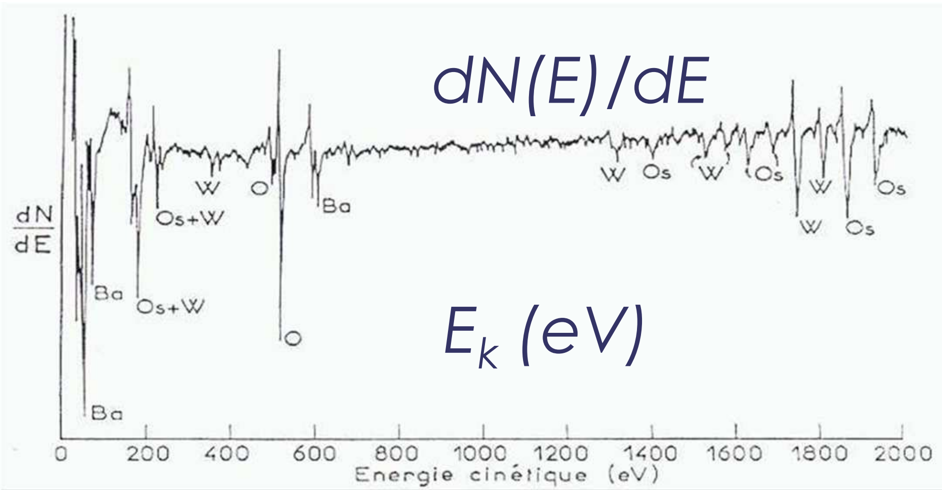


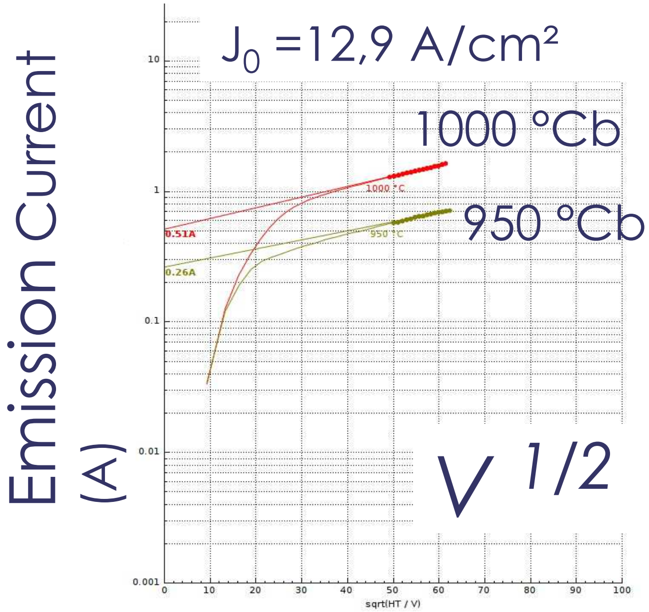
In situ image of cathode by SED: e spots by « carbon pinning »



Characterization of cathodes (physical and chemical)

- Auger spectroscopy combined with in in-situ emission meas't (J_0)
- Only Ba, O, W and Os detected on cathode surface after activation
- Selection of « Best in class cath. »

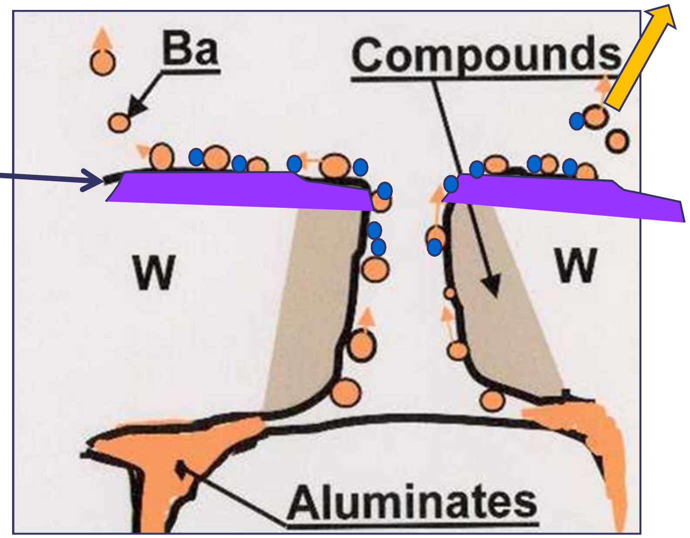




Model of dispenser cathode

- Chemical reactions inside the pores, Ba and O transport over the W surface
- Build-up of 1monolayer (θ = 1) or sub-monolayer (θ< 1) of Ba-O

Os/W

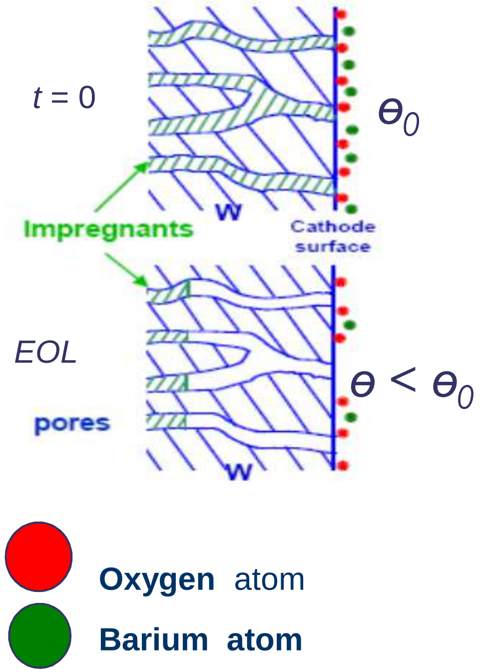


Oxygen

Baryum

M-type cathode

Model of dispenser cathodes



LIFETIME MODEL COMMON BASIS: The study on dispenser cathode life of Longo (Hugues Aircraft) shows a trend of emission slump

$* \Delta J_n \sim t^{1/2}$.

His life model is based on calculation of Ba coverage $\boldsymbol{\theta}$ variation with time.

