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Kinetic Study of Reduction of $[Tc(V)OBr_5]^{2-}$ in Concentrated HBr

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Abstract

Pertechnetate is rapidly reduced in concentrated (8.7 M) HBr to Tc(V). Subsequently reduction to give $TcBr_6^{2-}$ is a slow process. The kinetics of this last process have been investigated. They indicated a combination of first and zero order reactions in the presence of the high HBr concentration. The first order rate constant was 4.8×10^{-2} h^{-1}, and the zero order process constant was 6.0×10^{-6} mol l^{-1} h^{-1}.

Introduction

The hexabromotechnetate-99m (IV) obtained by the reduction of $^{99m}TcO_4^-$ by hydrobromic acid was proposed for the preparation of Tc(IV)-radiopharmaceuticals [1]. Recently it was shown that the reduction of TcO_4^- by concentrated HX (X = Cl, Br) leads to the $[Tc(V)OX_4]^-$ ion which readily undergoes substitution reactions with a variety of ligand types [2, 3]. These facts suggest that a detailed study of the reaction of TcO_4^- with concentrated HBr is necessary. A chromatographic investigation of the reduction of pertechnetate at different HBr concentration and temperatures has been reported [4–6] but no quantitative data on the kinetics of the reduction reactions were given. Under the condition used in this study, TcO_4^- is rapidly reduced to $[TcOBr_5]^{2-}$.

The aim of this work is to study the influence of the technetium concentration and the temperature on the: Tc(VII) → Tc(V) → Tc(IV) reduction reactions.

Experimental

Materials

Tc-99 was obtained from the Radiochemical Center Amersham as ammonium pertechnetate solution. Analytical grade tetrabutylammonium bromide (Fluka) was used without further purification. Hydrobromic acid (47%, 8.7 M), dichloromethane, isopropyl alcohol, were p.a. quality.

Kinetic Run

Solutions 10^{-2} and 10^{-3} M in conc. HBr were prepared from the original ammonium pertechnetate (29 mg/ml or 34 mg/ml) solution, the final volume being kept at 1 ml.

10^{-4} and 10^{-5} M NH_4TcO_4 in conc. HBr were obtained from a 10^{-3} M NH_4TcO_4 aqueous solution. Tc concentrations in each case were determined by measuring the radioactivity of ^{99}Tc with a Packard TRI-Carb 460 CD liquid scintillation system.

The kinetic studies were carried out by ascending paper chromatography and by spectrophotometry. In some cases electrophoresis was used.

Paper Chromatography

At appropriate time intervals a 5 μl aliquot from the reaction solution was put on the paper strips (Schleicher-Schull No 2040B). The developing solvent was 1 M HBr, the temperature was kept the same as for the reduction reaction except for the runs carried out at 30 °, 40 ° and 50 °C for which the temperature for development was 20 °C. The time for chromatographic development was 40 and 30 min for temperatures of 0 ° and 20 °C respectively. The solvent front was at 15 cm. The Rf values of the Tc(V) species and of $TcBr_6^{2-}$ were 0.26–0.28 and 0.78–0.80 respectively.

Electrophoresis

A low voltage electrophoresis apparatus was used. 5 μl of solution was applied to the paper strip Schleicher-Schull No 2040B (1.5 × 40 cm). The supporting electrolyte was 1 M HBr. A voltage of 400 V was applied for 1.5 h. The hydrolysed Tc(V) anionic species migrated about 1.5 cm and the $TcBr_6^{2-}$ about 7 cm. In the supporting electrolyte further hydrolysis of the Tc(V) species occur. The proportion of Tc(V) was always the same in chromatographic and electrophoretic separations. The ^{99}Tc was measured with a TLC Linear Analyser LB 282 consisting from a position sensitive proportional counter tube connected to a multichannel analyser.

