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# Behavior of Indium at Tracer Concentrations

Katheryn L. Lawson

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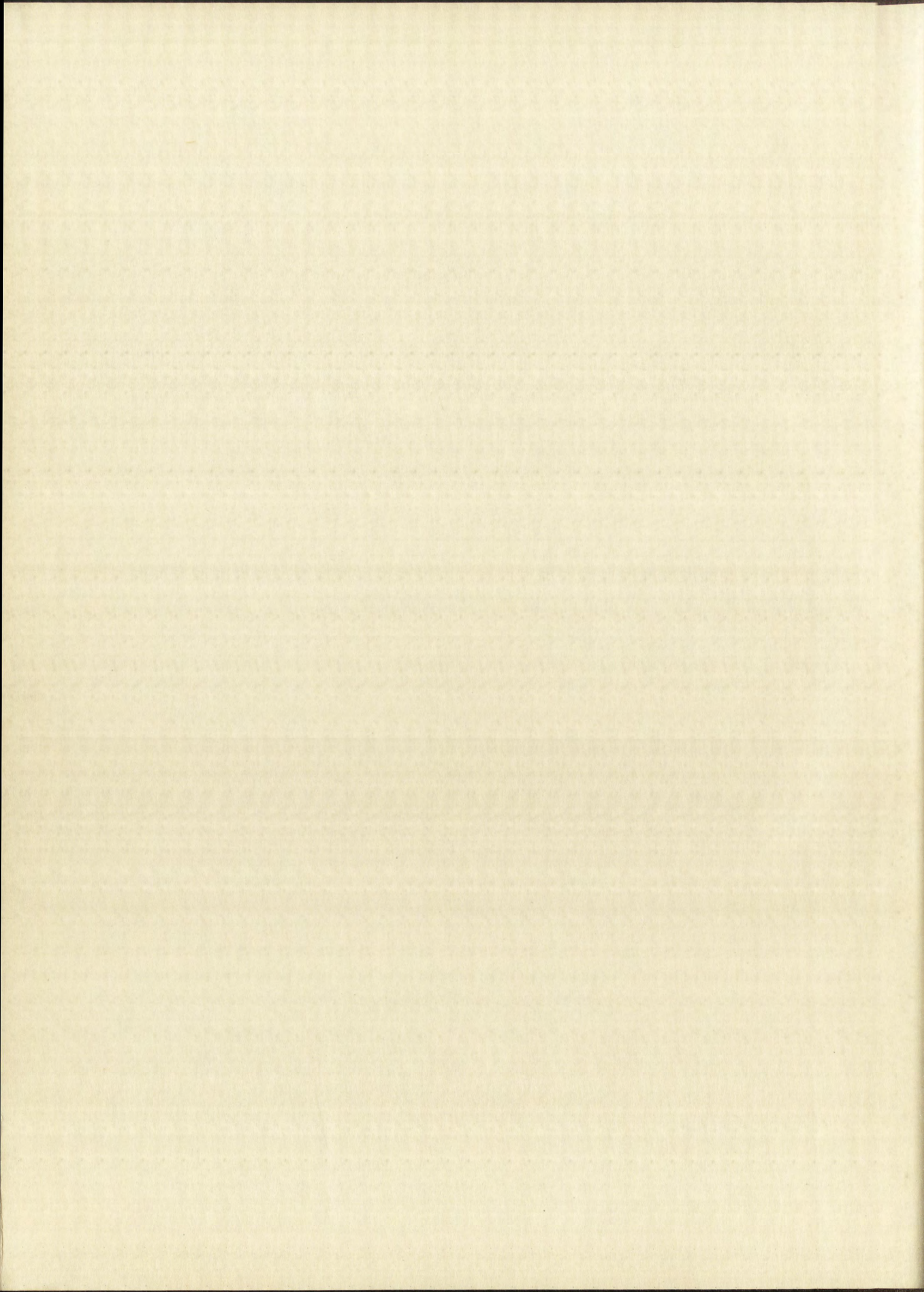
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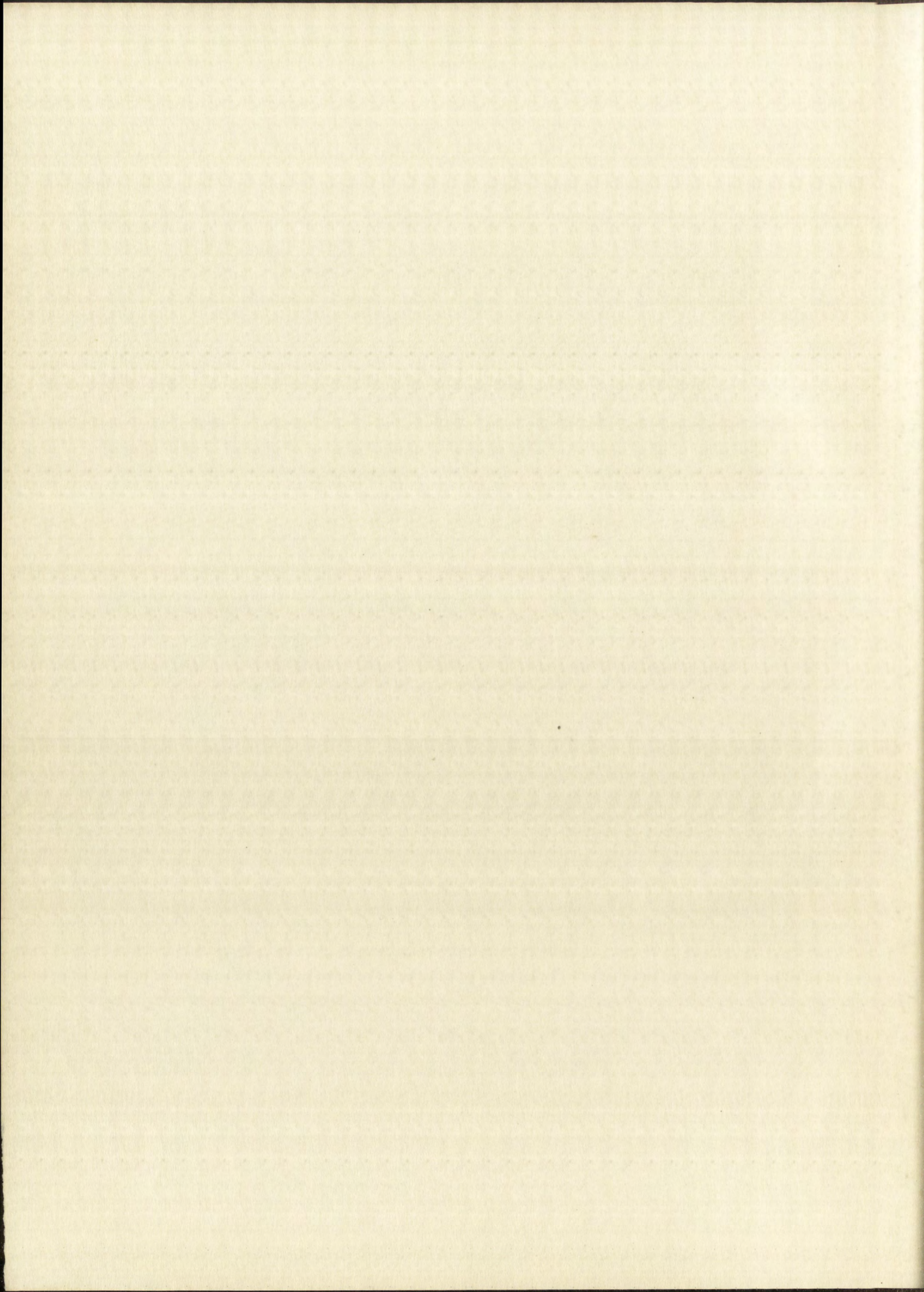














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BEHAVIOR OF INDIUM AT TRACER CONCENTRATIONS

by

Katheryn L. Lawson

A Thesis

In Partial Fulfillment of the  
Requirements for the Degree of  
Doctor of Philosophy in Chemistry

The University of New Mexico

1957







This dissertation, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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This dissertation directed and approved by the committee  
committee, has been accepted by the Graduate Committee of the  
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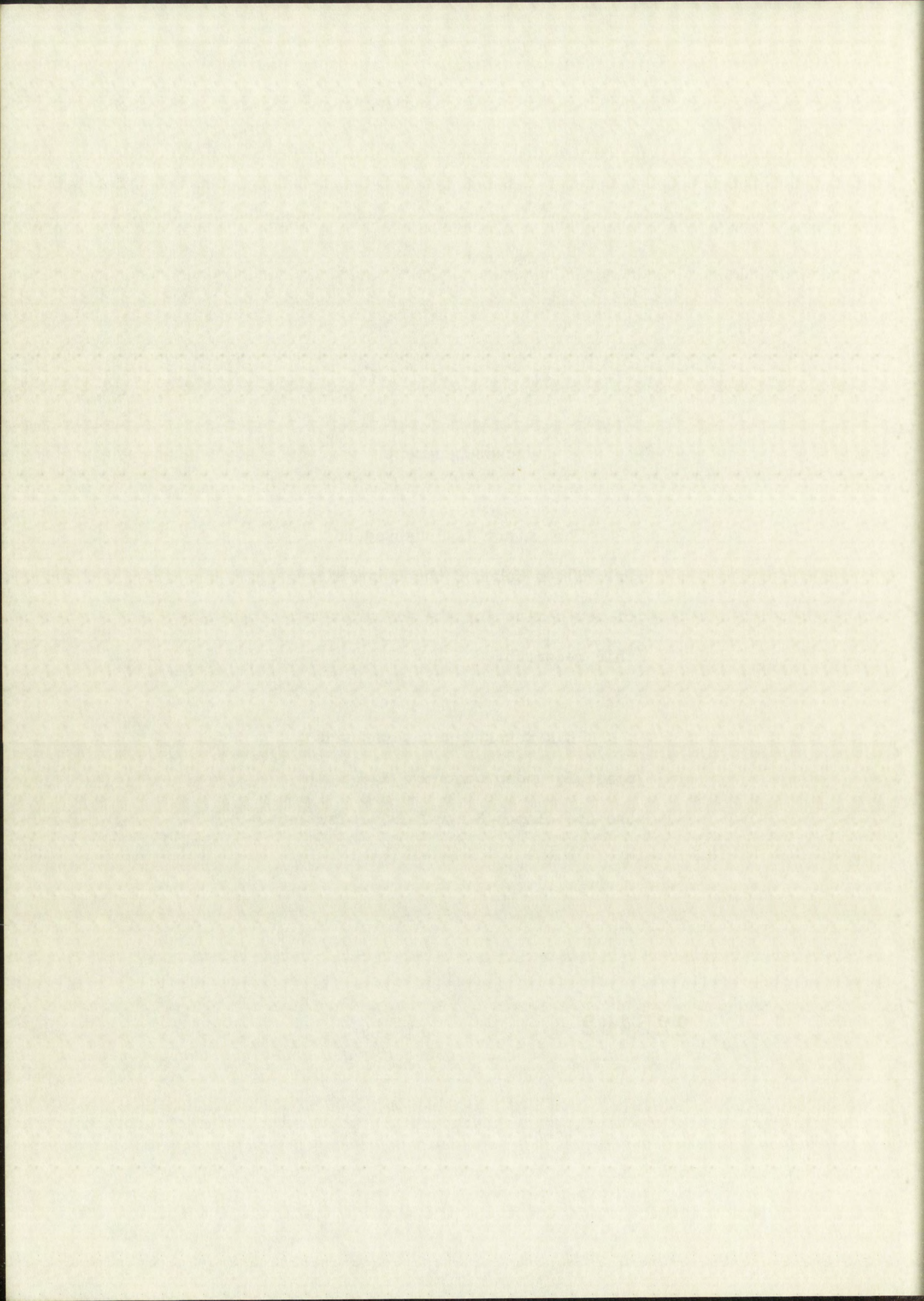
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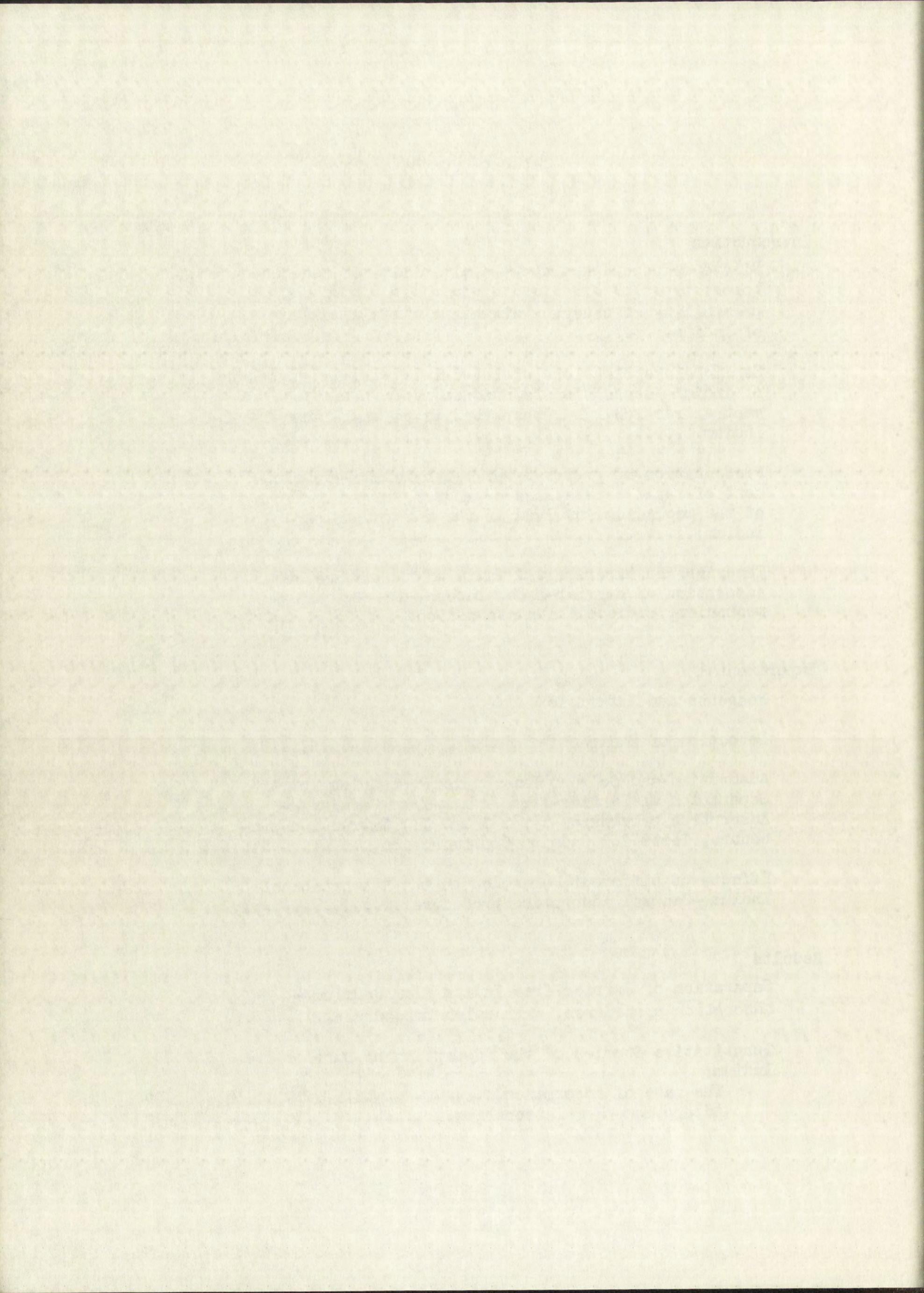