The trend $\Delta J_n \sim t$ ½ has been confirmed by several authors:

- **Mita**(NEC), **Higuchi** (Toshiba), **Shroff**(Thales)

$*J_n$ = cathode operating current density in tube

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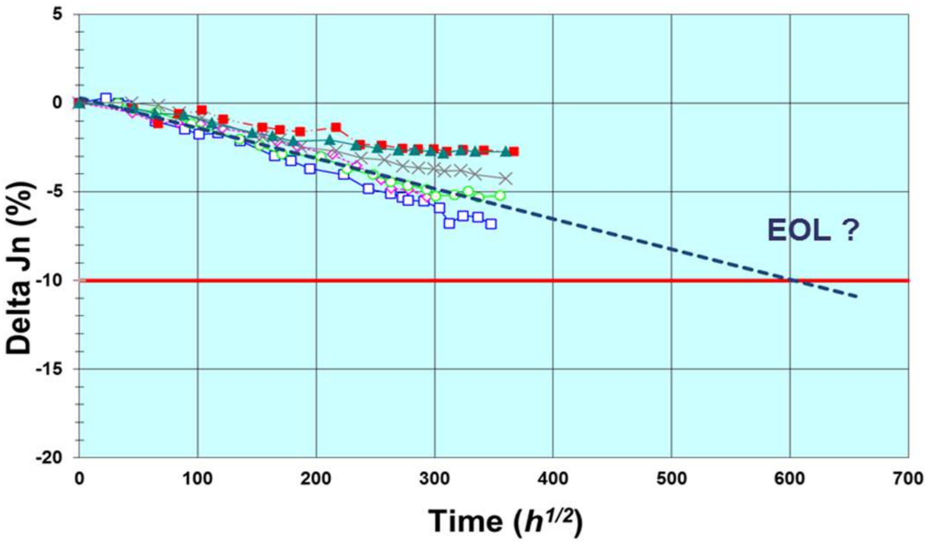
Model of dispenser cathodes

Decrease of nominal current of the cathodes with time

- $\Delta J_n \sim t^{1/2}$ trend verified on TWT's at Thales
- Can we extrapolate the trend to determine the End Of Life?



20 W –Ku :

- J_n = 0,7 A/cm²
- T = 1010 °C_B

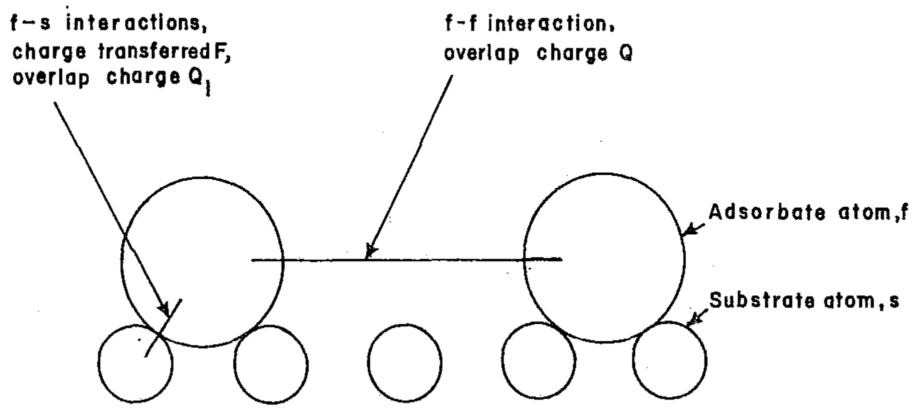
Model of dispenser cathodes

The different bricks to build the cathode lifetime model used in * Thales

Brick 1: Longo and Vaughan :

$$\frac{1}{(J_n)^n} = \frac{1}{(J_{SC})^n} + \frac{1}{(J_{TL})^n}$$

Brick 2: Gyftopoulos & Steiner:



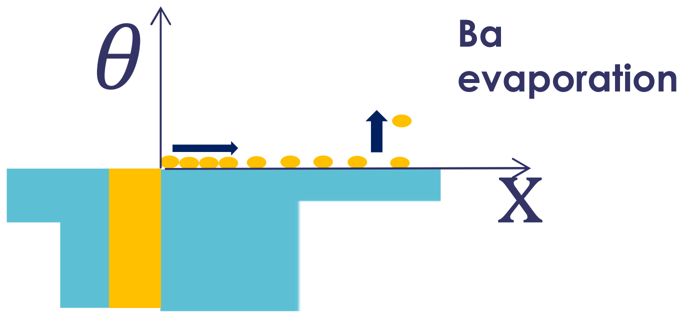
*** A.M. Shroff model**

Model of dispenser cathodes

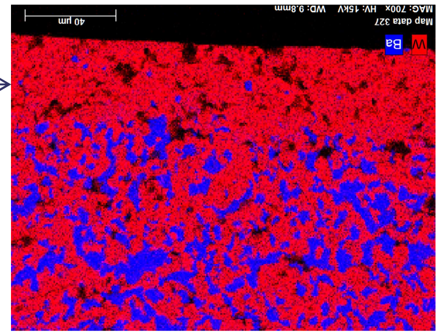
The different bricks to build the model of Shroff

Brick 3: Fote & Luey

Fraction of Ba monolayer θ as a function of distance from the matrix pore



Brick 4: Shroff study of Ba depletion



Cross section

Model of dispenser cathodes

Brick 1: Longo-Vaughan

Cathode nominal current Jn can be calculated using the *LONGO-VAUGHAN* equation

$$\frac{1}{(J_n)^n} = \frac{1}{(J_{SC})^n} + \frac{1}{(J_{TL})^n}$$

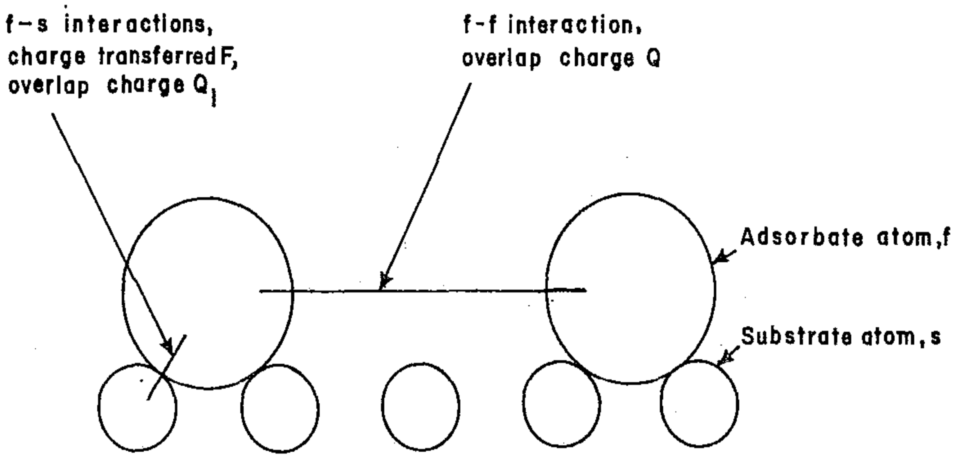
- J_n : operating current density of the cathode in the tube
- J_{sc} : current density of the cathode in space charge regime
- J_{TL} : *current density of the cathode in temperature-limited regime (~ J_0).
- n: Vaughan exponent between 1 and 6