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Spectrophotometry

The optical absorbancies during the Tc(V)–Tc(IV) reduction run were measured at λ = 383 nm (absorption maxima of $TcBr_6^{2-}$) with a Varian 635D double beam spectrophotometer using 1 cm quartz cells. Measurements on the freshly made cold solution show that $[TcOBr_5]^-$ does not absorb at this wavelength. At appropriate time intervals an aliquot from the reaction solution was transferred into a cooled cell containing 2 M or 4 M HBr. The Tc concentration in the cell, determined by the liquid scintillation system, was kept about 10^{-5} M. Solutions identical with the sample, except for the Tc complexes were used in the reference cell. All manipulations were carried out in the dark to prevent photolysis.

Because of the interference from the aquated Tc(IV) species, namely $[TcBr_5H_2O]^-$ formed in 2 M and 4 M HBr during the spectrophotometric determinations, the measurements were not performed at wave lengths higher than *ca.* 400 nm. We found that $[TcBr_5H_2O]^-$ has absorptions maxima at 400 and 450 nm.

When all the Tc(V) is reduced to Tc(IV), the concentration of $TcBr_6^{2-}$, determined using values of absorbances at 383 nm and an extinction coefficient of 6650 l mol^{-1} cm^{-1}, must be equal to the total concentration in the cell measured by the liquid scintillation system. Under the condition used no $[TcBr_5H_2O]^-$ would be present. A correction for the contribution of the Br_2 absorption had to be made. The Tc(V) concentration at any time t is given by:

$$\%Tc(V) = 100 - \%Tc(IV)$$

The importance of any back reaction was proved by carrying out a run in the presence and absence of Br_2 and finding no difference.

Results and Discussions

Chemical Species of Tc(V)

From the treatment of TcO_4^- with conc. HCl, salts of the type $M_2[TcOCl_5]$ ($M = NH_4^+$, K^+, Cs^+] were isolated [7, 8]. The infrared absorption bands, at 956 cm^{-1} for the Cs^+ salt and about 990 cm^{-1} for the other salts were assigned to the stretching of the Tc=O bond. The electronic structure and UV–Vis. absorptions were also discussed. Recently [9] $Cs_2[TcOBr_5]$ was isolated from the reaction of TcO_4^- with conc. HBr. For this complex a cubic structure was found. Alternatively, salts of the $[TcOX_4]^-$ ions, like $(n\text{-}Bu)_4N[TcOX_4]$ (X = Cl, Br), were isolated from the solution of TcO_4^- with conc. HX [10, 11]. The authors provide analytical and crystallographic evidence for $TcOCl_4^-$.

In the present work we tried to characterize spectrophotometrically the Tc(V) species formed in the reaction of TcO_4^- with conc. HBr (8.7 M). Accurate spectrophotometric measurements were possible only between 800 and 380 nm. At wave lengths below, *ca.* 350 nm, errors are introduced from the Br^- and Br_2 absorptions. It was difficult to balance out exactly the Br_2 absorption in the reference cell. The absorption spectrum of Tc(V) species formed by the reduction of 10^{-3} M TcO_4^- in conc. HBr is presented in Fig. 1. The spectrophotometric data from this work together with those obtained by others for Tc(V)-oxy-complexes are presented in Table I.

At present we consider that in 8.7 M HBr solution the Tc(V) species is $[TcOBr_5]^{2-}$. In all these measurements $[Br^-]$ was high and $TcOBr_4^-$ is presumably completely converted to $TcOBr_5^{2-}$ Recently [12] the same absorption maxima were found for