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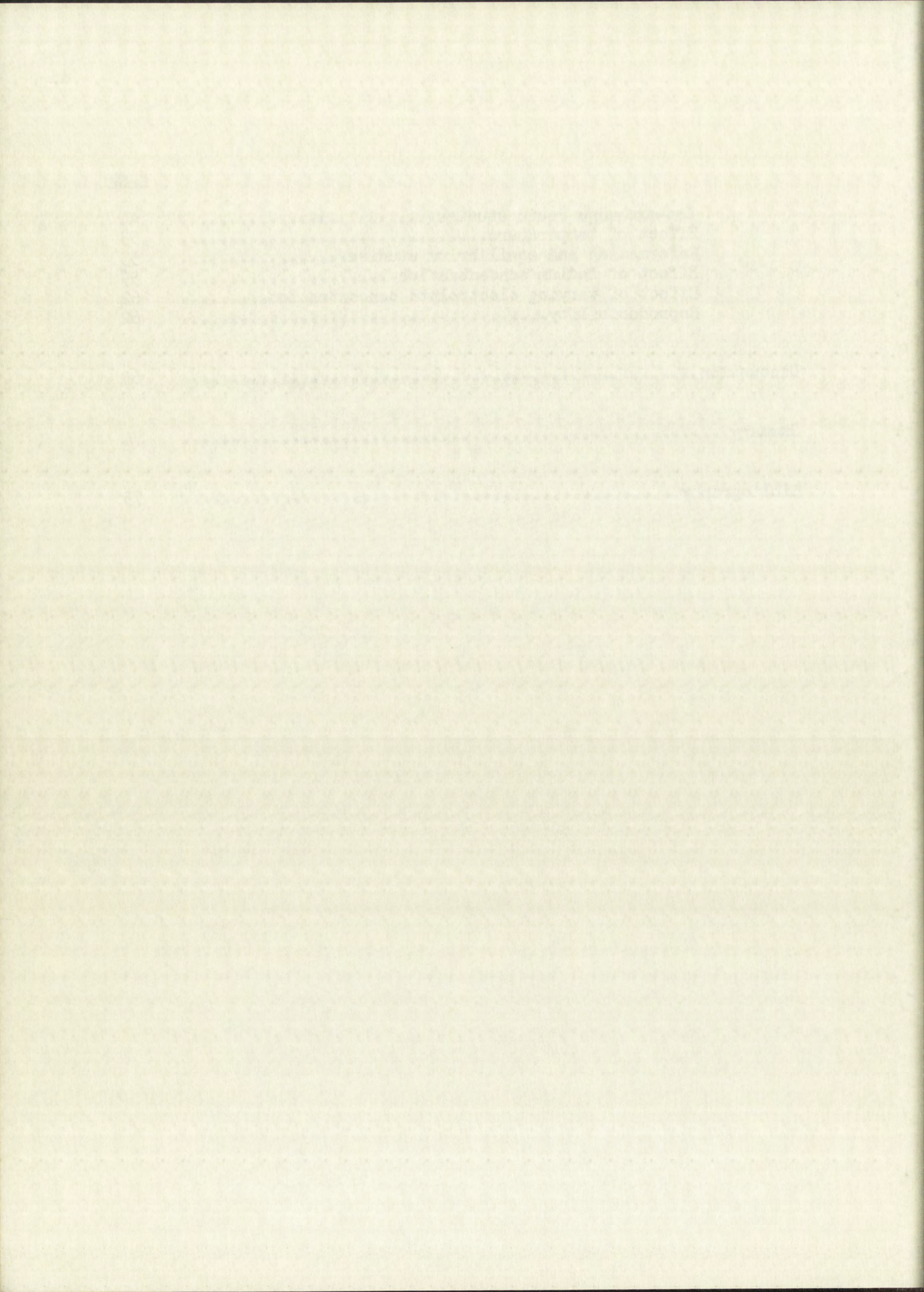






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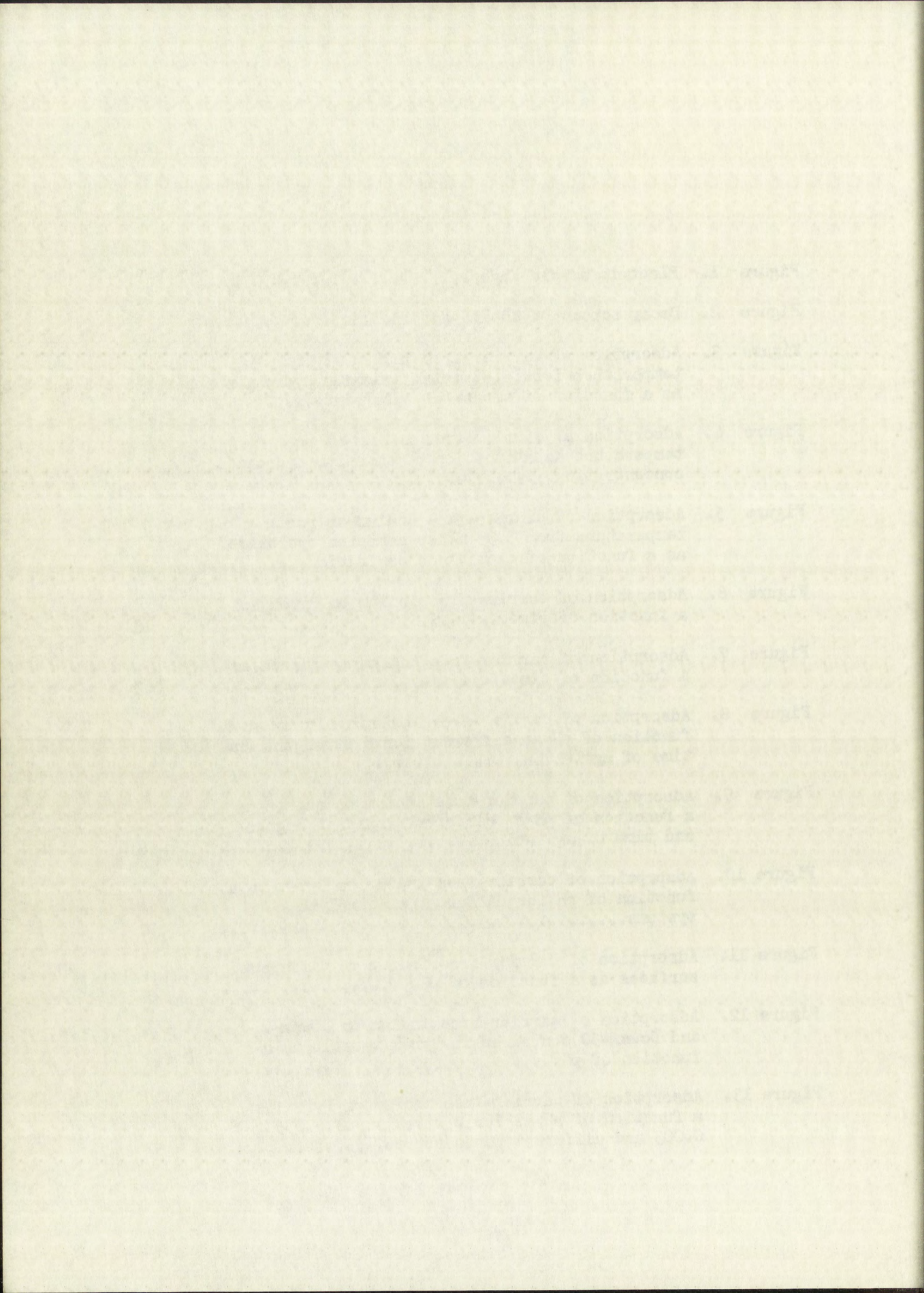




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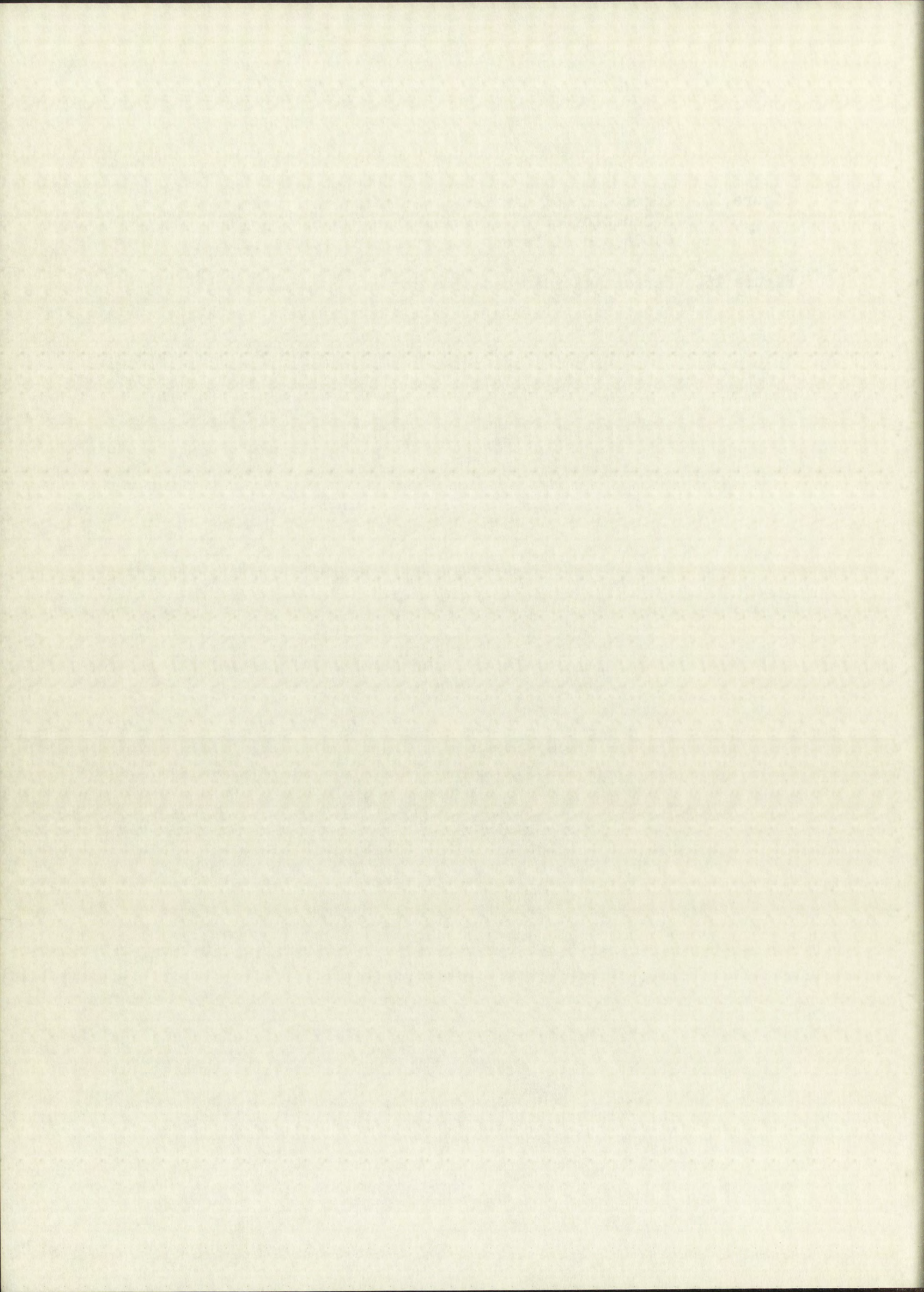






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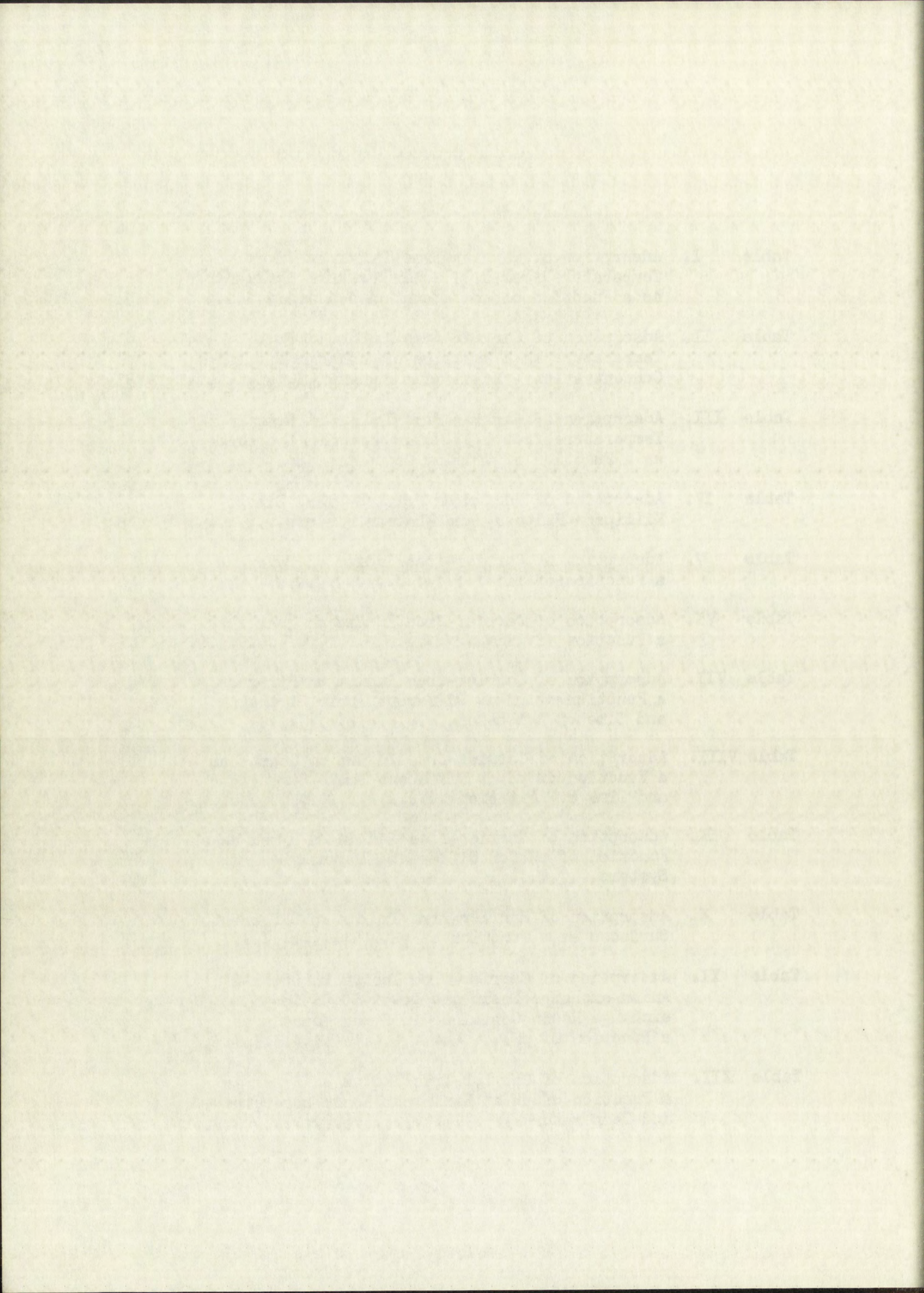




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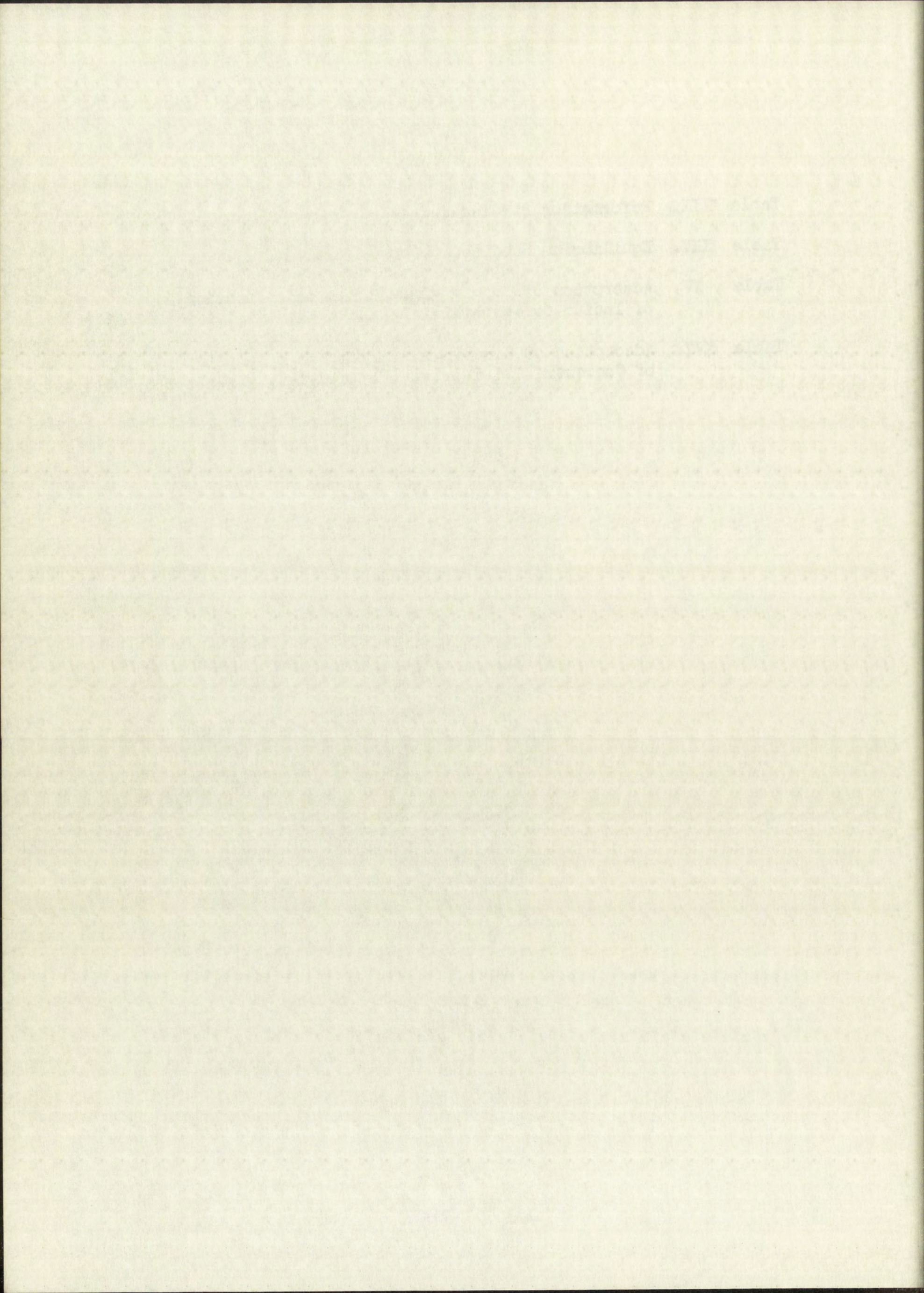