Model of dispenser cathodes

Brick 2: Gyftopoulos & Steiner

$$\Phi(\theta) = \Phi s + CQ(\theta) + bF(\theta)$$

$$\Phi(\theta) = \Phi s - (\Phi s - \Phi f) M(\theta) + bF(\theta)$$



Φs : substrate work function

$CQ(\theta)$: covalent contribution

$bF(\theta)$: dipole moment

Φf : film work function

$M(\theta)$: Morse function $(M(1) = 1; M(0) = 0)$

Model of dispenser cathodes

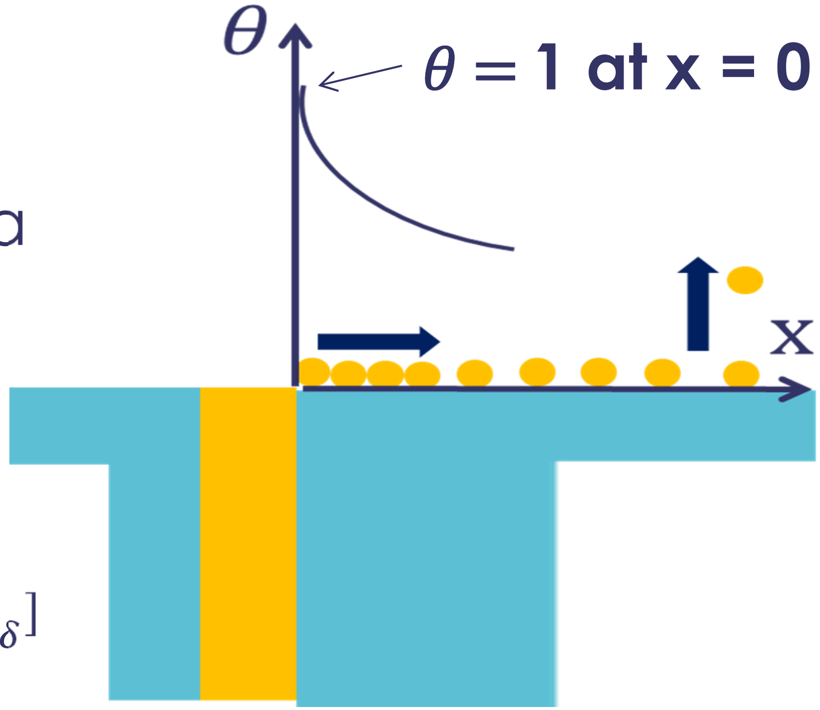
Brick 3: Fote and Luey: transport of Ba over the emitting face

➔ θ as a function of distance x from the Ba source

$$D\frac{d^2\theta}{d^2x} = \frac{\theta^\nu}{\tau}$$

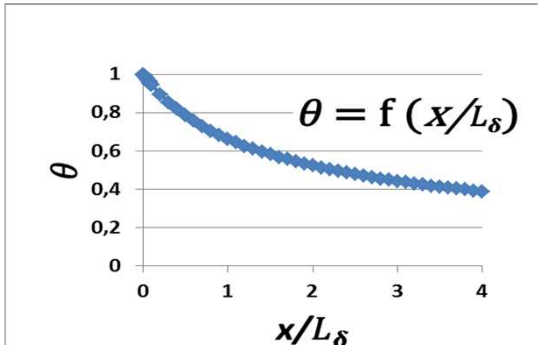
$$L_\delta = (D.\tau)^{1/2}$$

$$L_{\delta(cm)} = 8.10^{-5}.e^{\left[\frac{11600}{T}V_{L_\delta}\right]}$$



Model of dispenser cathodes

Fote & Luey unidimensional model: θ as a function of distance from the Ba source scaled to L_δ



$$\theta_x = \left[1 + \frac{\nu - 1}{\sqrt{2(\nu + 1)}} . \frac{x}{L_\delta}\right]^{-2/(\nu - 1)}$$

L_δ *is the "effective diffusion length" over which emission is space charge limited (slotted pore geometry)*

At $x = L_\delta$ *the value of* θ *is* $0{,}67$ $(i.e\ \frac{2}{3}$ *of* $ML)$

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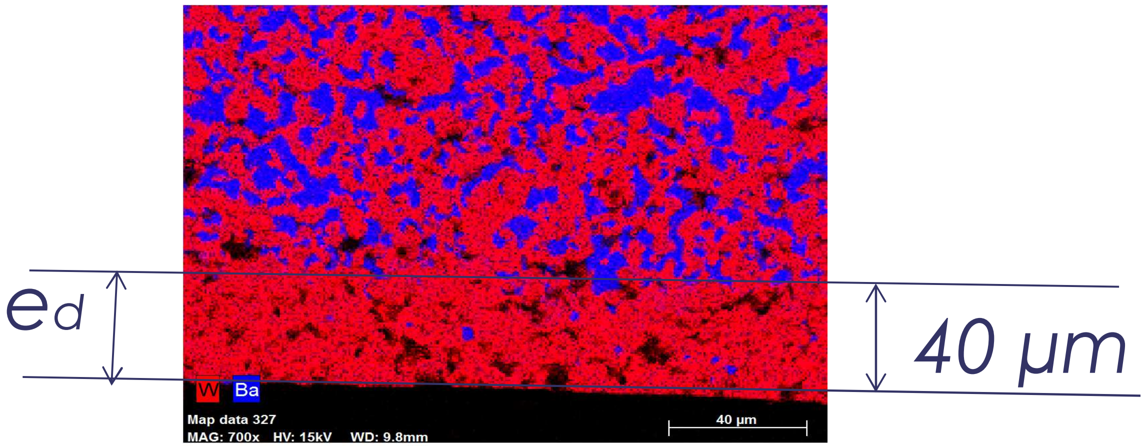
Model of dispenser cathodes

Brick 4: Schroff's study of Ba depletion

- Ba depletion e_d measured by EDX
- On real cathodes in diodes at different intervals of time and temperature