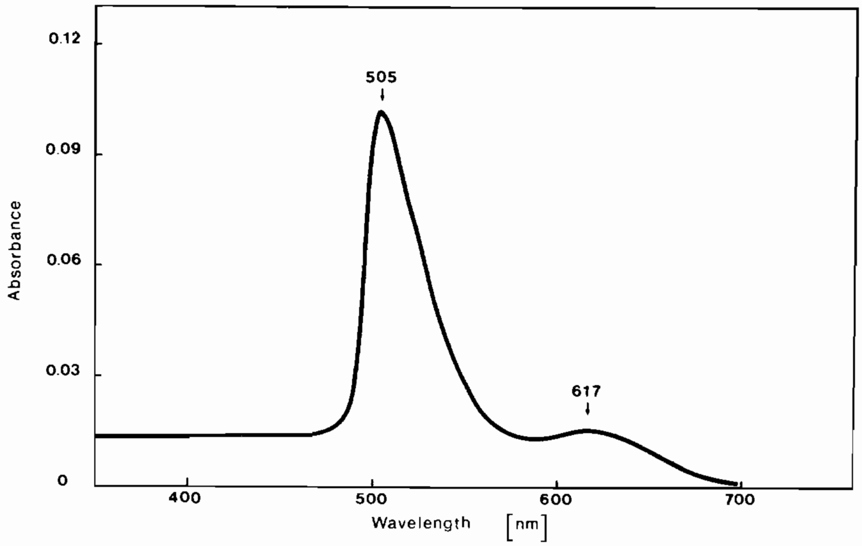

Fig. 1. Absorption spectrum of $^{99}Tc(V)$ species in conc. HBr.

TABLE I. Absorbtion Spectra of Tc(V) Oxy-Complexes.

Compound	Solvent	Band position (nm)	ϵ ($l\ mol^{-1}\ cm^{-1}$)	Ref.
$(NH_4)_2[TcOCl_5]$	11M HCl	935	18	
		599	6	[7, 8]
		485	24	
		294	4400	
		229	10570	
$Bu_4N[TcOBr_4]$	CH_2Cl_2	615 –	22	[10]
		478 (475)	113 (90)	
		353 (358)	3750 (4500)	
		248 (253)	10400 (9500)	This work
Solution of Tc(V) resulted in the reaction of TcO_4^- with conc. HBr at 0°. TcO_4^- conc. = 10^{-3} M[a]		617	8	This work
		505	98	

[a] Solid $(NH_4)_2[TcOBr_5]$ has not yet been obtained.