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## INTRODUCTION

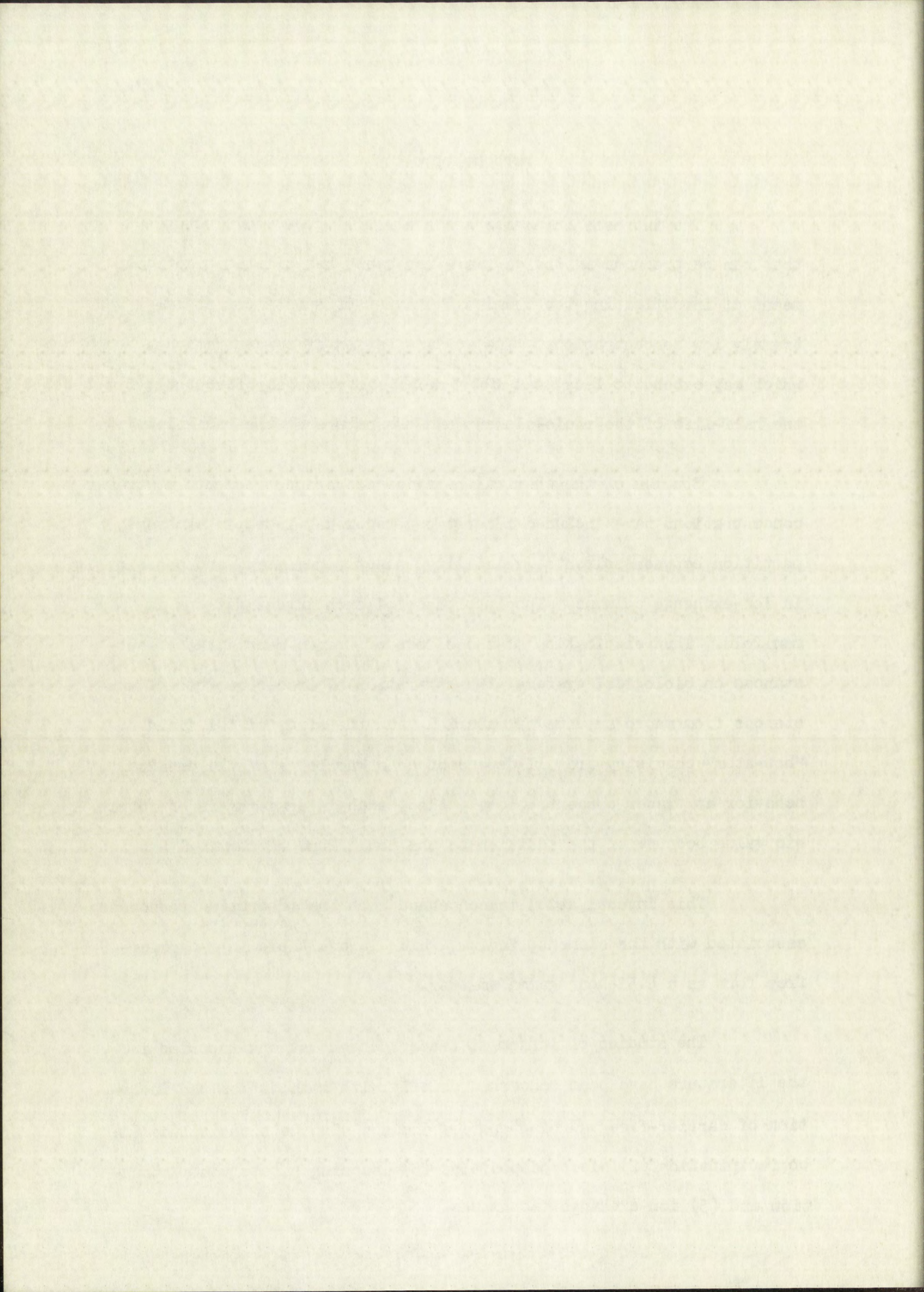
The increase in number and availability of radioisotopes that can be produced in the carrier-free state has offered practical means of investigating the chemical behavior of substances at extremely low concentrations. The working region of concentrations, which may extend to less than  $10^{-14}$  molar, is generally fixed only by the half-life of the radio-element and the nature of the radiation.

Studies of the chemical behavior of various elements at tracer concentrations have included adsorption phenomena, isotopic exchange, partition between solvents, volatility, electrochemistry, and behavior in ion-exchange columns. The importance of such investigations is manifold. Thus elucidation of the effect of tracer quantities of substances on biological systems, the separation of tracer amounts of substances from macro amounts of material, and the study of the field of "hot-atom" chemistry are all dependent on a knowledge of the chemical behavior at tracer concentrations. Also, such information is of intrinsic value because of the addition to the total fund of chemical knowledge.

This investigation is concerned with the adsorption phenomenon associated with the element, indium, which is available in a carrier-free form as a 4.53-hour gamma emitter.

The studies of indium at tracer concentrations reported in the literature have been concerned chiefly with methods for the isolation of carrier-free radioisotopes of indium. The methods include (1) coprecipitation (2) electrodeposition (3) leaching (4) solvent extraction and (5) ion-exchange techniques.



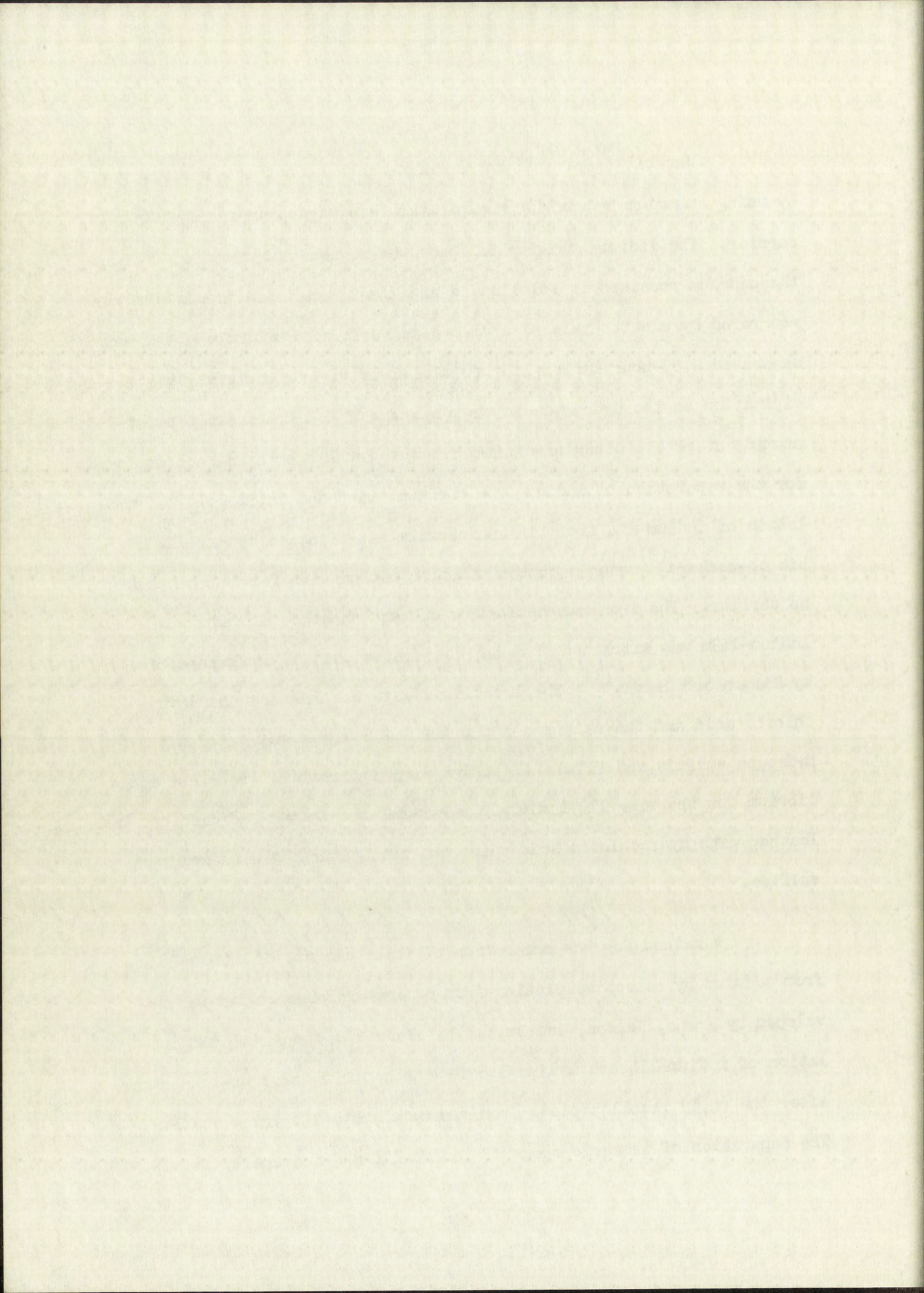




Jacobi<sup>(1)</sup> separated carrier-free indium from a cadmium target by using ammonium hydroxide precipitation and magnesium as non-isotopic carrier. The indium activity followed the magnesium hydroxide, whereas the cadmium remained in solution as an ammonia complex. The indium was recovered by electrolysis of a dilute sulfuric acid solution. Laurent<sup>(2)</sup> separated 4.53-hour indium-115m from cadmium on indium carrier by precipitation as the hydroxide in the presence of 0.1 molar ammonium hydroxide at pH 7. Other precipitation-type techniques have been employed for the separation of indium from cadmium, tin, and antimony. The isolation of indium-114 from tin and cadmium was effected by Maxwell and his co-workers<sup>(3)</sup> using a coprecipitation method with ferric hydroxide as carrier. The iron was removed by subsequent ether extraction. Indium-113m was extracted from an "irradiated unit of antimony-125" by Kimura and Ikeda.<sup>(4)</sup> The irradiated unit was dissolved in hydrochloric acid and the sulfides of tin and antimony precipitated with hydrogen sulfide and filtered. After the attainment of transient equilibrium for the tin-113-indium-113m system, the indium radioisotope was leached with hydrochloric acid which had been saturated with hydrogen sulfide.

A method for the separation of trace amounts of indium-115m from cadmium by selective elution from an ion-exchange column was developed by Kraus, Nelson, and Smith.<sup>(5)</sup> Herr<sup>(6)</sup> has reported the isolation of indium-114 and indium-116 in a practically carrier-free state after the  $(n, \gamma)$  recoil process from the metal phthalocyanine complex. The separation of isomeric atoms of indium-114 and indium-112 in an







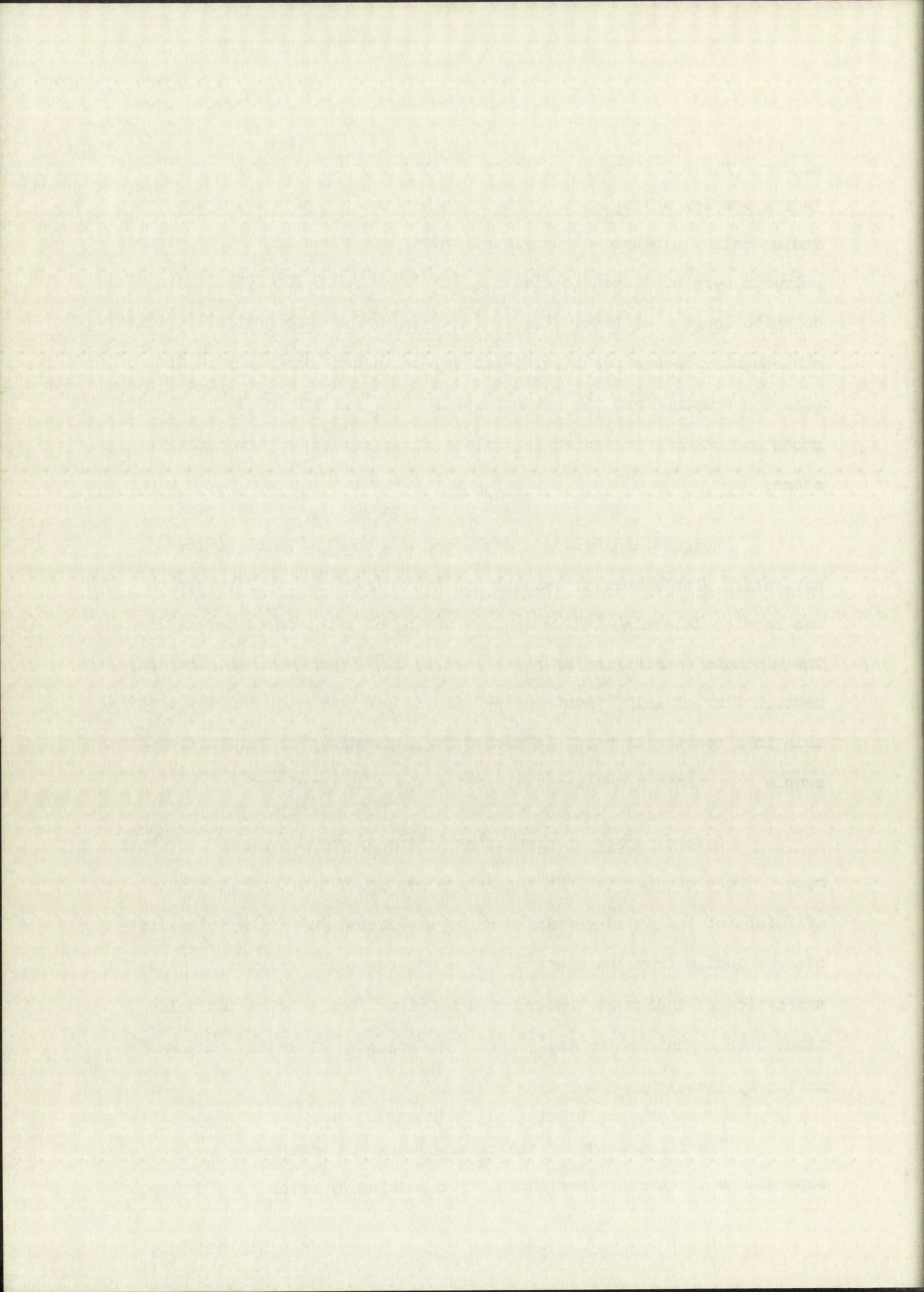
electric field has been studied by Jacobi<sup>(7)</sup> and by Goldsmith and Bleuler.<sup>(8)</sup> Indium complex salts, such as indium quinolinol, indium dithizone, and indium salicylaldehyde-o-phenylenediamine, dissolved in various organic solvents were subjected to electric fields of 7,500-15,000 volts/cm. for definite lengths of time. The indium ions, which were initially positive, subsequently became positive, negative, or neutral depending on the starting compound and the solvent used. Analysis of the deposit on the anode and cathode indicated the extent of separation of the isomeric atoms.

Hudgens and Nelson<sup>(9)</sup> developed a method in which neutron-activation with a nuclear reactor and with a radium-beryllium source was used to determine indium concentrations of a few parts per million. The ultimate sensitivity of the method is  $10^{-11}$  gram when the thermal neutron flux of  $4 \times 10^{12}$  neutrons per second per square centimeter obtainable in a reactor is used. A method for separating the indium from other sample components by solvent extraction was also developed.