Ba mapping by EDX

Model of dispenser cathodes

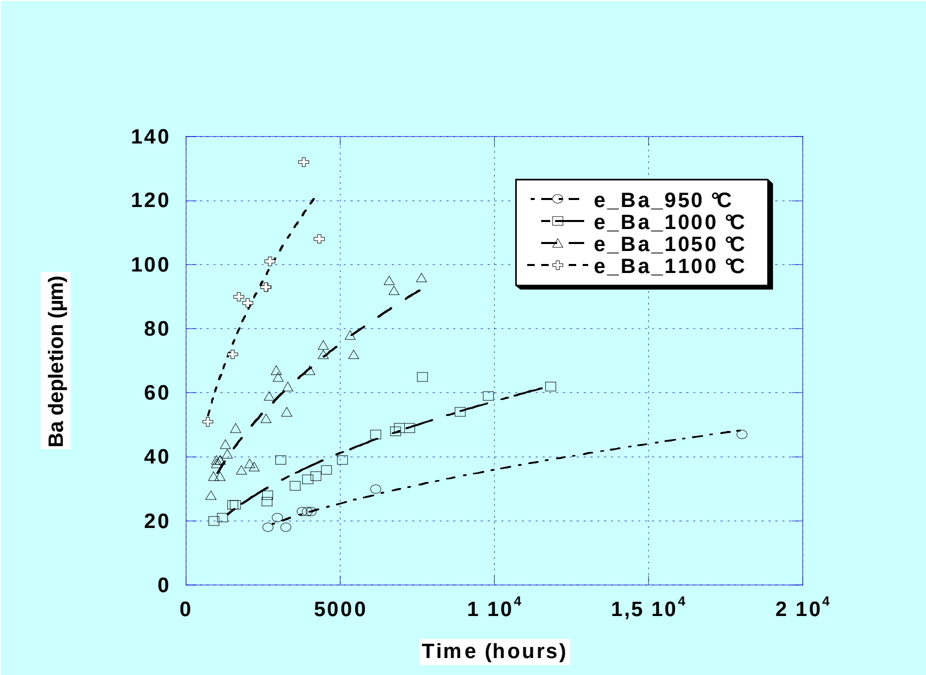
Ba depletion depth with time (experimental)

$$e\,(t,T) = A_{\prod}.\,t^{1/2}.\,e^{\left[\frac{-11600}{T}\left(\frac{V_e}{2}\right)\right]}$$

V_e : activation energy of

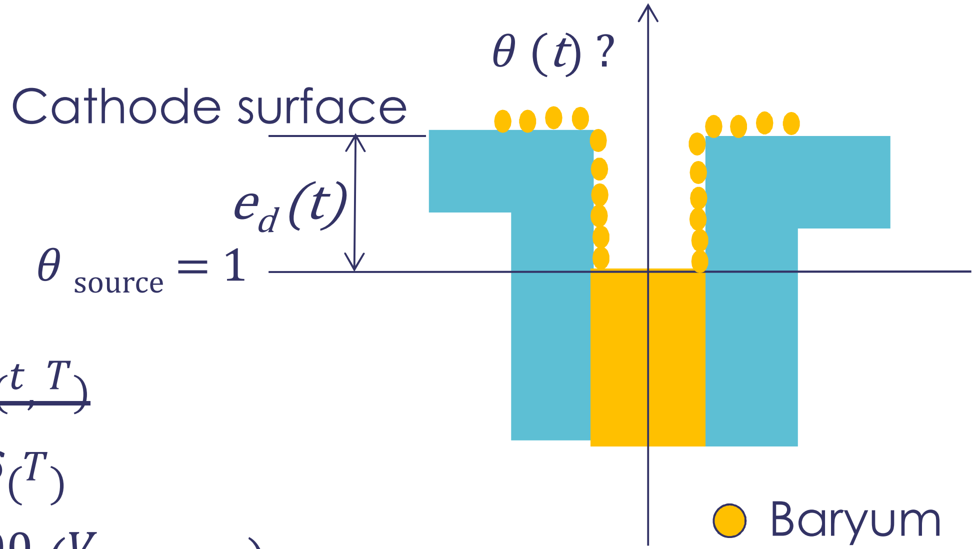
the depletion deduced from experiment

Depletion measurements presented by J.M. Roquais *et al.* IVESC 2002 in Saratov



Model of dispenser cathodes

Shroff 's model: surface diffusion inside the pores (unidimensional)



$$\theta\,(t,T) = 1 - \sqrt{2/\nu + 1}\,.\,\frac{e_{d}(t,T)}{L_{\delta}(T)}$$

$$\Delta\theta\,(t,T) = -\,\alpha\,.\,t^{1/2}\,.\,e^{\left[\frac{-11600}{T}\left(\frac{V_{ed}}{2}+V_{L\delta}\right)\right]}$$

$$V_\theta(eV) = \left(\frac{V_{ed}}{2} + V_{L_\delta}\right)$$

$$2{,}1 < V_\theta < 2{,}4$$

Model of dispenser cathodes

- **Saturation and space charge currents can be calculated at any time with following approximations:**
  - $J_0\ (t, T) = f(\Phi) = f(\theta)$
  - $J_{sc}\ (t, T) = J_{sc}\ (t=0).\ \theta\,(t)/\theta_0$

Calculation of *Jsc* and *Js* evolution with time ➔ J_n vs time

$$\frac{1}{(J_n)^n}(t) = \frac{1}{(J_{sc})^n}(t) + \frac{1}{(J_0)\hat{}n}(t)$$

Model vs. Experimental results

Available experimental data

- J0 as a function of time (measured in **bulbs in diode configuration**)
- Jn as a function of time measured in **TWT's** and **Test vehicles (TV's)**

Calculation method (Excel)

- Parameters initially set (for M-type cathode):
  - Temperature: T= life-test operating temperature
  - J0 (t=0) = 11 A/cm² at 1000 °CB
- Adjustable parameters :
  - V_θ : Activation energy of θ
  - initial coverage θ_0: 0,8 -1,0

Model vs. Experimental results

Gyftopoulos & Steiner applied to our M-type cathode

$$\Phi(\theta) = \Phi s + CQ(\theta) + bF(\theta)$$

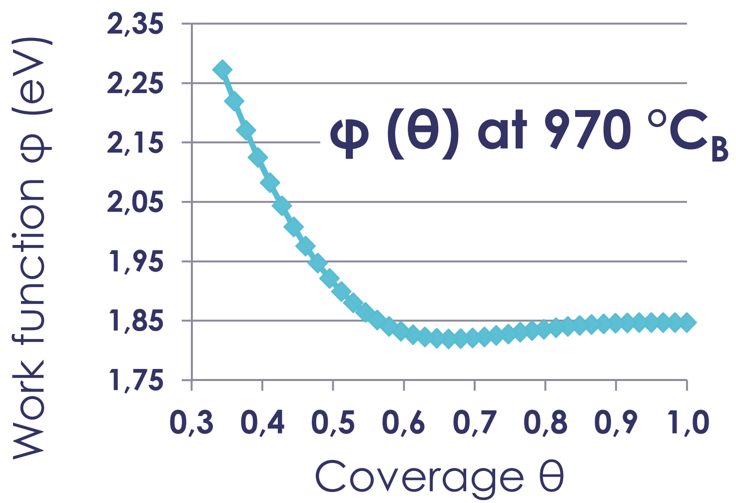
$$\Phi(\theta) = \Phi s - (\Phi s - \Phi f)M(\theta) + bF(\theta)$$

Φs : substrate work function (W-Os)

Φf : film work function (exp. values)

$CQ(\theta)$: covalent contribution (G-S calc.)