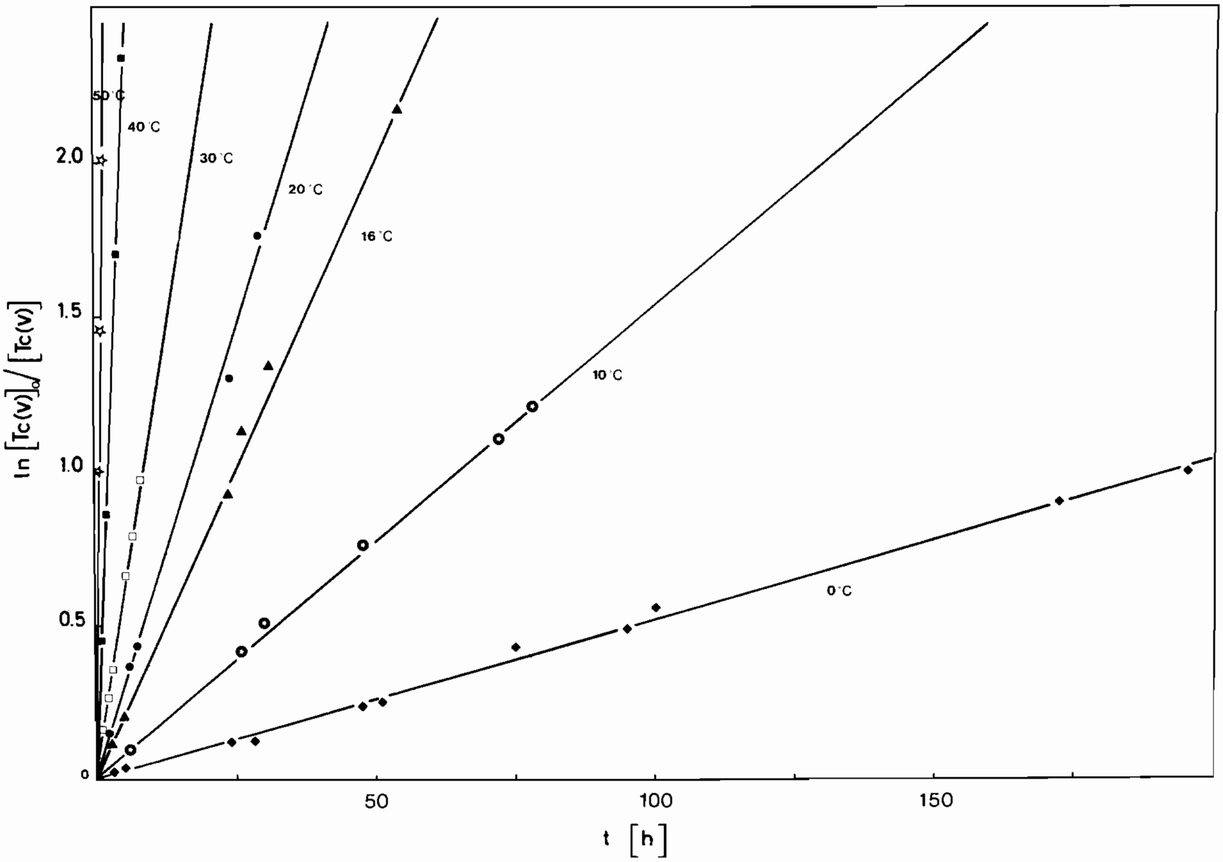

Fig. 2. ln c_0/c *vs.* time for different temperatures; $c_0 = 1.12 \times 10^{-2}$ M.

the solution after treatment of NH_4TcO_4 with conc. HCl as for solid $(NH_4)_2[TcOCl_5]$ dissolved in conc. HCl. In both chloride and bromide system aquation of the $TcOX_5^{2-}$ takes place at lower concentrations of [HX].

Reduction of TcO_4^- by Conc. HBr

This reaction takes place in two steps:

(i) $TcO_4^- + 6HBr \longrightarrow TcOBr_5^{2-} + 1/2Br_2 + 3H_2O$

(ii) $TcOBr_5^{2-} + 2HBr \longrightarrow TcBr_6^{2-} + 1/2Br_2 + H_2O$

Step (i) is a very fast reaction, practically independent of the temperature and not explored under our conditions. Step (ii) is a temperature controlled reaction, consequently kinetic study of this reaction was performed.

Influence of Temperature

The concentrations of Tc(V) were 1.12×10^{-2} M and 1.3×10^{-3} M and of HBr was 8.7 M. The rate for step (ii) is given by the eqn. (1):

$$\frac{-\mathrm{d}[\mathrm{Tc(V)}]}{\mathrm{d}t} = k_2[\mathrm{Tc(V)}][\mathrm{HBr}]^2 \qquad (1)$$

As the concentration of HBr is in large excess, the rate constants were determined supposing a pseudo first order process

$$\frac{-\mathrm{d}[\mathrm{Tc(V)}]}{\mathrm{d}t} = k[\mathrm{Tc(V)}] \qquad (2)$$

Plots of $\ln c_0/c$ (c_0 is the initial concentration of Tc(V), equal to the total Tc concentration, and c the unreacted Tc(V) at time t) *vs.* time gave straight lines (Fig. 2, 3). The slope of the plots gave the rate constant k (Table II). Plots of the rate constants, k *vs.* $1/T$ using Arhenius procedure and the chromatographic values of Table II gave straight lines (Fig. 4). These plots yield a value of the activation energy of 81 ± 1.7 kJ/mol.

TABLE II. k Values at Different Temperatures: Chromatographic Method.

$[^{99}\mathrm{Tc(V)}]$ (M)	T (°C)	k (h^{-1})[a]
1.12×10^{-2}	50	1.31
	40	4.32×10^{-1}
	30	1.18×10^{-1}
	20	5.80×10^{-2}
	16	4.09×10^{-2}
	10	1.52×10^{-2}
	0	5.30×10^{-3}
1.30×10^{-3}	40	8.23×10^{-1}
	30	4.50×10^{-1}
	20	1.13×10^{-1}
	16	5.47×10^{-2}
	0	9.36×10^{-3}

[a] Correlation coefficient = 0.99.