Several other studies using indium in small amounts have been made. These studies include the determination of the distribution coefficient of indium in germanium on crystallization,<sup>(10)</sup> the volatilization of indium from the electrode in spectrographic analysis,<sup>(11)</sup> the extraction of indium at tracer concentrations from acid halide solutions into organic solvents,<sup>(12)</sup> and the detection of indium complex formation by ion-exchange sorption studies.<sup>(13)</sup>

The first phase of the present work was undertaken to develop separations of carrier-free indium from cadmium by methods which involved





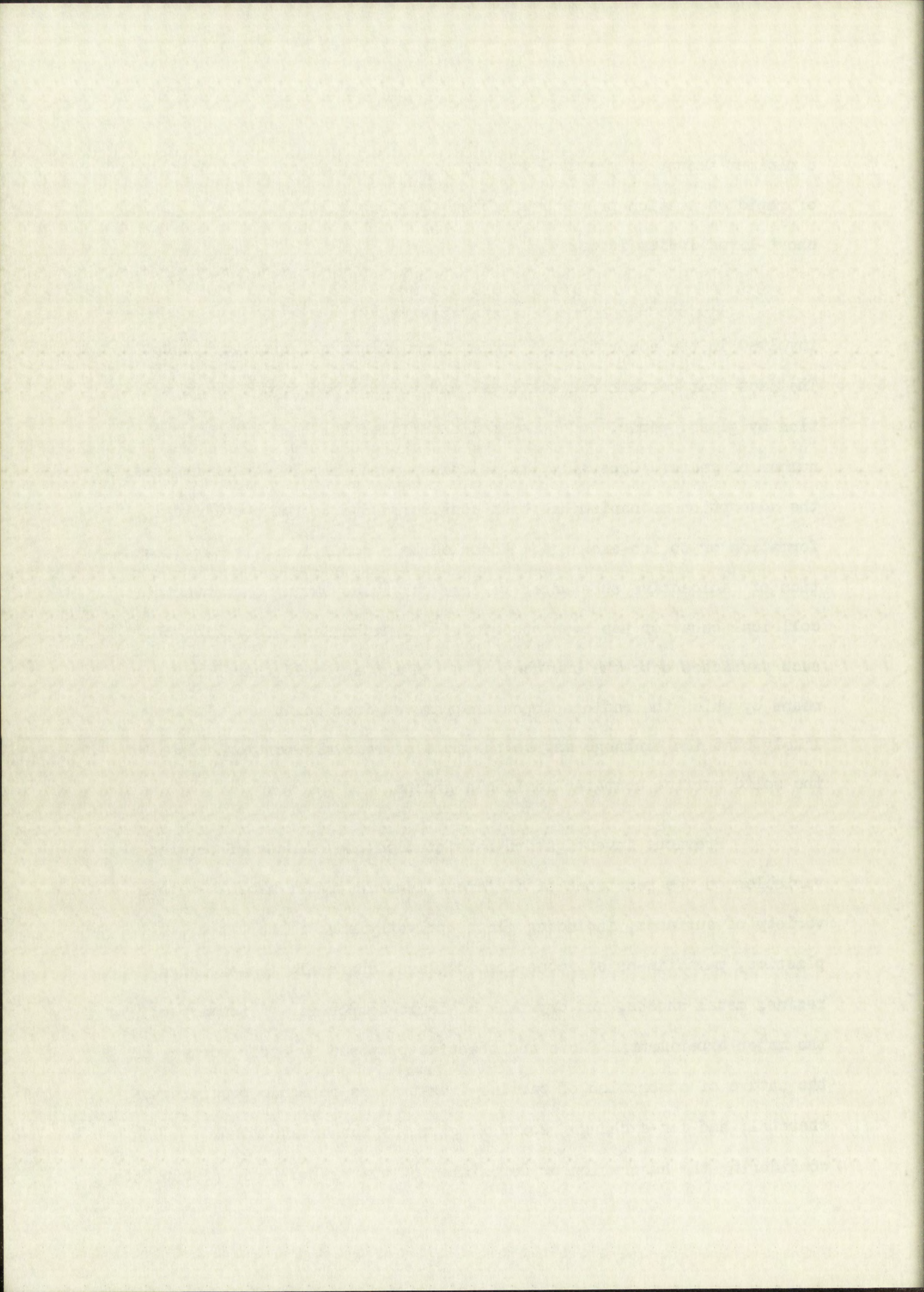


a minimum amount of chemical and physical manipulation. The development of rapid separation procedures offers the possibility of investigating short-lived indium isomers.

In another phase of this work, investigations of the mechanisms involved in the adsorption of indium from dilute solution were made. The fact that certain radioisotopes can be adsorbed from aqueous solution by glass, paper, and other solid surfaces has been known for a number of years. Generally, in solutions which are  $10^{-8}$  molar or less, the adsorption mechanism has been considered due to radio-colloidal formation or to ion-exchange. Under certain conditions, the agglomeration of radioactive substances to form particles having characteristic colloidal behavior has been observed.<sup>(14)</sup> Mechanical adsorption of such particles onto the surfaces of solid matter could therefore be a means by which the radioisotopes are removed from solution. It is likely that ion exchange may be the mode of removal, particularly if the solid surface contains ionizable groups.

Previous investigators have studied the effects of certain variables on the reactions of different ions in tracer amounts with a variety of surfaces, including glass, polyethylene, filter paper, plastics, paraffin-or silicone-coated glass, charcoal, ion-exchange resins, metal sheets, and crystals of ionic compounds. A summary of the major experimental facts and theories proposed by early workers on the nature of adsorption of carrier-free tracers on ionic precipitates, charcoal, and ion-exchange resins is given by Bonner and Kahn.<sup>(15)</sup> In considering the adsorption or deposition of tracers on ionic precipitates,



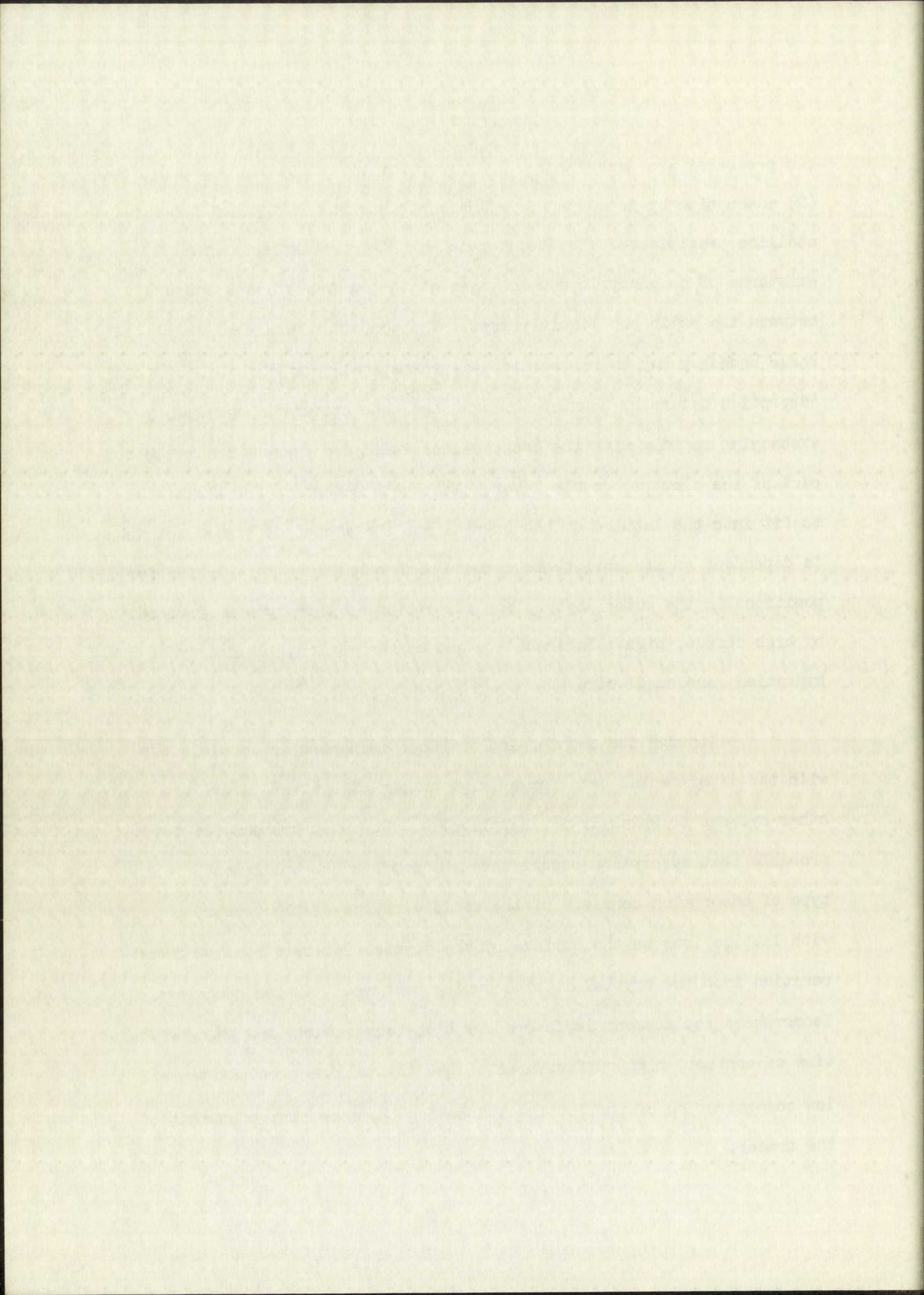




two processes are described: (1) adsorption by counter ion-exchange and (2) adsorption by isomorphous replacement into the lattice of the crystalline precipitate. The counter ion-exchange mechanism assumes the existence of an electric double layer at the surface of separation between the solid and liquid phases. The condition which exists at the phase boundary may be represented diagrammatically by Figure 1. When adsorption occurs by counter-ion exchange, the tracer is adsorbed by exchanging rapidly with the counter-ions which are present in the outer part of the electric double layer. It is not necessary for the tracer to fit into the lattice of the crystal but the amount of tracer adsorbed is dependent on its ability to compete with other ions in solution for positions in the outer layer. Ion adsorption of this type is favored by high charge, high polarizability and concentration, low energy of hydration, and small size.

Although the counter-ion exchange mechanism is consistent with the experimental data for a large number of systems, there are other systems to which it is inapplicable. For such systems, it is probable that adsorption occurs through isomorphous replacement. This type of adsorption consists of the rapid exchange of the tracer ion with lattice ions on the surface of the crystal followed by slow incorporation into the crystal lattice during recrystallization processes. Isomorphous replacement is favored by high temperature, low pH, long time of contact, high surface area of the crystalline precipitate, and low concentration of the lattice ion having the same charge as that of the tracer.







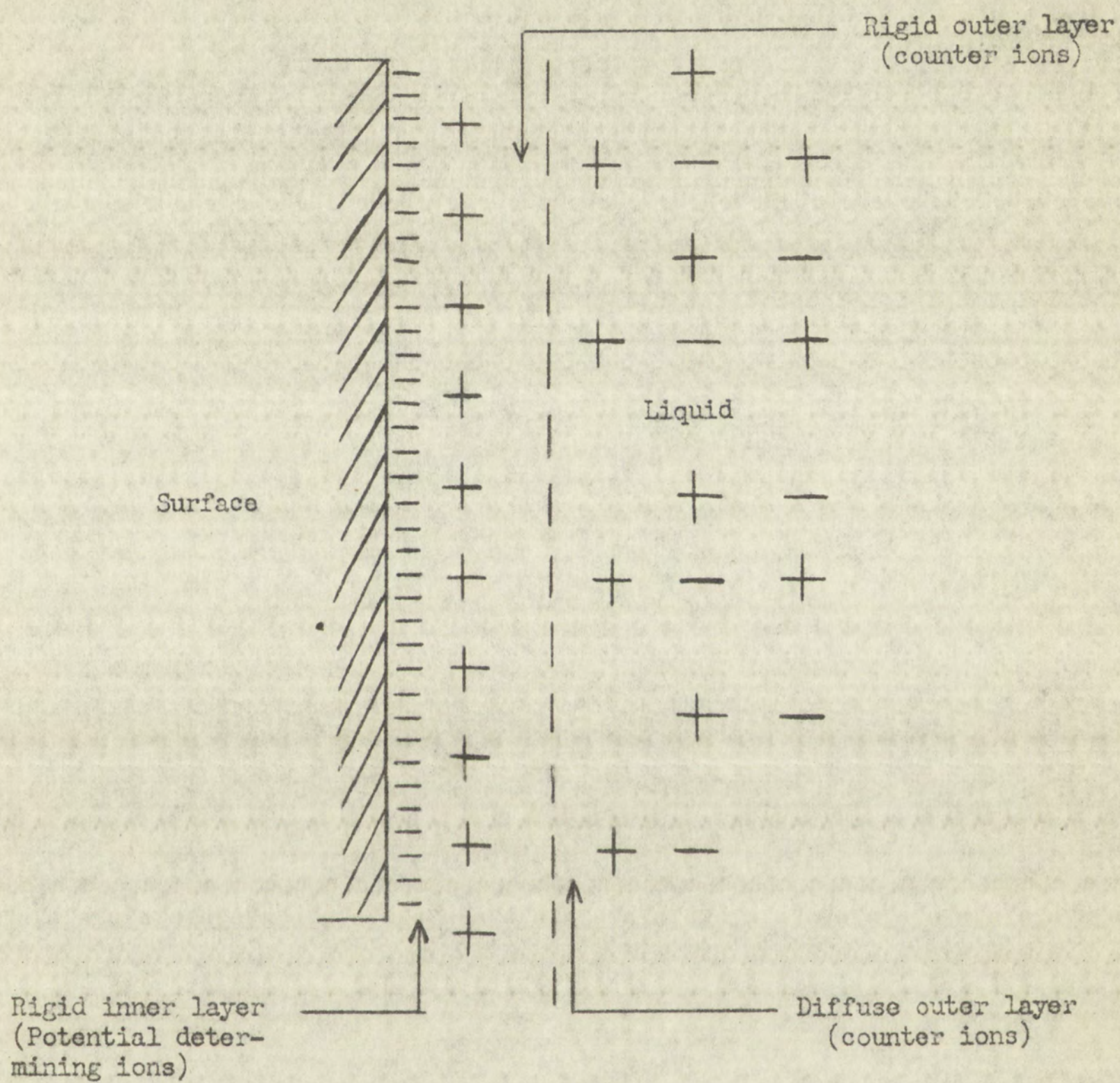
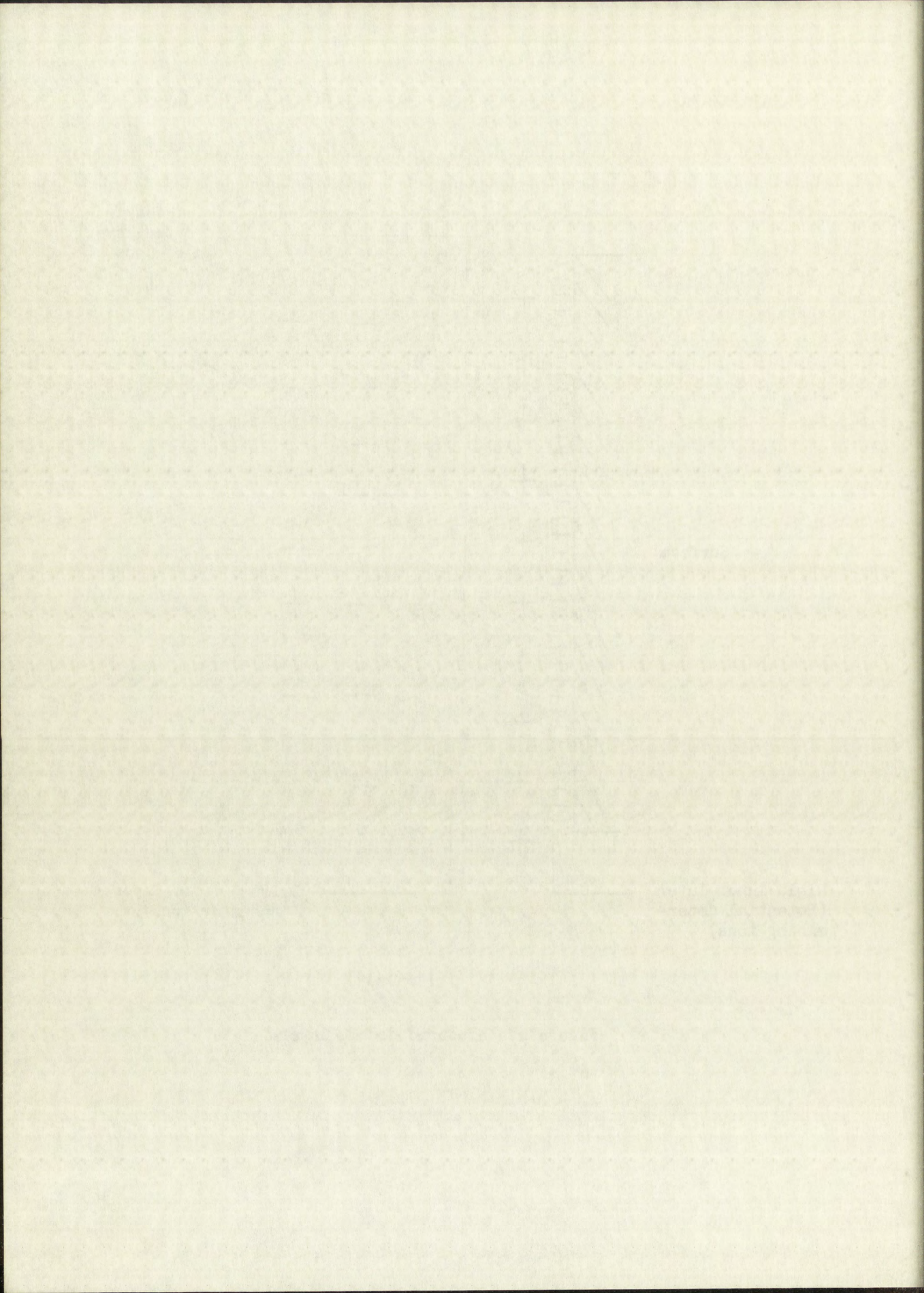


Figure 1. Electric double layer.







Adsorption of carrier-free tracers on charcoal has not been studied extensively. However, this process has been used as a separation technique for 24.5-day uranium  $X_1$  ( $\text{Th}^{234}$ ) from uranyl nitrate solutions when other methods were undesirable. (16)

Schubert and Richter<sup>(17)</sup> have shown that organic cation exchangers may be used to investigate the radio-colloidal behavior of radioelements. The index for differentiating between true ionic species and radio-colloids is the equilibrium distribution coefficient,  $K_D$ .