$bF(\theta)$: dipole moment (G-S calc.)



Minimum of $\Phi(\theta)$ occurs for $\theta \sim 2/3$

Model vs. Experimental results

J_0 *vs. Time* : comparison of our model with meas. in diodes at 1000 °C_B

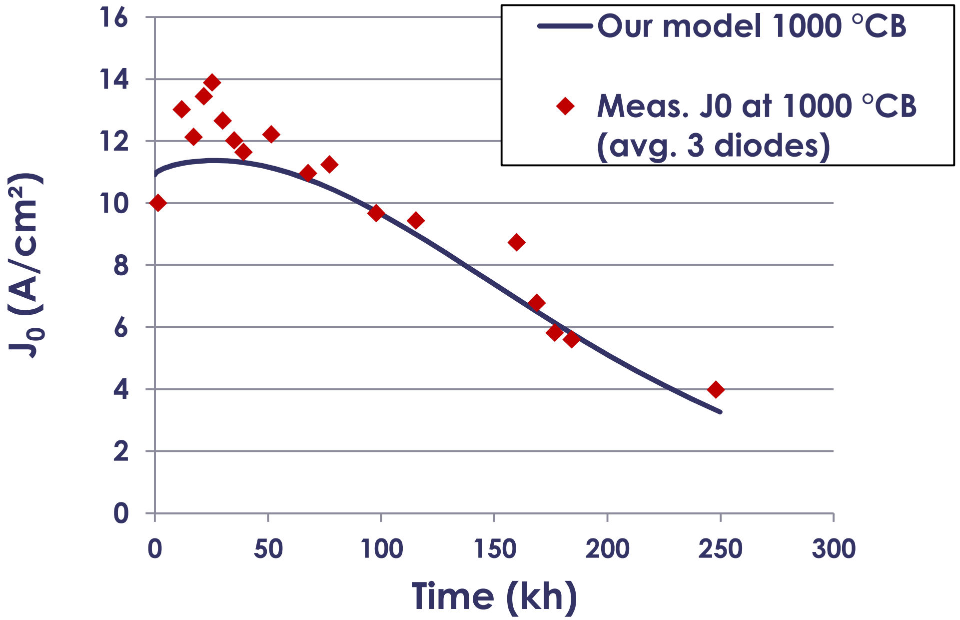
Calculation at 1000 °C_B:

$\theta_{(t)}$ => $\varphi_{(t)}$ => * $J_{0(t)}$

With:

$\theta_0 = 0{,}8$

$V_\theta = 2{,}13$ eV (Schroff's value)



* J_0 calculated using the Richardson-Dushman equation

Model vs. Experimental results

J_0 vs. *Time* : comparison of our model with meas. in diodes at 1030 °C_B

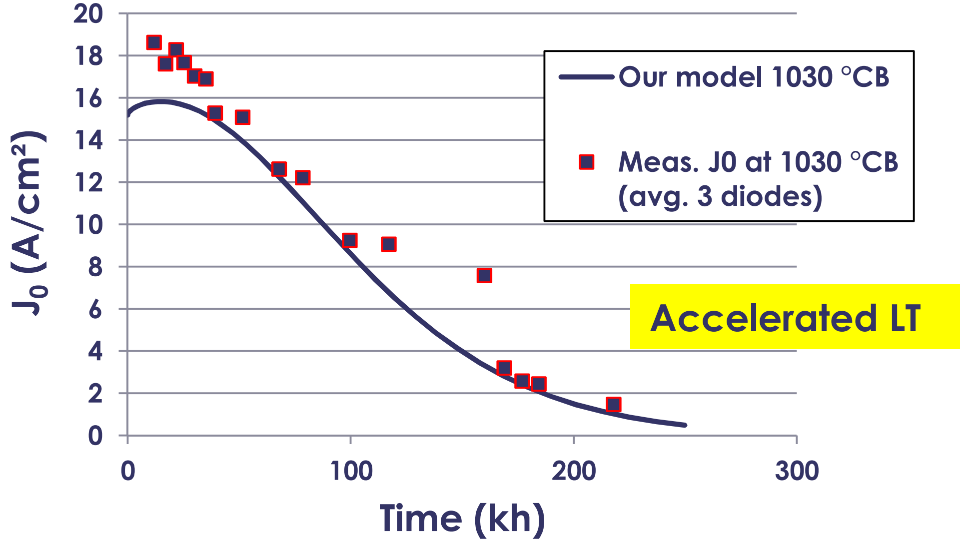
Calculation at 1030 °C_B:

$\theta_{(t)} \Rightarrow \varphi_{(t)} \Rightarrow J_{0(t)}$

With:

$\theta_0 = 0{,}8$ (best fit)

$V_\theta = 2{,}13$ eV (Schroff's value)



The good fit at 1000 and 1030 ° C_B validates our calculation of θ(t) and φ (t)

Model vs. Experimental results

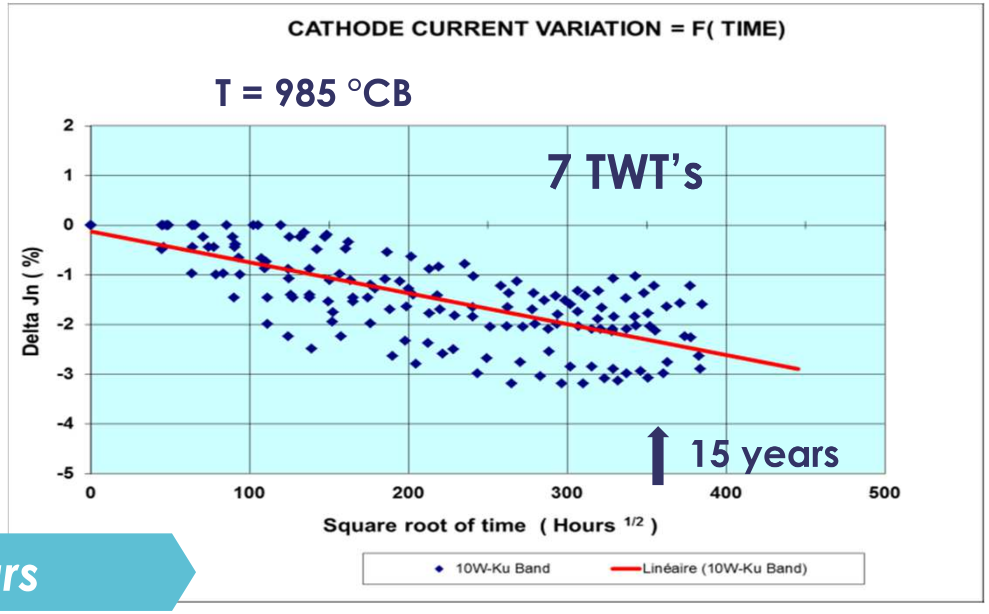
Calibration of $\Delta\theta\,(t,T)$ *using experimental data of tubes life-test*