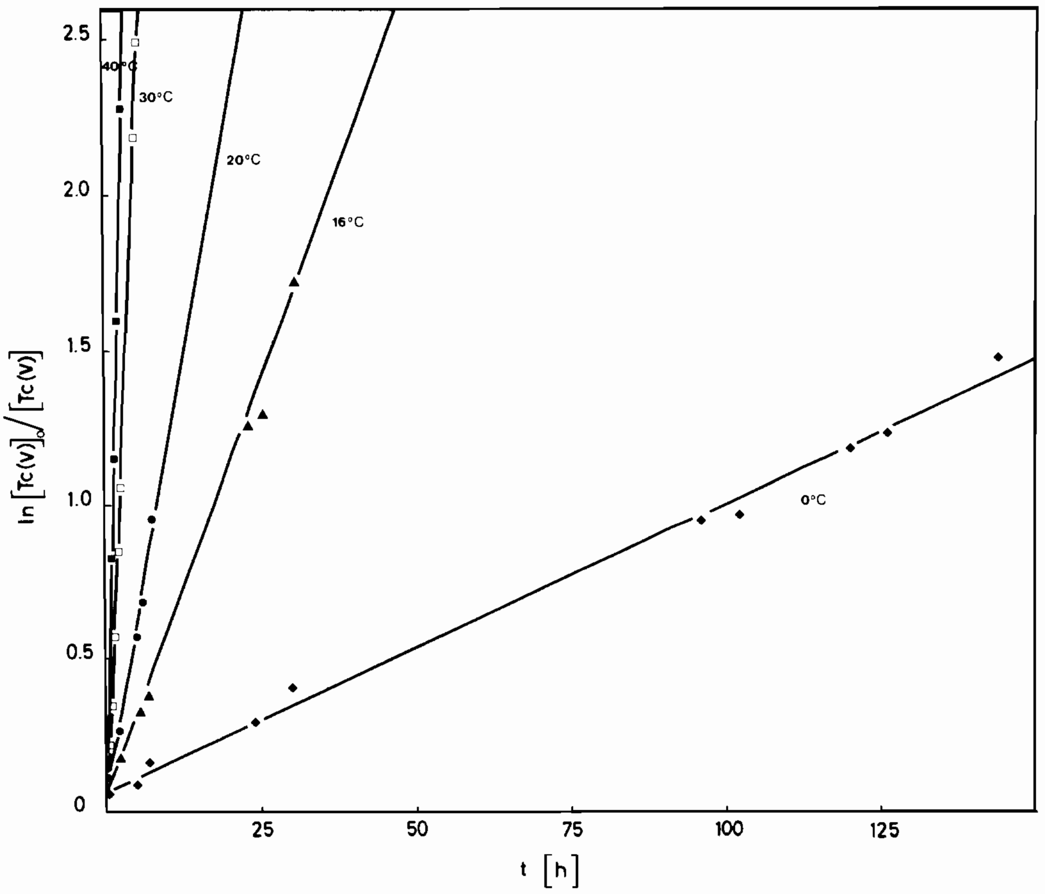

Fig. 3. $\ln c_0/c$ *vs.* time for different temperatures; $c_0 = 1.30 \times 10^{-3}$ M.