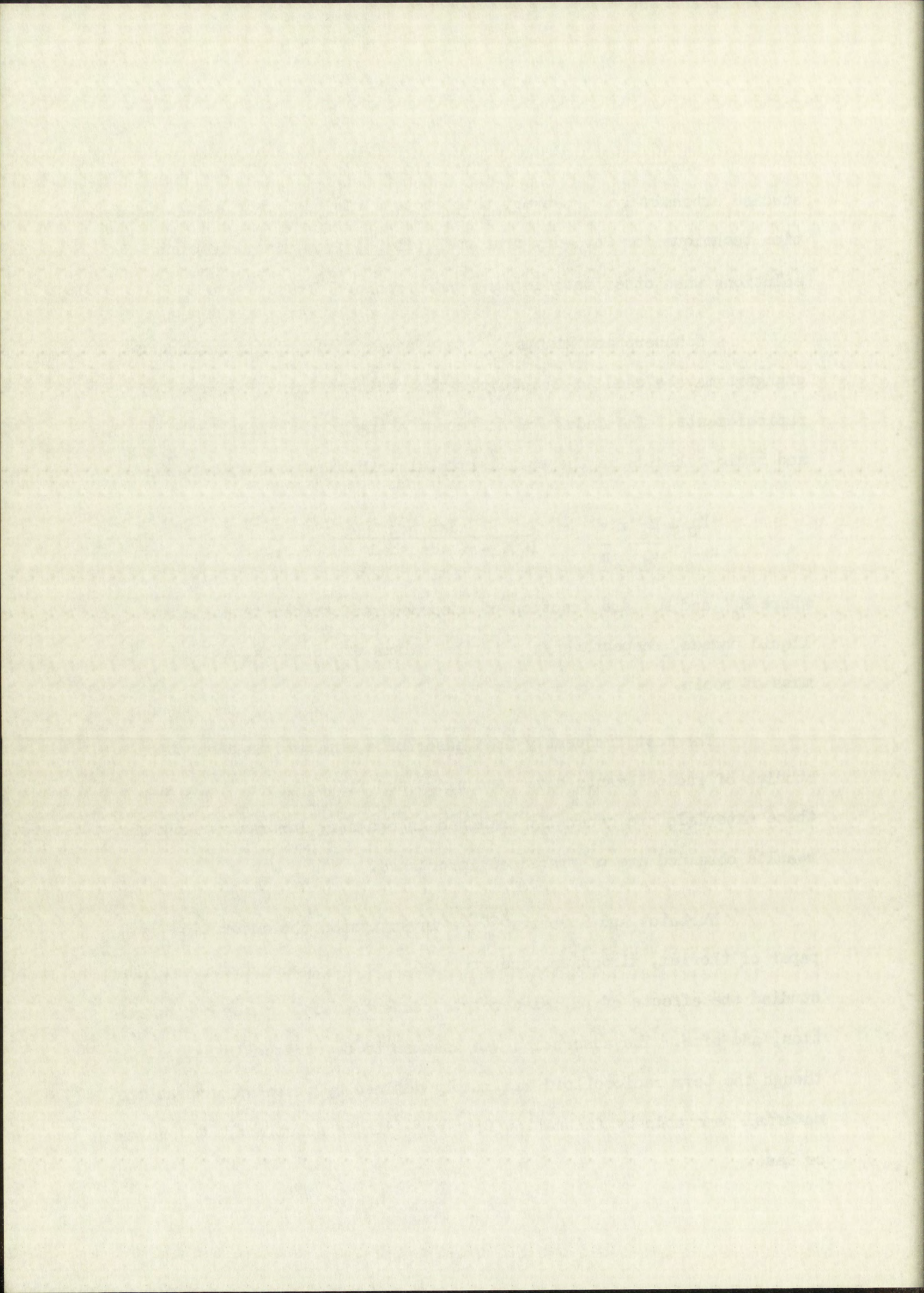
$$K_D = \frac{M_s}{M_l} \times \frac{v}{m} = \frac{\% \text{ adsorbed}}{100\% - \% \text{ adsorbed}} \times \frac{v}{m},$$

where  $M_s$  and  $M_l$  are fraction of adsorbed radiotracer in solid and liquid phases, respectively,  $v$  is the volume of solution, and  $m$  is the mass of resin.

The most frequently used adsorbents employed in adsorption studies of radioelements have been glass and filter paper. Because these materials are generally employed in ordinary laboratory work the results obtained are of practical importance.

Kurbatov and Kurbatov<sup>(18-20)</sup> investigated the adsorption by paper of thorium, zirconium, and yttrium in tracer concentrations. They studied the effects of pH, electrolyte concentration, tracer concentration, and time. The adsorption was assumed to be radiocolloidal, although the term radiocolloid was simply defined by these workers as the material removable by filtration from very dilute solutions,  $10^{-9}$  molar or less.







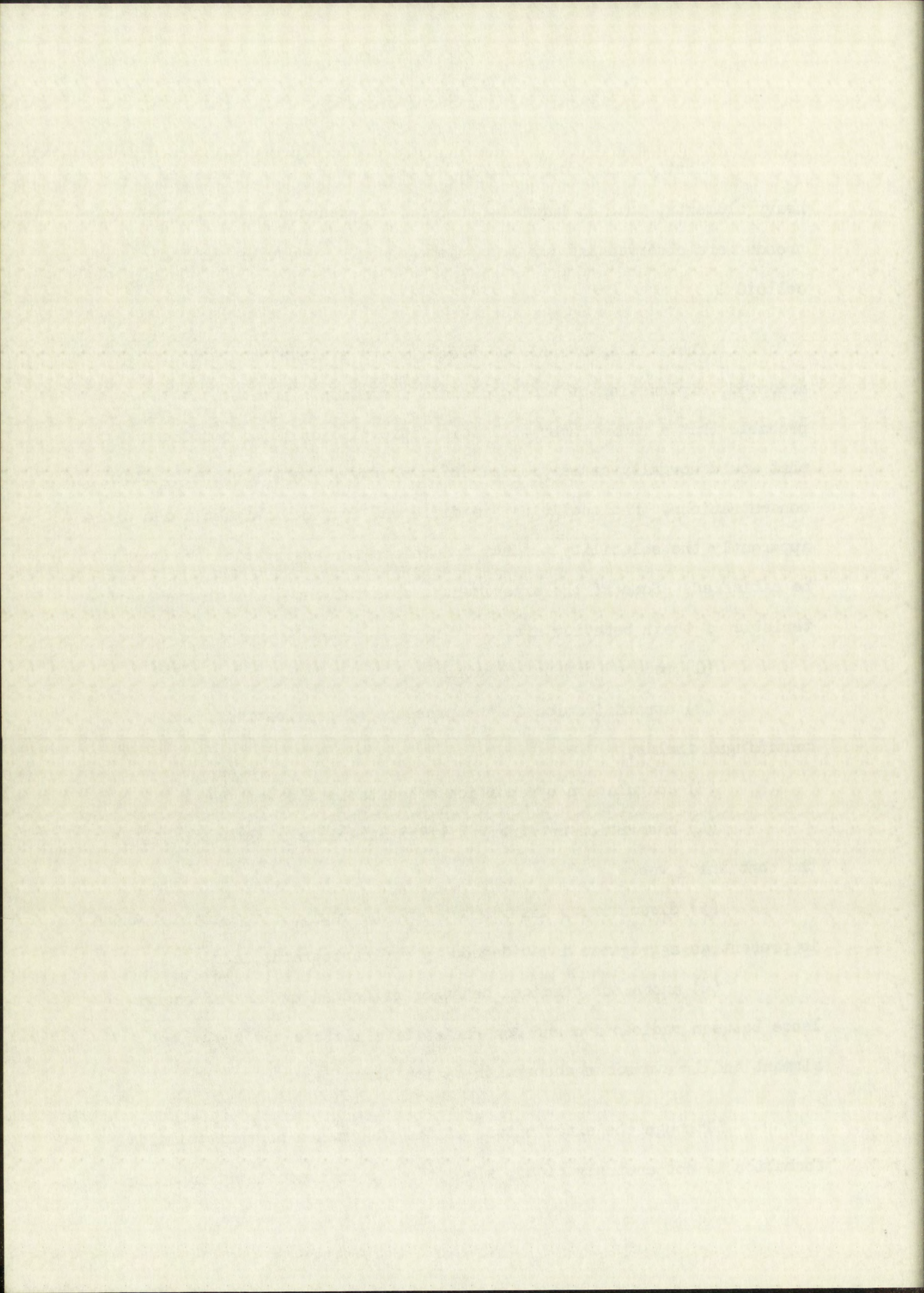
Most of the early studies of this nature were conducted with heavy elements, such as bismuth, thorium, polonium, and lead. Similar trends were observed and the mechanism generally described as radiocolloidal.

There is apparently no adequate, or at least universally accepted, explanation of radiocolloidal formation. However, it is probable that a radiotracer will form radiocolloids under conditions that would normally cause precipitation of the element present in macro concentrations. Radiocolloids are different from ordinary colloids since apparently the solubility product conditions for aggregation need not be satisfied. Some of the experimental observations<sup>(21)</sup> which are characteristic of their behavior are:

- (1) reduced diffusion rates,
- (2) stratification in the presence of gravitational and centrifugal fields,
- (3) coagulation by addition of suitable electrolytes,
- (4) adsorption on finely divided materials or on the walls of the containing vessel,
- (5) discontinuous distribution of the radioactive material which is present as aggregates as evidenced by radioautographs, and
- (6) anomalous chemical behavior evidenced by lack of equivalence between radioactive and non-radioactive isotopes of the same element and irreversible adsorption on ion exchangers.

Although the exact nature of the phenomenon of radiocolloidal formation is not entirely clear, adsorption is an exceedingly important







factor in its detection. The adsorption behavior of radiocolloids is different from that of the cationic forms of radioisotopes.

Schönfeld and Broda<sup>(22)</sup> have used paper and glass adsorption of radiotracers as an indication of the presence of radiocolloids. They observed that adsorption due to ion-exchange occurs when a  $10^{-15}$  molar lead (ThB) solution is brought in contact with paper or glass. If, however, the solution is saturated with hydrogen sulfide, radiocolloids are formed which are adsorbed by a different mechanism. When ion-exchange adsorption occurs, the addition of electrolytes decreases the amount adsorbed, whereas with colloid adsorption such electrolyte addition either has no effect or increases the amount of ThB adsorbed. Specifically, 12% of ThB was adsorbed by paper from a hydrogen sulfide saturated solution of the radioelement. Upon the addition of 0.01 molar potassium chloride or barium chloride, the adsorption was increased to 71-87%. These investigators also differentiated between the two adsorption mechanism by observing the difference in exchange rates between the adsorbed radioisotope and the inactive ion of the same element. When paper containing adsorbed radiocolloidal lead sulfide was brought in contact with 0.01 molar inactive lead nitrate, the exchange was very slow. When paper containing adsorbed lead ion was brought in contact with the inactive lead nitrate solution, the exchange was rapid.

In a later publication,<sup>(23)</sup> Schönfeld and Broda suggested that the two adsorption processes could also be differentiated by means of the Langmuir isotherm. The Langmuir isotherm,







$$\frac{x}{m} = \frac{K_1 C}{K_2 C + 1}$$

where  $x$  = mole of solute removed,

$m$  = weight of adsorbant in grams,

$C$  = equilibrium concentration of the solute in mole/liter, and

$K_1$  and  $K_2$  are constants, is followed by the ion exchange process, but may or may not be followed by colloidal adsorption.

Schweitzer and his co-workers<sup>(24-29)</sup> have investigated the possibility of radiocolloid formation of a number of elements under various conditions. The radionuclides used were yttrium-90, antimony-125, silver-111, sodium-22, cesium-134, calcium-45, iodine-131, sulfur-35, phosphorus-32, and lanthanum-140. Employing filtration and centrifugation as separation methods, these investigators determined the effects of pH, coagulation time, method of removal, and the presence of non-aqueous solvents and electrolytes on the percentage of radionuclide removed from the solution. In the cases where the radiocolloidal phenomenon was observed, a method was devised for the separation of the carrier-free nuclide and the ability of the radiocolloid to reform after an initial removal was studied. Lanthanum, silver, and yttrium were shown to form radiocolloidal aggregates in solution. Various grades of filter paper were used to determine the efficiency with which the radiocolloidal aggregates were retained. In general, the harder grades of paper removed more activity than did the softer or more porous types. This would seem to indicate that adsorption is not the prime factor since it would normally be expected that the more porous papers, having larger surface areas, would adsorb more.







Variations in the length of time allowed for coagulation to occur revealed a rapid increase followed by a slow decrease in the amounts of radiosilver and radioyttrium removed. With lanthanum, the percentage removed remained constant after a very short initial period.

The studies relating the effect of pH to the amount of activity removed revealed an initial rise then decrease, giving % removal-pH curves similar to that of the bell-shaped curve for yttrium and silver. However, with lanthanum the percent of radiocolloid removed was found to increase to a maximum of almost 100% as the pH increased. After attainment of the maximum at a pH slightly greater than 5, further increase in pH had little effect upon the percent removed.

Generally, substances which tend to complex with the tracer decreased the radiocolloidal formation, whereas the presence of other electrolytes either had no effect or enhanced removal by radiocolloidal formation.

Non-aqueous solvents decreased the amount of activity which could be removed from solution, the amount of activity removed being almost inversely proportional to the concentration of the non-aqueous solvent. The repressing effect was greater the lower the dipole moment of the solvent. Similar results have been reported by other workers. Experiments on the formation of radiocolloids in gaseous media by Harrington<sup>(30-31)</sup> gave evidence of the necessity of nuclei for radiocolloidal formation. Harrington investigated aggregate formation in



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tubes in which radon and various other gases were sealed. Aggregates were formed only when polar molecules were present. The explanation proposed was: Ions and recoil atoms present as a result of ionizing action of radiations and radioactive disintegrations tend to cluster together upon collision. A certain proportion of the polar molecules would be expected to remain in the cluster because of the tendency of these molecules to adsorb on such groups. An aggregate once formed would continue to grow until removed through gravitational action or by adsorption. The magnitude of the observed effects increased with increase of concentration of polar molecules. Chamie<sup>(32)</sup> suggested that these same considerations might explain radiocolloidal behavior in solutions.

Other experiments were performed by Schweitzer and his co-workers to determine whether any considerable amount of radiocolloid would reform upon aging after that initially formed was removed by filtration or centrifugation. The results indicated that once the initially formed aggregates are removed further colloidal formation is not too pronounced.

Although yttrium, silver, and lanthanum were found to exhibit radiocolloidal behavior, no evidence of similar behavior was established for antimony, calcium, sodium, cesium, or any of the anions employed by this group of investigators. Antimony, calcium, and phosphate ions showed some type of aggregation but the adsorption curves obtained were not similar to those of elements which are radiocolloidal. The other radionuclides used showed no evidence of radiocolloidal







formation. Sodium, cesium, sulfate, and iodide were removed in erratic amounts by filtration through paper or glass. Practically no adsorption was detected when centrifugation was used as the separation technique. The slight removal observed by the filtration processes was attributed to physical adsorption and ion-exchange. The filter papers used had been soaked with an inactive solution of identical salt concentration and pH prior to filtration of the active sample. In general, the percentage removal by filtration through paper was less than that through fritted glass. This strongly suggested the ion-exchange mechanism for removal on glass and paper, the removal on paper being somewhat less due to the previous saturation of the surface with inactive ions.

There is reported in the literature a number of experimental observations and theories in support of the ion-exchange mechanism for removal of radioelements from solution. Schönfeld and Broda<sup>(33)</sup> studied the uptake of lead and rubidium in tracer amounts by surfaces of paper and glass. With both surfaces the adsorption was attributed to ion exchange. In the case of paper, carboxyl groups with replaceable hydrogen ions were considered responsible for ion-exchange, whereas with glass the exchange was made possible through the ionization of weakly acidic silicic acid groups.

There is much evidence in favor of the opinion that glass in contact with salt solutions acts as an ion exchanger. It is generally agreed that the surfaces of glass, silica gels, and quartz are covered with acidic  $\equiv \text{Si-OH}$  groups which ionize according to equation 1:<sup>(34)</sup>



1. The first step in the process of the investigation was to determine the scope of the problem.

2. The second step was to identify the causes of the problem.

3. The third step was to develop a plan of action to solve the problem.

4. The fourth step was to implement the plan of action.

5. The fifth step was to evaluate the results of the investigation.

6. The sixth step was to report the findings of the investigation.

7. The seventh step was to recommend corrective action.

8. The eighth step was to follow up on the corrective action.

9. The ninth step was to prevent the problem from recurring.

10. The tenth step was to document the entire process.

11. The eleventh step was to communicate the findings to the appropriate personnel.

12. The twelfth step was to ensure that the corrective action was effective.

13. The thirteenth step was to monitor the situation for any further problems.

14. The fourteenth step was to review the investigation process for continuous improvement.

15. The fifteenth step was to close the investigation.

16. The sixteenth step was to archive the investigation report.

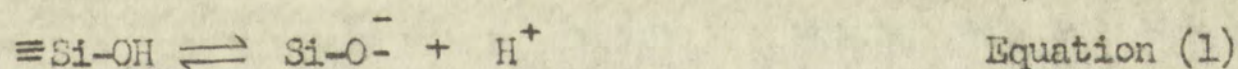
17. The seventeenth step was to provide training to the staff.

18. The eighteenth step was to update the policies and procedures.

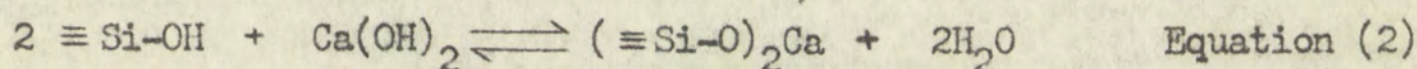
19. The nineteenth step was to conduct a final review.