V_θ adjusted to match emission decay in TWT's

$$\Delta\theta\,(t,T) = -\,\alpha.t^{1/2}.e^{\left[\frac{-11600}{T}V_\theta\right]}$$

$$\Delta J_{SC}\,(t,T)/J_{SC0} = \Delta\theta\,(t,T)/\theta_0$$

$$V_\theta \sim 2{,}13\ \text{eV} + \Delta V_\theta$$



Decay is only ~3% after 15 years

Model vs. Experimental results

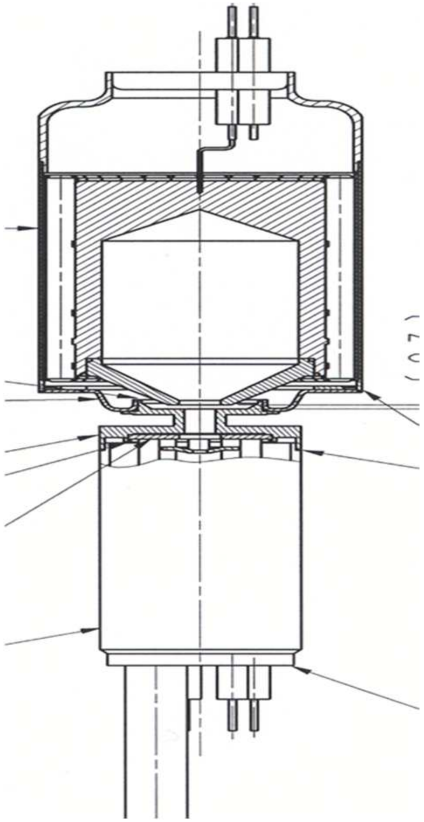
Test vehicle: gun/collector

Conditions

- No microwave signal
- 3 x TV's in life at 2 different T°C:
    - **985 °CB (2 TV's)**
    - **1045 °CB (1 TV): accelerated LT**

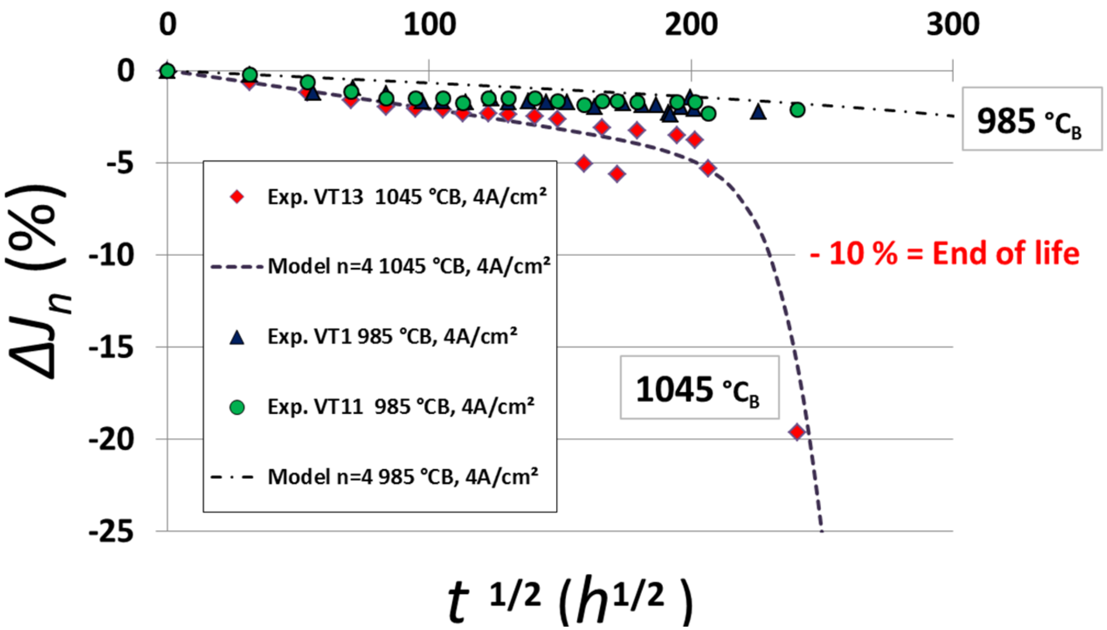
Measurements

- **Jn vs. time**



Model vs. Experimental results

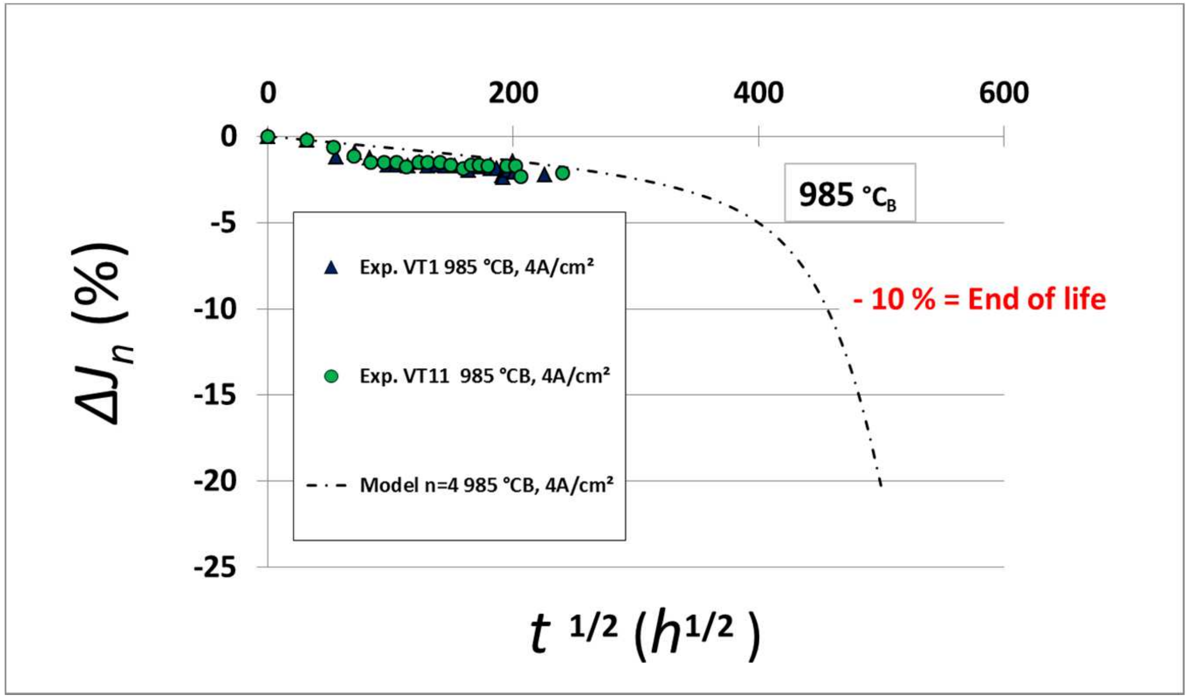
- Gun/collector vehicle
- Jn $_{(t=0)}$ = 4 A/cm²
- 1 VT at 1045 ° C_B
- 2 VT's at 985 ° C_B



Model describes well experimental results. Jn departs from t ½ law at 1045 °C_B at t ~ 40 kh.