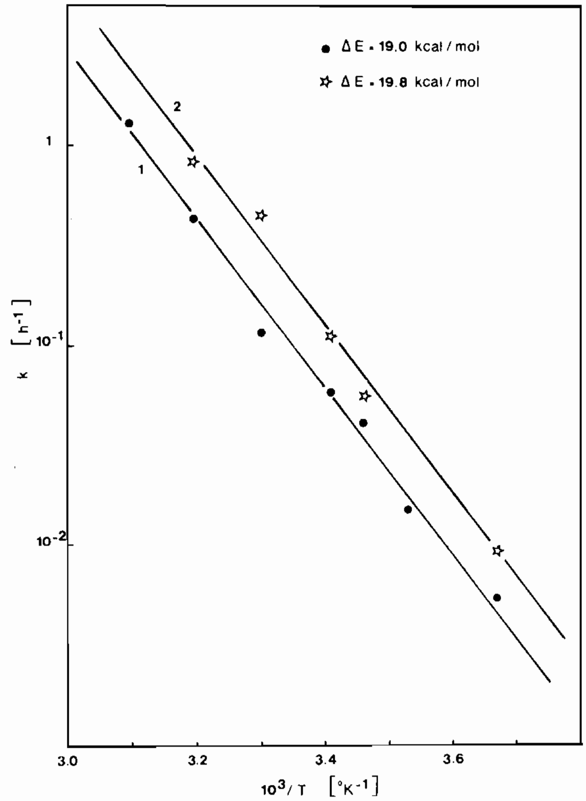

Fig. 4. Temperature dependence rate constants for 1.12 × 10^{-2} and 1.30 × 10^{-3} M ^{99}Tc(V) in conc. HBr.

Influence of Complex Concentration

Shukla [13] has reported that the reduction of two anions, $^{99}TcO_4^-$ and $^{99m}TcO_4^-$ by concentrated HCl and HBr follows the same path *i.e.*: Tc(VII) → Tc(V) → Tc(IV) but at different rates. The $^{99m}TcO_4^-$ was reduced more readily than $^{99}TcO_4^-$. The ^{99m}Tc(V) stability in conc. halogenated acids was much lower than of ^{99}Tc(V). The difference in the reduction rate was explained by the formation of radiolytic products in the solution of technetium-99m [13].

In other respects, the Tc(V) formed in the reduction of $^{99}TcO_4^-$ (conc. = 3.5 × 10^{-3} M) by concentrated HBr at 0 °, 8 °, 24 °C [5] show a comparable behaviour with that found in this work (Table II). Therefore, it seemed interesting to us to check the effect of Tc(V) concentration on the reaction rate at a constant temperature. The Tc(V) conc. varied from 10^{-2} to 10^{-5} M, keeping the hydrobromic acid constant at 8.7 M and the temperature at 16 °C. The rate constants were calculated as was described above. For Tc(V) concentration lower than 10^{-3} M a linear plot was obtained only up to 45% of reduction. The plot of ln c_0/c *vs.* time for 1.44 × 10^{-4} M Tc(V) concentration showed a faster process taking place after about 5 h. The reduction of 10^{-5} M Tc(V) to Tc(IV) by conc. HBr is very rapid (*ca.* 3 h). It is obvious that for ^{99}Tc(V) concentrations below 10^{-5} M the reduction rate is too fast to allow a kinetic study by radiochromatographic methods; a fortiori the reduction process $^{99m}TcO_4^-$ → ^{99m}Tc(V) → ^{99m}Tc(IV) at 16 °C could not be measured. Within *ca.* 25 min about 92% of all technetium represented $^{99m}TcBr_6^{2-}$.

The *k* values for Tc(V) concentrations between 10^{-2} and 10^{-3} M are presented in Table III. In some runs the rate was also followed spectrophotometrically. The spectrophotometric values of *k* are generally in satisfactory agreement with those obtained by chromatography. Nevertheless this last method is more simple and more accurate because it permits a good separation of Tc(V) because of its strong absorption on the paper. The pale yellow spot left after drying of the paper suggests that Tc(V) aquation product still contains Br$^-$ ligands. As this species has absorption bands at wave lengths below *ca.* 300 nm no complete spectrum could be obtained.

Apparently the rate law so far assumed only appears to be valid for [Tc(V)] ≈ 10^{-3} M. Below this concentration, the reaction proceeds more rapidly the lower the [Tc(V)].