20. The twentieth step was to complete the investigation.

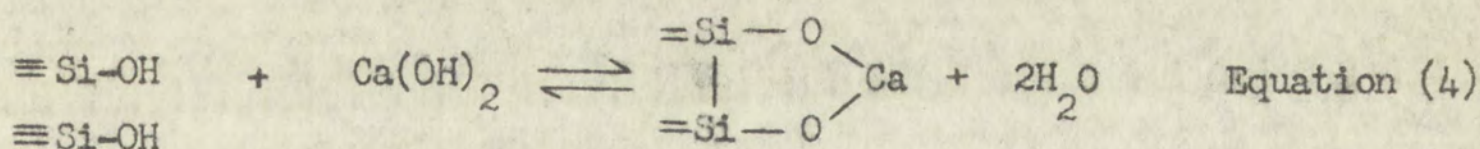
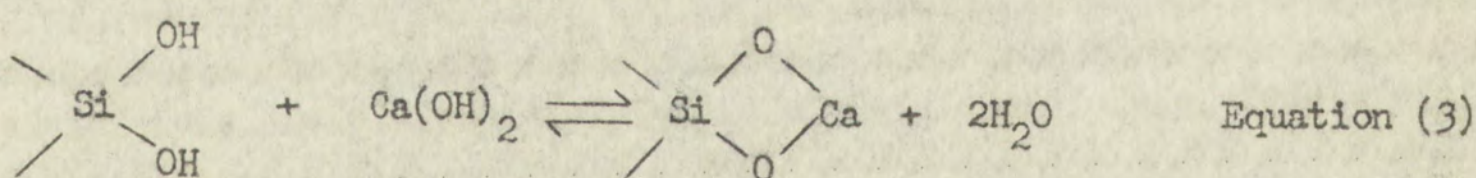




In addition, a small amount of silicic acid and its ions and colloidal silica are found in solution. Polyvalent metal ions are adsorbed from aqueous solution on glass, silica gels, or quartz providing the pH is not much less than that at which the metal hydroxide itself would be precipitated. Adsorption of monovalent ions from solution has also been observed. Utilizing macro amounts of substances, the adsorption of calcium hydroxide by silica was studied by Greenberg.<sup>(35)</sup> The reaction between the  $\equiv\text{Si-OH}$  surface and calcium hydroxide was assumed to be that of a weak acid and strong base, as shown in equation 2.



The hydrolysis of the surface  $\equiv\text{Si-O}^-$  proceeds due to the low ionization constant of silicic acid. Two possible reactions of calcium hydroxide with the surface are shown by equations 3 and 4.



The results of this study confirmed the hypothesis that chemisorption of calcium ions by acidic  $\equiv\text{Si-OH}$  groups is the primary step in the reaction between calcium hydroxide and silica. The hydrogen ions in the  $\equiv\text{Si-OH}$  groups could be replaced by calcium ions in solutions of pH values between 5 and 13.







Rydberg and Rydberg (36) measured the adsorption of tracer amounts of thorium on glass and polyethylene as a function of thorium perchlorate concentration, time, pH, wall material, ionic strength, and complex-forming anions. As the pH of the thorium perchlorate solution was increased the percentage of thorium adsorbed on the walls of the glass and polyethylene vessel increased up to a certain pH value, after which further increase in pH resulted in decreased adsorption. In explaining the adsorption on glass, Rydberg and Rydberg assumed the existence of two competing reactions: (1) the dissociation of silicon acid groups on the glass surface and (2) the hydrolysis of thorium (IV). At low pH values the silicon acid groups dissociate providing sites where other positive ions can adsorb. Thorium (IV) undergoes no appreciable hydrolysis at  $\text{pH} \leq 3$ , particularly at the low concentrations used, and is therefore strongly adsorbed. After pH 4 hydrolysis of thorium (IV) predominates over the glass dissociation. This results in a decrease in available thorium (IV) and charged species of hydrolyzed thorium such as  $\text{ThOH}^{+3}$  or  $\text{ThO}^{+2}$  and an increase in uncharged thorium hydroxide or probably colloidal aggregates of  $\text{ThO}(\text{H}_2\text{O})_2$ . Consequently, at the higher pH values, the adsorption on glass diminishes.

The adsorption on polyethylene observed by these investigators showed the same general pH dependence. It is difficult to conceive of polyethylene functioning as an ion exchanger, since the surface is comprised of polymerized ethylene. It was suggested that the two adsorption mechanisms were different. With polyethylene adsorption was assumed to be due to neutral aggregates of thorium hydroxide rather



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than to an ion exchange. This was substantiated by the fact that adsorption on polyethylene at  $\text{pH} < 3.4$  is smaller than the adsorption on glass. The decrease in adsorption on polyethylene at  $\text{pH} > 9$  may be due to the fact that the aggregates of  $\text{ThO}_2(\text{H}_2\text{O})_n$  become negatively charged by the excess hydroxyl ions, thus making the colloids more soluble.

The reactions of radioactive tracers in aqueous solution with glass have been studied by Willard, Hensley, and Long.<sup>(37-39)</sup> The effect of time of contact, pH, temperature, and pretreatment of the surface on the sorption of sodium, cesium, and silver ions was observed. Although some of the results suggested an ion-exchange mechanism, there was other evidence that ion exchange is not the uniquely controlling factor. The following observations, made while using radiosodium as tracer, were presented as either inconsistent with the ion exchange mechanism or indicative that such a mechanism does not give the complete picture of the interaction between glass and aqueous salt solutions.

(1) Glass previously soaked in 0.2 normal solutions of hydrogen, barium, or potassium ions for 330 hours lost sodium ions readily when immersed in water for ten minutes.

(2) Water was as effective as 0.1 normal hydrogen ion solution in leaching sodium ions from glass.

(3) Glass soaked in 6 normal hydrochloric acid for 50 hours showed approximately the same ability to sorb sodium ions from neutral solution as did glass soaked in water for 50 hours.







(4) A change of  $10^6$  or more in hydrogen ion concentration of the immersion solution changed the amount of sodium ion sorbed on glass by only ten- or twenty-fold.

(5) Under certain conditions, sodium ion was lost from glass to a neutral solution faster than it was gained.

(6) The rate of sorption of sodium ions by glass was increased by prolonged standing of the sorption solution in soft glass or borosilicate glass, prior to the tests for adsorption which involved immersing glass plates into the solution. No increase was noted in the sorption rate when the solutions were allowed to stand in contact with platinum.

(7) Physical tests showed an attack and/or swelling of glass surfaces by prolonged contact with aqueous media.

(8) Glass adsorbed phosphate ions, the amount of sorption being dependent on the extent of pretreatment of the glass with caustic.

These observations were interpreted as meaning that one or more processes other than the base exchange process probably play a part in controlling the adsorption of sodium ion. The other processes suggested were (1) diffusion of the hydrated sodium ion through the liquid film on the glass surface, (2) the dehydration of the ions as a function of temperature, (3) the changes in hydration and bonding structure of the glass which may, in turn, be a function of temperature and pH, and (4) the process of diffusion of ions into and out of the interior of the glass.



(1) The first part of the paper is devoted to a description of the experimental apparatus and the method of measurement. The second part is devoted to a description of the results of the measurements. The third part is devoted to a discussion of the results and to a comparison with the results of other workers. The fourth part is devoted to a summary of the results and to a conclusion. The fifth part is devoted to a list of references.

The experimental apparatus consists of a glass tube of length 10 cm and diameter 1 cm, which is closed at both ends by glass plates. The tube is filled with a liquid of known viscosity. The liquid is heated by a coil of wire which is wound round the tube. The temperature of the liquid is measured by a thermometer which is inserted into the tube. The pressure of the liquid is measured by a manometer which is connected to the tube. The velocity of the liquid is measured by a method which is described in the paper.

The results of the measurements are shown in Table I. The table shows the velocity of the liquid as a function of the temperature and of the pressure. The velocity increases with increasing temperature and with increasing pressure. The results are compared with the results of other workers in the table.

The discussion of the results shows that the velocity of the liquid is a function of the temperature and of the pressure. The results are compared with the results of other workers. The conclusion is that the velocity of the liquid is a function of the temperature and of the pressure.

The summary of the results is given in Table II. The table shows the velocity of the liquid as a function of the temperature and of the pressure. The conclusion is that the velocity of the liquid is a function of the temperature and of the pressure.

The list of references is given at the end of the paper.



Despite the considerable number of investigations of the interactions between glass and ions in solution, the exact nature of the processes which control the interaction remains obscure. The ion exchange phenomenon has, however, been exhibited with filter paper as well as with glass. Carrier-free cesium-137 was adsorbed on filter paper from aqueous solutions at different pH values and cesium concentrations.<sup>(40)</sup> No radiocolloidal properties were apparent. Instead the adsorption followed the Langmuir isotherm and revealed other properties characteristic of ion-exchange.

In the present investigation, procedures are given for the rapid separation of tracer quantities of indium from macro amounts of cadmium by adsorption and extraction techniques. The indium was adsorbed onto glass, paper, or cellulose ester fibers from ammoniacal solution and was extracted from buffered acetate solutions by 8-hydroxyquinoline in chloroform. It is estimated that the concentration of indium in the carrier-free solutions was  $\sim 10^{-12}$  molar.

These dilute solutions have been used to investigate the mechanisms of indium adsorption on solid surfaces, principally Pyrex glass. Other surfaces used have been quartz, polyethylene, and paraffin. This study includes (1) rate studies at different pH values, (2) effects of pH, ionic strength, adsorbate concentration, added electrolytes, surface material, centrifuging, and temperature, (3) adsorption on cation and anion exchange resins as a function of pH, (4) reformation studies, i.e., the tendency for further adsorption to occur on a new



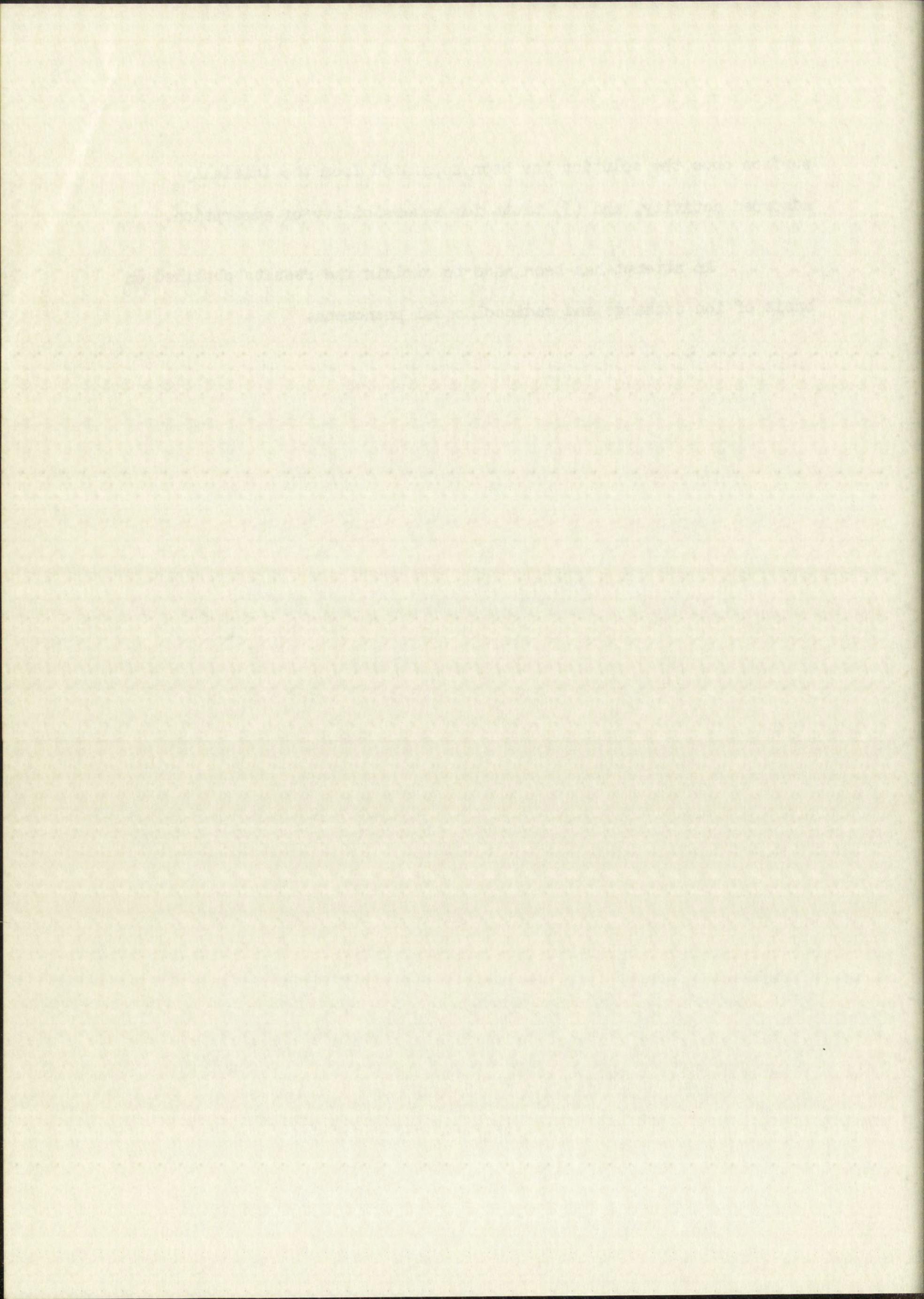




surface once the solution has been separated from the initially adsorbed activity, and (5) tests for reversibility of adsorption.

An attempt has been made to explain the results obtained on basis of ion exchange and radiocolloidal phenomena.







## EXPERIMENTAL

## Reagents and Materials

Cadmium-115-indium-115m active solution. Samples of cadmium acetate dihydrate were weighed into quartz tubes and irradiated in one of the reactors of the Los Alamos Scientific Laboratories. The irradiated samples were dissolved in 0.2 molar acetic acid or 0.035 molar perchloric acid and allowed to stand at least until transient equilibrium for the cadmium-115-indium-115m system was established.

Carrier-free indium-115m stock solution. The separation of indium-115m from the cadmium solution was effected by selective adsorption on glass in the presence of excess ammonium hydroxide. The indium activity was retained by the glass whereas the cadmium remained in solution as the ammonia complex. Three milliliters of cadmium-115-indium-115m stock solution, (in transient equilibrium) 0.2 molar in acetic acid, was added to 0.300 gram of powdered glass in a 15 ml. Pyrex cone. Three milliliters of 4 molar ammonium hydroxide was added and the mixture stirred for approximately 3-5 minutes, then centrifuged in an ordinary clinical centrifuge. After discarding the supernatant liquid, the powdered glass and walls of the cone were washed with 4 molar ammonium hydroxide to remove any traces of cadmium adhering to the surface. The activity which remained on the glass surfaces was dissolved in 0.035 molar perchloric acid and its decay followed for 40 hours. No cadmium contamination was detected and the measured half-life of the isolated activity was 4.5 hours, in satisfactory agreement with previously reported values.<sup>(41)</sup> The concentration of indium-115m was calculated by the equation:







$$x = \frac{dN}{dt} \left( \frac{t_{1/2}}{0.693} \right) \left( \frac{1}{6.02 \times 10^{23}} \right), \text{ where}$$

$\frac{dN}{dt}$  = the indium activity, corrected for counter efficiency to yield disintegrations per minute,

$t_{1/2}$  = the half-life of indium-115m, 4.53 hours, and

$x$  = the moles of indium-115m.

The calculated value was of the order of magnitude of  $10^{-12}$  molar.