Model vs. Experimental results

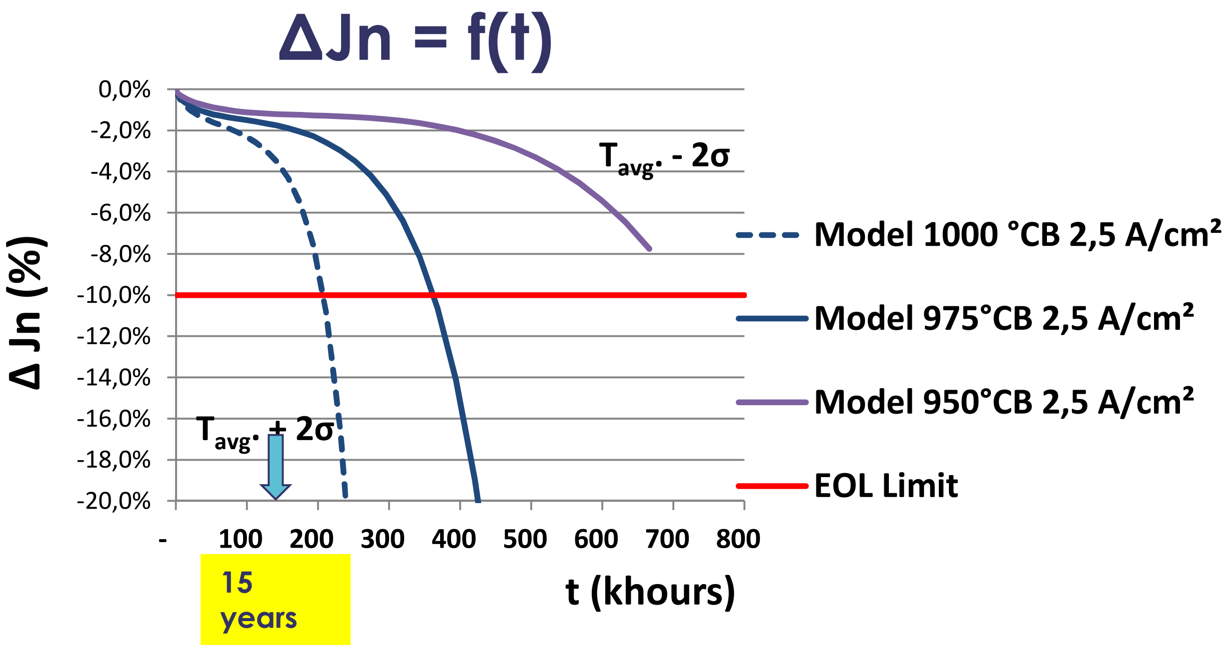
- Projection of lifetime with model
- Jn $_{(t = 0)}$ = 4 A/cm²



Projected EOL > 160 000 h at 985 °CB for Jn = 4 A/cm

Long-term LT: Prediction

- **Prediction of cathode life in Tubes**
- **Jn (t = 0) = 2,5 A/cm²**
- **T avg. = 975 °C_B**
- **Calculation at:**
  - T avg. + 2 σ
  - T avg.
  - T avg. - 2 σ



CONCLUSION

As a summary on the Long-term life tests and model:

Experimental:

- In diodes, the M-type cathodes are still capable of J_0 = 8A/cm² after 15 years at 1000 °C_B
- In TWT's at 0,6 A/cm², **Δ J_n ~ - 3% after 15 years at 985°C_B**

Model/ lifetime calculation :

- The long-term data have allowed to adjust the model parameters
- The law of variation of J_n is well predicted by the lifetime model **including the final abrupt decay observed in accelerated lifetests**
- For 975 °CB at 2,5 A/cm², or 985 °CB at 4 A/cm² **the cathode lifetime exceeds clearly 15 years**

Thank you for your attention !!

Long-term LT: Prediction

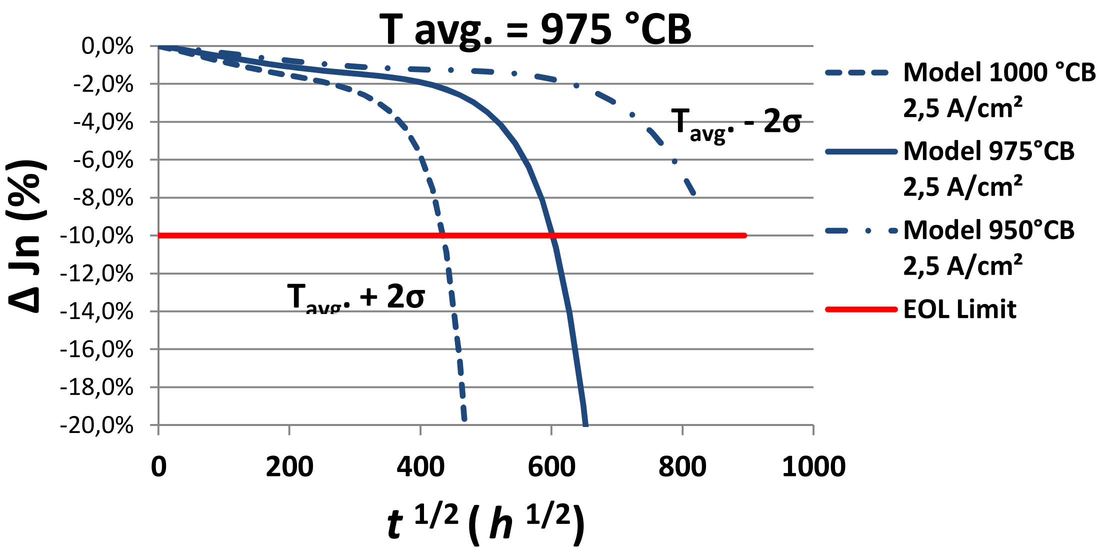
Prediction of cathode life in Tubes

Jn (t = 0) = 2,5 A/cm²

Calculation at:

- T avg. + 2 σ
- T avg.
- T avg. - 2 σ

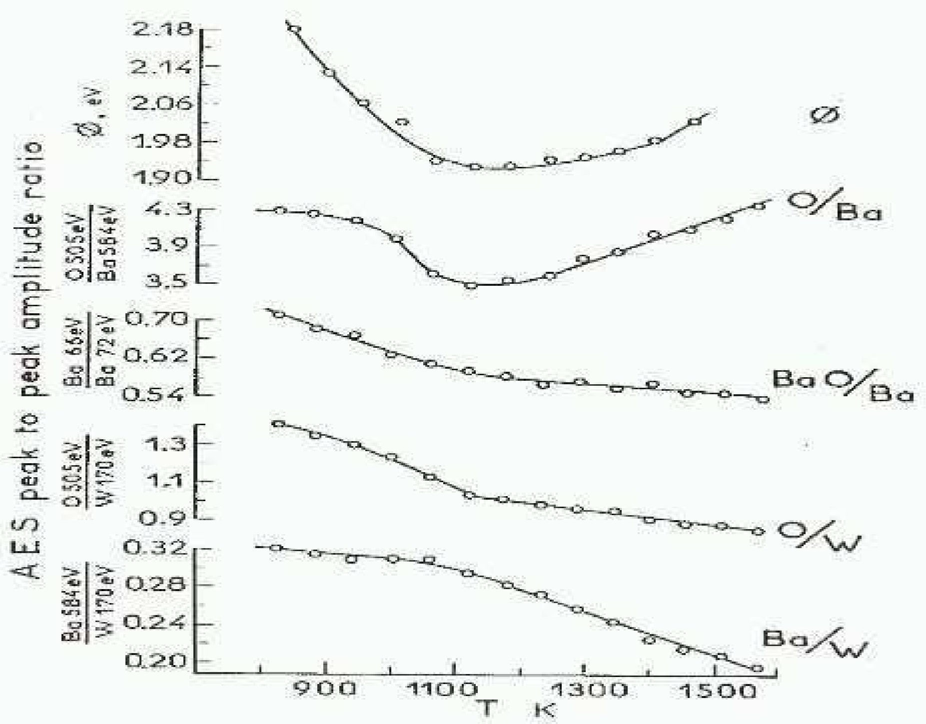
$$\Delta Jn = f(t^{1/2})$$

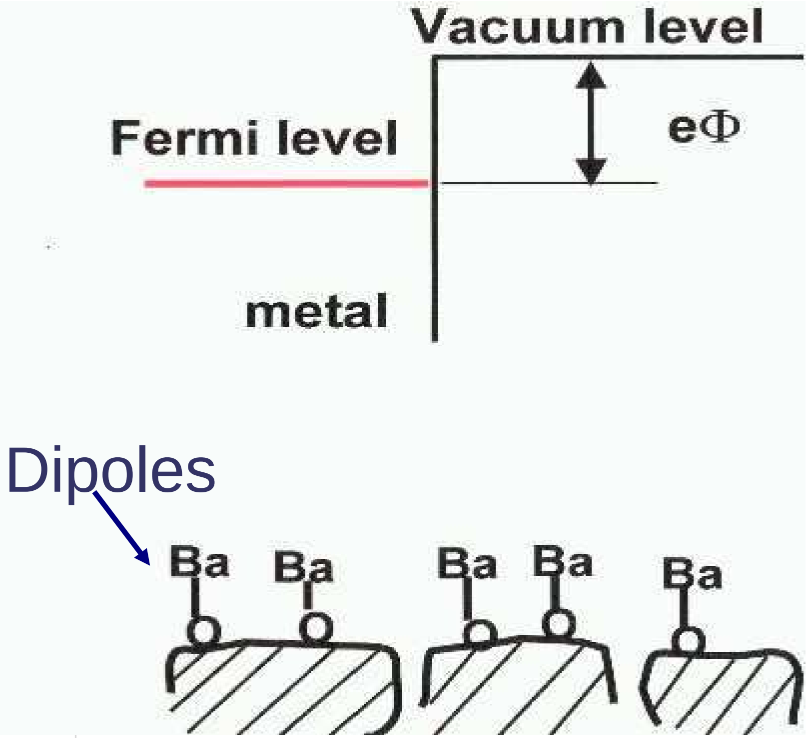


Back-up

Characterization of cathodes (physical and chemical)

Evolution vs. temperature of Auger peaks (Ba/W, O/Ba,……) correlated with work function Φ for an S-type cathode (D. Brion et al.)





Different types of thermionic cathodes and their application

Design cathodes MBK (Multi-Beam Klystron), 7 cathodes

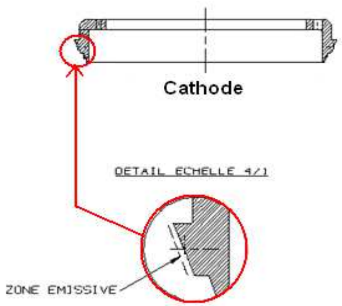
Ex: **TH1802 (1.3GHz)**

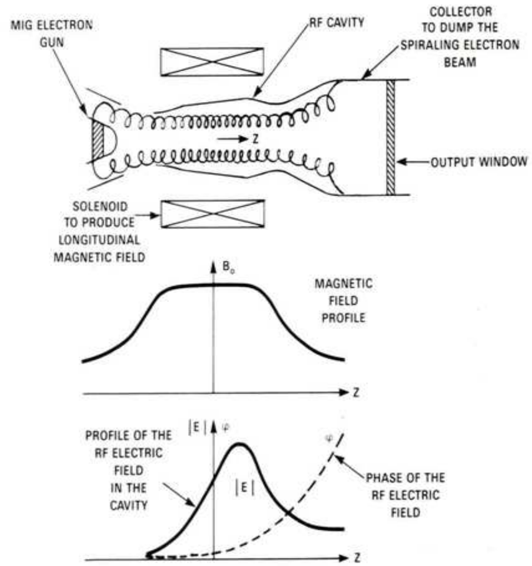
- cathodes M (4.1.1)
- Ik= 135 A (5A/cm²) ,
- Tk = 1010 °Cb
- Lifetime ~ 60 000 Hours

Cathode loading = 5.0 A/cm²

Design cathode Gyrotron

Ex: **TH1507 (140Ghz)** - Cathode S (4.1.1) Ik=40A (2,5 A/cm²; T.L. régime) Tk = 900-950 °Cb





Different types of thermionic cathodes and their application

TED GYROTRON : TH1507

Application : Thermonuclear fusion (Stellarator W 7-X Germany)

- Frequency : 140 GHz
- Output power : 1MW CW
- 45 % efficiency

- S type cathode 4.1.1.
- Ik= 42 A
- Jk = 2.4 A/cm²
- Tk = 900-950 °C (TL regime)
- required cathode life time: 50000 Hrs