Now assuming that the reaction is a combination of a first order with a zero order process, it was possible to find a rate law fitting all experimental data. The zero order process could arise from some material absorption or from a surface reaction. The reaction rate can be written as:

$$\frac{-\mathrm{d}[\mathrm{Tc(V)}]}{\mathrm{d}t} = k[\mathrm{Tc(V)}] + k' \qquad (3)$$

By integrating this eqn. the following solution is obtained:

$$\frac{[\mathrm{Tc(V)}]_t}{[\mathrm{Tc(V)}]_0} = \mathrm{e}^{-kt}\left\{1 + \frac{k'}{k[\mathrm{Tc(V)}]_0}\right\} - \frac{k'}{k[\mathrm{Tc(V)}]_0} \qquad (4)$$

This general solution gives no possibility to determine the constants *k* and *k'* using the experimental data. However in the limiting cases, depending on the relation between the terms in the right hand side of eqn. (3), approximate solutions can be found.

If $k' << k$[Tc(V)], *i.e.* for enough high Tc(V) concentrations (> 10^{-3} M), *k'* can be neglected and the solution is then:

$$\frac{[\mathrm{Tc(V)}]_t}{[\mathrm{Tc(V)}]_0} = \mathrm{e}^{-kt} \qquad (5)$$

By plotting ln $[\mathrm{Tc(V)}]_t/[\mathrm{Tc(V)}]_0$ against *t*, the constant *k* was determined for a set of experiments, Table III, and the mean value was found equal to $k = 4.84 \times 10^{-2}$ h^{-1}.

At sufficiently low concentrations (1.76 × 10^{-5} M), k[Tc(V)] $<< k'$ and another approximate solution is given by:

$$\frac{[\mathrm{Tc(V)}]_t}{[\mathrm{Tc(V)}]_0} = 1 - k' \frac{t}{[\mathrm{Tc(V)}]_0} \qquad (6)$$

TABLE III. Rate Constants for Tc(V) Reduction in 8.7 M HBr, T = 16 °C.

$[^{99}Tc(V)]$ (M)	Chromatography k (h^{-1})	Spectrophotometry HBr 2 M k (h^{-1})	Spectrophotometry HBr 4 M k (h^{-1})
1.34×10^{-2}	4.31×10^{-2}		
1.12×10^{-2}	4.09×10^{-2} [a]		
0.98×10^{-2}	5.17×10^{-2}	4.9×10^{-2}	5.4×10^{-2}
1.73×10^{-3}	4.93×10^{-2}		
1.26×10^{-3}	5.05×10^{-2}		
1.24×10^{-3}	5.47×10^{-2}	6.3×10^{-2}	5.4×10^{-2}

[a] Similar k value was found by electrophoresis.

A plot of $[Tc(V)]_t/[Tc(V)]_o$ against $t/[Tc(V)]_o$ is linear and gives the slope $k' = 6.0 \times 10^{-6}$ mol l^{-1} h^{-1} (Fig. 5). The types of processes describing the reaction rate at different Tc(V) concentrations are summarized in Table IV. Using the values of k and k' found above and the general solution (4) a set of curves $[Tc(V)]_t/[Tc(V)]_o$ as a function of time are plotted in Fig. 6. A good fit with experimental data was obtained for all Tc(V) concentrations.

It must be noted that the reduction of Tc(V) to Tc(IV) at a concentration higher than 1.34×10^{-2} M could not be studied because the resulting $TcBr_6{}^{2-}$ starts to crystallise during the reaction. The solubility of $(NH_4)_2TcBr_6$ in HBr is 1.08×10^{-2} M independently of the acid concentration [14].

At a Tc(V) concentration less than 10^{-5} M the validity of the given rate law could not be tested because of the time consuming separation method. It seems however that there are no fundamental reasons that the law should not be valid for such low concentrations.