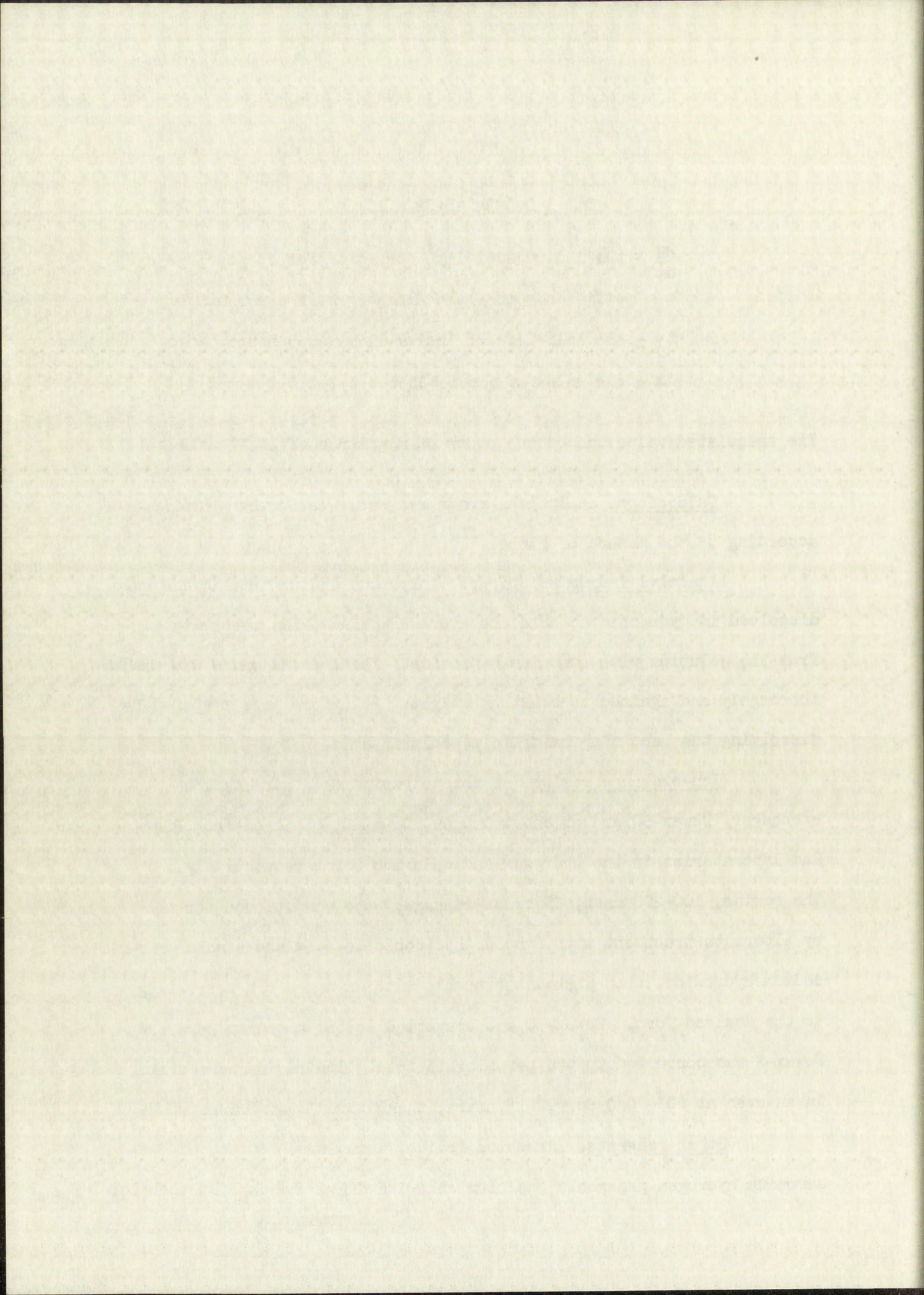
Chloroform, analytical grade reagent, was further purified according to the method of Fieser.<sup>(42)</sup>

Inactive indium solutions. Anhydrous indium trichloride was dissolved in hydrochloric acid and hydrous indium oxide precipitated from the solution with ammonium hydroxide. The hydrous oxide was washed thoroughly and ignited to constant weight. Solutions were prepared by dissolving the resulting oxide in perchloric acid.

Ion-exchange resins. Exchange resins used were cation-exchanger, Dowex-50 and anion-exchanger, Dowex-2, obtained from Bio-Rad laboratories in the hydrogen and chloride forms respectively. The resins, 100-200 mesh, 8% cross linkage, were conditioned for use by alternate treatment with 6 molar hydrochloric acid and 6 molar sodium hydroxide, then washed thoroughly with water before converting to the desired form. Dowex-50 was converted to the ammonium form and Dowex-2 was converted to the perchlorate form. The resins were dried in an oven at 60°-70°C for 12-15 hours, then stored over Drierite.

Other reagents. Ammonium iodide, ammonium chromate, diammonium hydrogen phosphate, calcium chloride dihydrate, sodium acetate,







sodium perchlorate, and 8-hydroxyquinoline, obtained as analytical grade reagents, were used without further purification. Ammonium perchlorate, analytical grade, was recrystallized from water and dried in an oven at  $100 \pm 5^{\circ}\text{C}$  for two hours. The water used was obtained by redistillation of ordinary distilled water from an alkaline permanganate solution. All alkaline solutions were stored in polyethylene bottles; other solutions were stored in glass-stoppered Pyrex bottles.

Adsorption vessels. Several types of vessels were used in the adsorption experiments. Type I consisted of 15 ml. quartz, polyethylene, and Pyrex cones. The Pyrex cones were used either alone, with added paper mash or powdered glass, or were coated with paraffin (Texwax). The paraffin-coated cones were used without further treatment. The other cones were cleaned by soaking overnight (several hours in the case of polyethylene) in concentrated nitric acid, then washed with distilled and re-distilled water, and finally air-dried at room temperature.

Type II adsorption vessels were Pyrex glass tubes, 20mm. o.d. x 100-105mm., which were sealed off at a standard height, 95mm. from the base, after the addition of the solutions. These tubes were cleaned in the manner described above.

Type III adsorption vessels were fritted-glass disc Pyrex funnels of fine, medium, and coarse porosity. These vessels were also cleaned in the previously described manner, but were dried in an oven at  $110^{\circ}\text{C}$ .

Extraction vessels. Ten-milliliter Pyrex cones fitted with ground glass stoppers were used in the extraction procedures.







Millipore filters. VF and PH white, plain filters, 1-inch in diameter, were secured from Millipore Filter Corporation, Watertown, Massachusetts. The pore sizes were 10 mu and 300 mu for the VF and PH filters, respectively.

Paper mash. Three circles of Whatman No. 42 (7.0 cm.) filter paper were cut into small pieces and stirred with 50 ml. of distilled water until completely disintegrated. The final volume of the mash was brought to 100 ml. with water.

Other papers used for adsorption were 1-inch circles of Whatman No. 42 and Whatman No. 50 filter paper.

Powdered glass. Pieces of Pyrex tubing were powdered, then screened. The 200<sup>+</sup> mesh fraction was purified by washing with 5-9 molar hydrochloric acid, chromic acid cleaning solution, ethanol, and water. The purified glass was dried for approximately 12 hours at 110°C, then stored over Drierite.

#### Detection of Radioactivity

The  $\gamma$ -rays associated with the decay of indium-115m and cadmium-115 were detected with a scintillation counter employing a #5819 RCA phototube and a thallium-activated sodium iodide crystal. All active solutions were prepared for counting by dilution with 5-10 molar hydrochloric acid to a standard height in calibrated 18x150mm. Pyrex tubes. The solutions were air-stirred with a capillary pipet before counting. The number of counts was always high enough to get 1% standard deviation or better and the observed activities of all indium-115m samples were corrected for decay.







The decay scheme for the cadmium-115-indium-115m system is shown in Figure 2.<sup>(43)</sup> The disintegration energies are given in million-electron volts and the total angular momentum and parity of the states are included.

#### Adsorption and Solvent Extraction Procedures for the Separation of Carrier-free Indium from Cadmium

Two types of adsorption experiments were employed in this investigation. In the first type, the adsorbing surface was the walls of a Pyrex cone, either alone or with added powdered glass or paper mash. In the second type, the adsorbing surface was a fritted-glass disc funnel, Whatman filter paper, or a Millipore filter. In the experiments utilizing paper or Millipore filters as adsorbents, the filters were clamped between a ground-edge glass chimney, 89mm. high and 18mm., i. d., and a Hirsch funnel without sides and with its surface ground flat.

Adsorption procedure-Type I. Five milliliters of carrier-free indium-115m solution, 0.035 molar in perchloric acid, and of known inactive cadmium concentration, was added to 5ml. of ammonium hydroxide of the appropriate strength. The mixture was stirred in contact with the adsorbing surface for ten minutes and then centrifuged in an ordinary clinical centrifuge for ten minutes. The percentage indium adsorbed was calculated from the activity of the supernatant liquid. In over 95% of the experiments, the activity adsorbed was removed from the surface with 5 molar hydrochloric acid and counted. In those instances where cadmium was added, the adsorbent was washed



The second series of experiments was conducted in the same manner as the first, but with the following modifications:

(a) The temperature of the water was maintained at 20°C.

(b) The concentration of the solution was 0.1 M.

(c) The volume of the solution was 10 ml.

(d) The time of observation was 10 minutes.

(e) The results were recorded on a graph.

(f) The experiment was repeated three times.

(g) The average results were calculated.

(h) The results were compared with those of the first series.

(i) The results were discussed.

(j) The conclusions were drawn.

(k) The experiment was concluded.

(l) The results were recorded.

(m) The experiment was repeated.

(n) The results were compared.

(o) The conclusions were drawn.

(p) The experiment was concluded.

(q) The results were recorded.

(r) The experiment was repeated.



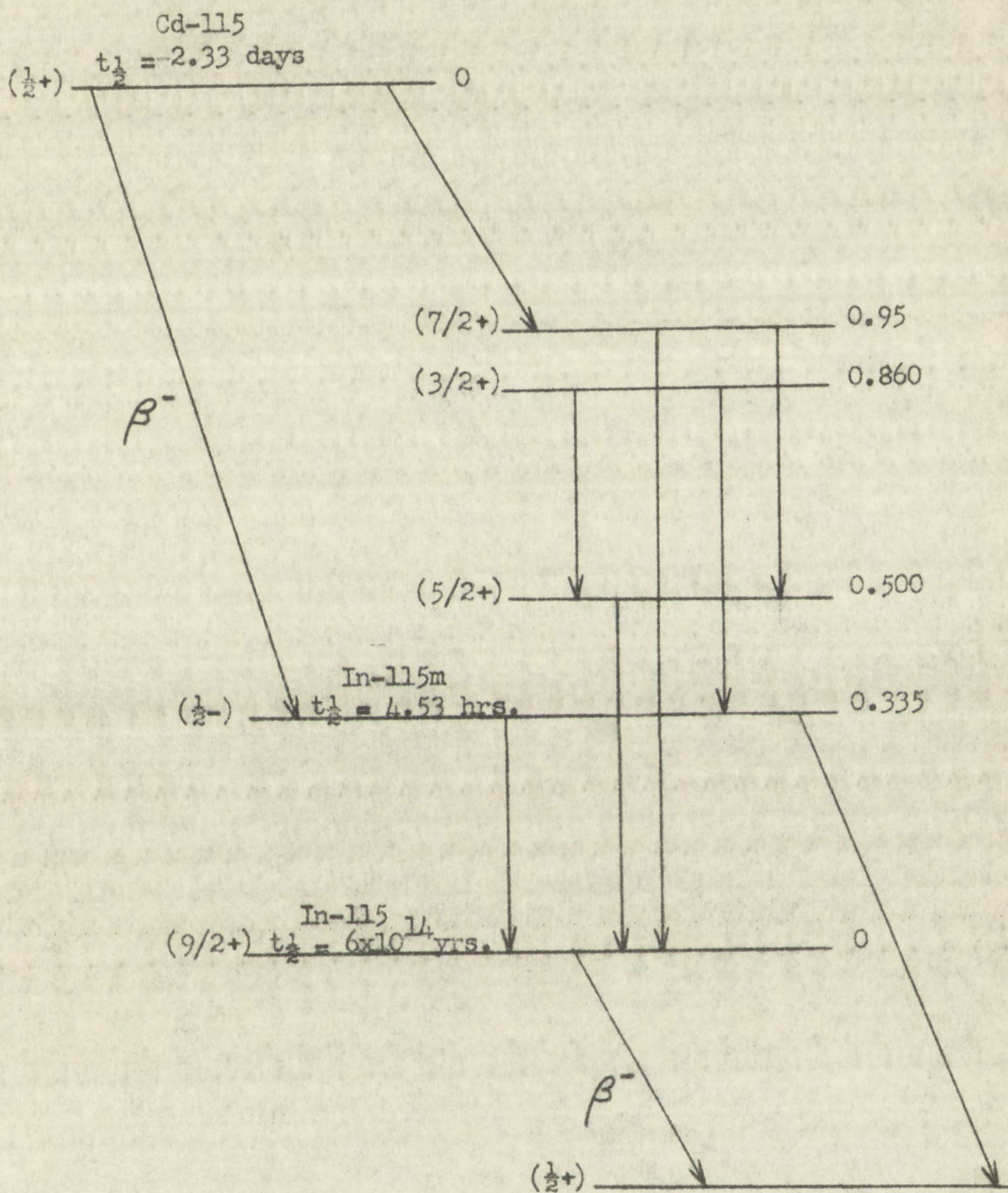


Figure 2. Decay scheme of Cd-115 and In-115m.







once with 5 ml. of ammonium hydroxide. The total activity recovered was always equal to at least 96% of the initial amount used.

Adsorption procedure - Type II. Three to five milliliters of 10.7 molar ammonium hydroxide was pipetted onto fritted-glass disc funnels, filter papers, or Millipore filters of different porosities. An equal volume of carrier-free indium - 115m in 0.035 molar perchloric acid was added. The solutions were mixed by air - stirring momentarily with a capillary pipet and then filtered with suction. After washing the filters with 10ml. of 10.7 molar ammonium hydroxide, the adsorbed activity was dissolved in 5-10 molar hydrochloric acid and measured.

Extraction procedure. An aliquot of carrier - free indium - 115m stock solution was adjusted to the appropriate pH by the addition of sodium acetate solution. In some instances, known amounts of inactive cadmium or indium were also added; the final volume being 4ml. in all cases. The aqueous solution was vigorously shaken with 4ml. of a 0.01 molar solution of 8 - hydroxy quinoline in chloroform for 5 minutes. After centrifuging at low speeds for approximately 2 minutes, the layers were separated; in the cases where cadmium was added, the organic layer was washed once with an aqueous solution of the same pH used in the initial extraction. The activity of each layer was determined.

Tests for cadmium contamination. The extent of coseparation of cadmium with the indium was determined by carrying out the adsorption or extraction procedures with solution containing 2.33-day cadmium - 115; the cadmium concentration, in all instances, was 0.01 molar. The radiochemical contamination of the separated activity was determined



the first of the two series of experiments.

The results of the first series of experiments are shown in Table I.

As shown in Table I, the results of the first series of experiments are shown in Table I.

The results of the second series of experiments are shown in Table II.

As shown in Table II, the results of the second series of experiments are shown in Table II.

The results of the third series of experiments are shown in Table III.

As shown in Table III, the results of the third series of experiments are shown in Table III.

The results of the fourth series of experiments are shown in Table IV.

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The results of the fifth series of experiments are shown in Table V.

As shown in Table V, the results of the fifth series of experiments are shown in Table V.

The results of the sixth series of experiments are shown in Table VI.

As shown in Table VI, the results of the sixth series of experiments are shown in Table VI.

The results of the seventh series of experiments are shown in Table VII.

As shown in Table VII, the results of the seventh series of experiments are shown in Table VII.

The results of the eighth series of experiments are shown in Table VIII.

As shown in Table VIII, the results of the eighth series of experiments are shown in Table VIII.

The results of the ninth series of experiments are shown in Table IX.

As shown in Table IX, the results of the ninth series of experiments are shown in Table IX.

The results of the tenth series of experiments are shown in Table X.

As shown in Table X, the results of the tenth series of experiments are shown in Table X.

The results of the eleventh series of experiments are shown in Table XI.

As shown in Table XI, the results of the eleventh series of experiments are shown in Table XI.



from decay curves which were obtained over a period of 30 - 45 hours. The gross cadmium contamination was determined by comparing the color developed when hydrogen sulfide was passed through a slightly alkaline solution of the separated activity with that developed in a set of standard cadmium solutions. In the extraction experiments, the indium was recovered from the chloroform layer by extraction with an equal volume of 1 molar nitric acid. The hydrogen sulfide tests were conducted on the active solution after destruction of the 8-hydroxyquinoline with a sulfuric acid-perchloric acid mixture. The lower limit of cadmium detection by the hydrogen sulfide method was  $2 \times 10^{-7}$  molar.

#### Effects of Different Variables on the Adsorption of Indium

Preliminary studies indicated that the adsorption of indium is sufficiently sensitive to a number of variables so that an investigation of these effects might furnish useful information as to the nature of the interactions between indium and the surface. The variables studied were pH, ionic strength, time, temperature, electrolytes, and surface material.

General adsorption procedure. Aqueous solutions of the appropriate pH and ionic strength were prepared directly in the adsorption vessel by mixing perchloric acid, ammonium hydroxide, and carrier-free indium-115m. In some experiments, the ionic strength was adjusted by the addition of ammonium perchlorate or neutral ammonium chromate. The final volume was 10-12 ml. in all cases. Because most of the solutions used in these studies exhibited little buffering action in the pH range of 3-7, some difficulties were encountered in obtaining







solutions of the desired pH by simply mixing the acid and base components. It was desirable (1) to have the adsorbing solution come in contact with no surface other than the adsorbent for the particular experiment and (2) to prepare the solutions as rapidly as possible so that the initiation of the adsorption process and the moment of addition of the indium activity could be considered essentially the same. To meet these requirements it was necessary to avoid titrations to the desired pH by the use of electrometric methods or outside color indicators. A typical example of the procedure used is as follows: Three milliliters of carrier-free indium-115m, in 0.035 molar perchloric acid, was transferred to a 50 ml. beaker. Seven milliliters of an ammonium hydroxide solution, calculated to give the approximate pH desired, was added. The exact pH of the solution was determined with a Beckman Model G pH meter. Depending on the value obtained, perchloric acid or ammonium hydroxide was added dropwise until the desired pH was reached. It was, generally, advantageous to use dilute acid or base ( $\leq 10^{-2}M$ ) in making this final adjustment in order to avoid overstepping the desired value or seriously altering the ionic strength of the solution. In order to test the reproducibility of the pH value, 3 ml. of the active solution was added to each of two or three beakers containing the other solution components. The mixture was stirred and the pH measured as before. When the reproducibility was good, similar solutions were prepared directly in the adsorption vessel; the active solution always being the last component added. If the reproducibility was not good, further attempts were made to obtain the desired pH by using acid and base solutions of other compositions. Because the plot







of pH versus ml. of base added for ammonium hydroxide- perchloric acid titration shows a sharp rise in the region 3 to 7, the pH sought is difficult to attain even with the greatest of care in the preparation of the solutions. Consequently, it was often necessary to make numerous attempts before the desired result was obtained.