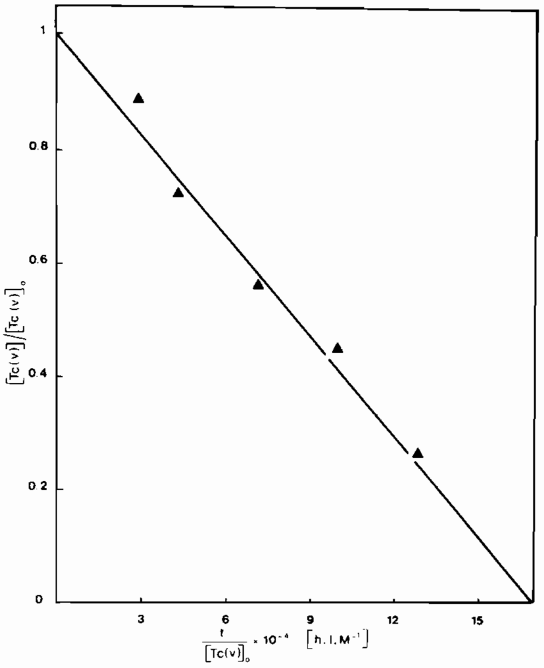

Fig. 5. c/c_0 vs. t/c_0 for 1.76×10^{-5} M $^{99}Tc(V)$ concentration.

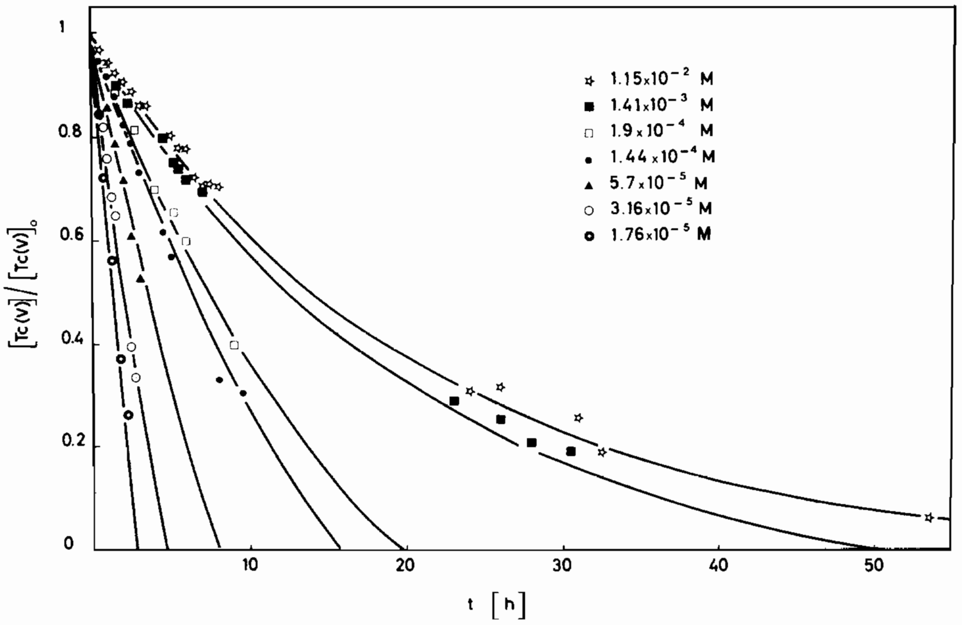

Fig. 6. c/c_0 vs. time for various $^{99}Tc(V)$ concentrations: full line – theoretical curves (eqn. (4)); symbols – experimental data.

TABLE IV. The Types of Processes Describing Reaction Rate at Different Tc(V) Concentrations.

$[^{99}Tc(V)]$ (M)	k (h^{-1})	k' ($mol\ l^{-1}\ h^{-1}$)	Type of equation
1.34×10^{-2}–1.24×10^{-3}	4.8×10^{-2}	–	First order process Eqn. (5)
1.90×10^{-4}	–	–	First and zero order processes Eqn. (4)
1.44×10^{-4}			
5.70×10^{-5}	–	–	
3.16×10^{-5}			
1.76×10^{-5}	–	6.0×10^{-6}	Zero order process Eqn. (6)

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