The adsorption process was carried out for definite lengths of time in a constant temperature bath maintained at  $32.2 \pm 0.2^{\circ}\text{C}$ . In some of the earlier experiments, mixing was accomplished by rotating the solutions in sealed Pyrex vessels. Later, the solutions were agitated and protected from the atmosphere by bubbling through nitrogen which had been saturated with water vapor at the same temperature. Except in the case of some of the reformation and equilibrium experiments, the solutions were centrifuged in an ordinary clinical centrifuge for ten minutes after the agitation period. The pH of the solution was determined after the adsorption. The percentage of indium adsorbed was calculated from the activity of the supernatant liquid. In the experiments where nitrogen was used for stirring, corrections were made for the amount of activity adsorbed on the nitrogen delivery tube--a capillary Pyrex tube. Essentially quantitative recovery of the initial amount of activity was obtained in all of these experiments.







## RESULTS

### Separation of Carrier-free Indium from Cadmium

Adsorption procedures. The results of experiments, using the Type I adsorption procedure, are summarized in Tables I - III and Figures 3 - 5. These results suggest that maximum adsorption occurs from solutions which are 2-5.3 molar in ammonium hydroxide and equal to or less than 0.01 molar in cadmium ion. Powdered glass was more effective than paper mash. Although the data indicated the use of 0.5-2.0 grams of powdered glass, it was found advantageous to use 0.3 gram in order to avoid excessive volumes of wash solution. Using the best conditions indicated for each of the three adsorbing surfaces, the tests for radiochemical contamination by cadmium were negative except for the experiments employing paper mash. In this case, the gross cadmium contamination, estimated from the decay curve, was about 0.5% and may be attributed to difficulties encountered in completely washing the mash. The gross cadmium contamination, determined by the hydrogen sulfide test, for experiments using Pyrex cones plus 0.3 gram of powdered glass as adsorbent was 0.2% after one wash with ammonium hydroxide. This amount of contamination can be reduced to less than 0.002% with a second ammonium hydroxide wash, but is accompanied by a reduction in yield from 91% to 72%. This adsorption procedure is adaptable to larger scale separation. An experiment carried out at the temperature of a steam bath showed only a slight increase (about 1%) in the percentage of indium adsorbed.



EXPERIMENTAL PROCEDURE

The experimental procedure was as follows:

The type of electrode used was a standard Ag-AgCl electrode.

The electrolyte was a 0.1 M solution of NaCl.

The cell was set up as shown in Figure 1.

The cell was allowed to equilibrate for 30 minutes.

The potential was then measured with a potentiometer.

The cell was then stirred and the potential was measured again.

The cell was then allowed to equilibrate for 30 minutes.

The potential was then measured with a potentiometer.

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The cell was then allowed to equilibrate for 30 minutes.

The potential was then measured with a potentiometer.



TABLE I

Adsorption of Carrier-free Indium at Room Temperature from 5.33 Molar Ammonium Hydroxide as a Function of the Amount of Adsorbent

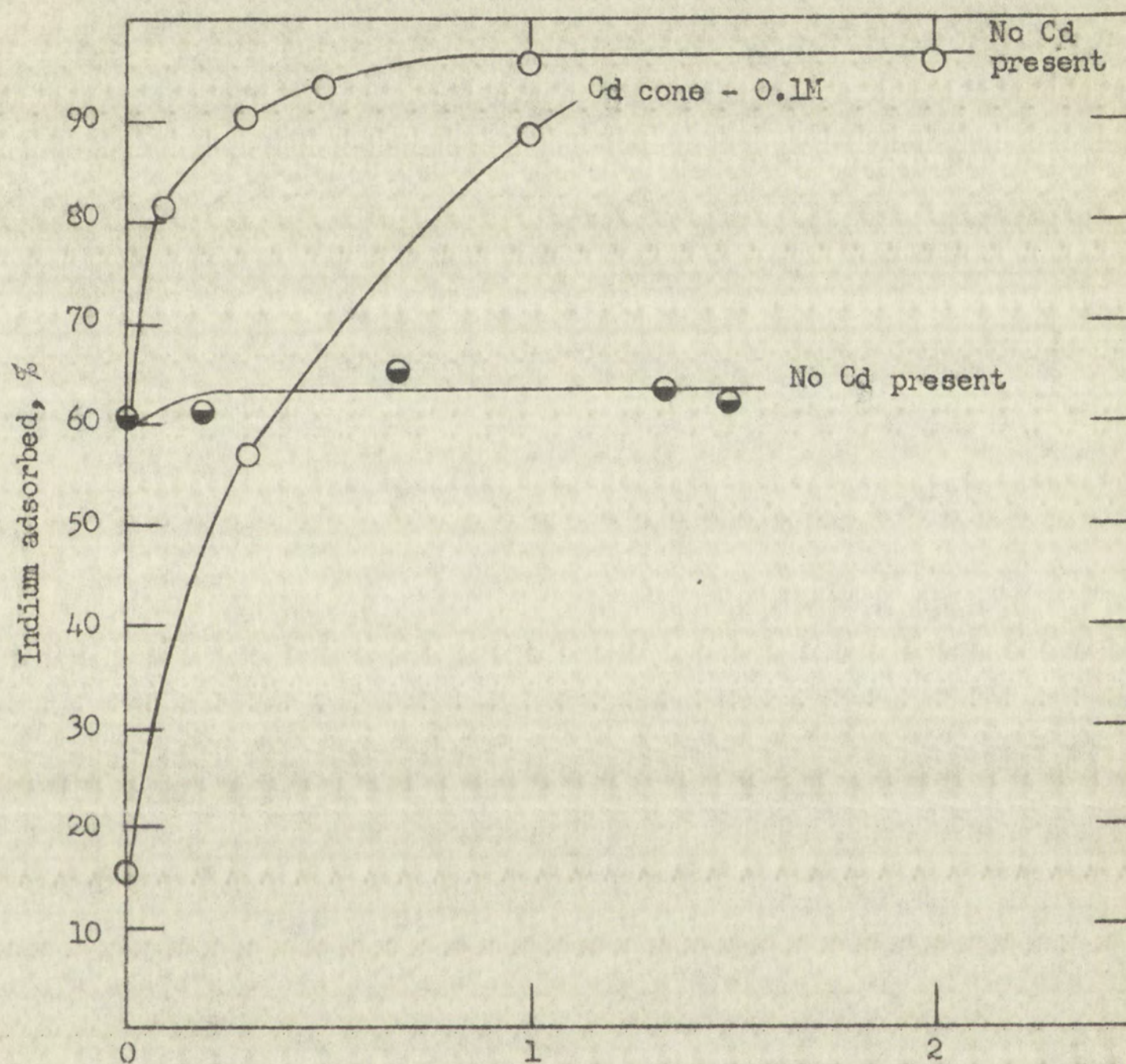
Weight of powdered glass, grams	Indium adsorbed, %		Centrifuged volume of paper mash, ML.(a)	Indium adsorbed, % No cadmium present
	No cadmium present	Cadmium concentration, 0.1M		
0.000	61	16	0.00	61
0.100	82	-	0.18	61
0.300	91	57	0.68	66
0.500	94	-	1.32	63
1.000	96	89	1.50	62
2.000	96	-		.

(a) Centrifuged volume of paper mash refers to the actual volume occupied by the paper after centrifuging a portion of the mash suspension for approximately one minute.









Weight of glass, grams or centrifuged volume  
of paper mash, milliliters

Figure 3. Adsorption of carrier-free indium at room temperature from 5.33M ammonium hydroxide as a function of amount of adsorbent.

Adsorbents: ○ Pyrex cone + powdered glass  
● Pyrex cone + paper mash



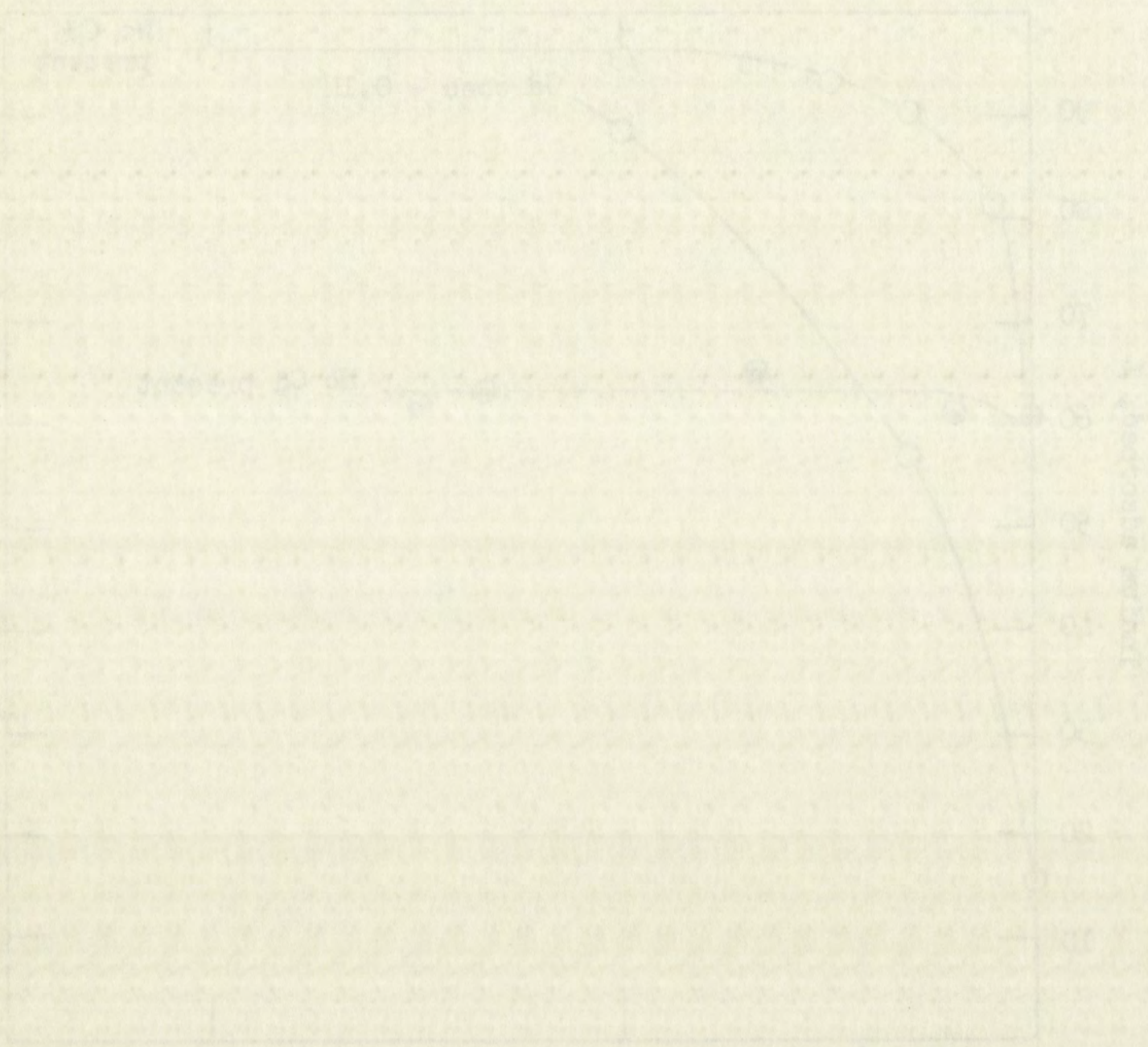


Figure 1. Adsorption of carbon tetrachloride on activated carbon at room temperature. The amount of adsorbate is plotted as a function of amount of adsorbent. The amount of adsorbent is plotted as a function of amount of adsorbate. The amount of adsorbate is plotted as a function of amount of adsorbent. The amount of adsorbent is plotted as a function of amount of adsorbate.



TABLE II

Adsorption of Carrier-free Indium at Room Temperature as a Function of Ammonium Hydroxide Concentration. No Cadmium Present.

Concentration of ammonium hydroxide, Molar	Indium adsorbed, %		
	Pyrex cone alone	Pyrex cone + 0.69 ml. paper	Pyrex cone + 0.300 gram powdered glass
5.33	61	66	91
2.11	63	66	87
1.05	50	-	79
0.52	45	63	68
0.20	16	53	44
0.004	9	34	28



Date		Description	
18	18	18	18
19	19	19	19
20	20	20	20
21	21	21	21
22	22	22	22
23	23	23	23
24	24	24	24
25	25	25	25
26	26	26	26
27	27	27	27
28	28	28	28
29	29	29	29
30	30	30	30
31	31	31	31



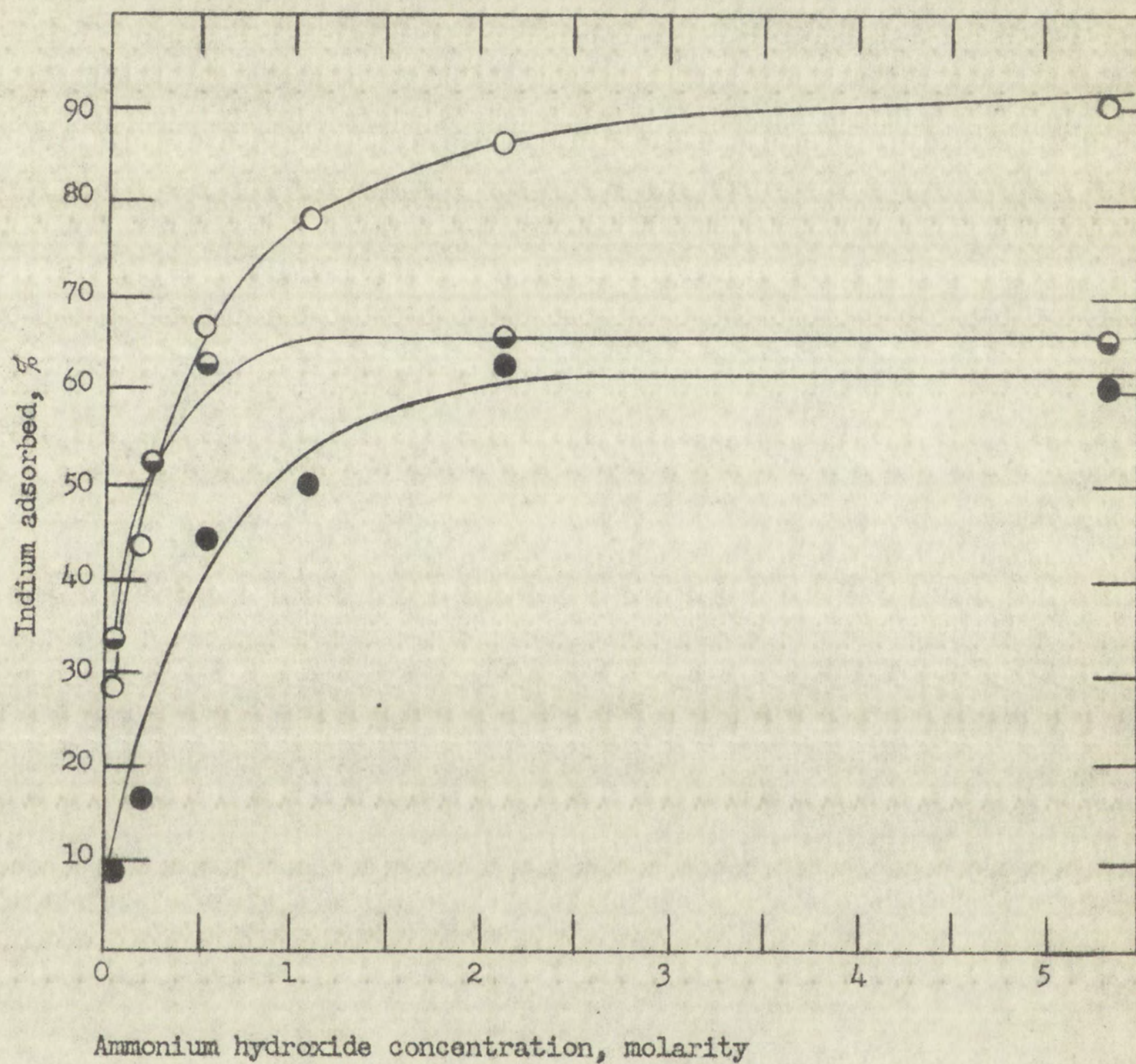


Figure 4. Adsorption of carrier-free indium at room temperature as a function of ammonium hydroxide concentration. No cadmium present.

Adsorbents: ○ Pyrex cone + 0.300 gram powdered glass  
 ● Pyrex cone + 0.69 milliliter paper mash  
 ● Pyrex cone







TABLE III

Adsorption of Carrier-free Indium at Room Temperature from 5.33 Molar Ammonium Hydroxide as a Function of Cadmium Concentration

Concentration of cadmium, Molarity $\times 10^3$	Indium adsorbed, %		
	Pyrex cone alone	Pyrex cone + 0.69 ml. paper	Pyrex cone + 1.000 gram powdered glass
0	61	66	96
1	43	51	95
10	27	33	95
100	16	27	89



THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

REPORT ON THE PROGRESS OF WORK

FOR THE YEAR 1954

BY

JOHN H. SCHWARTZ

AND

JOHN H. SCHWARTZ

PHYSICS DEPARTMENT

THE UNIVERSITY OF CHICAGO

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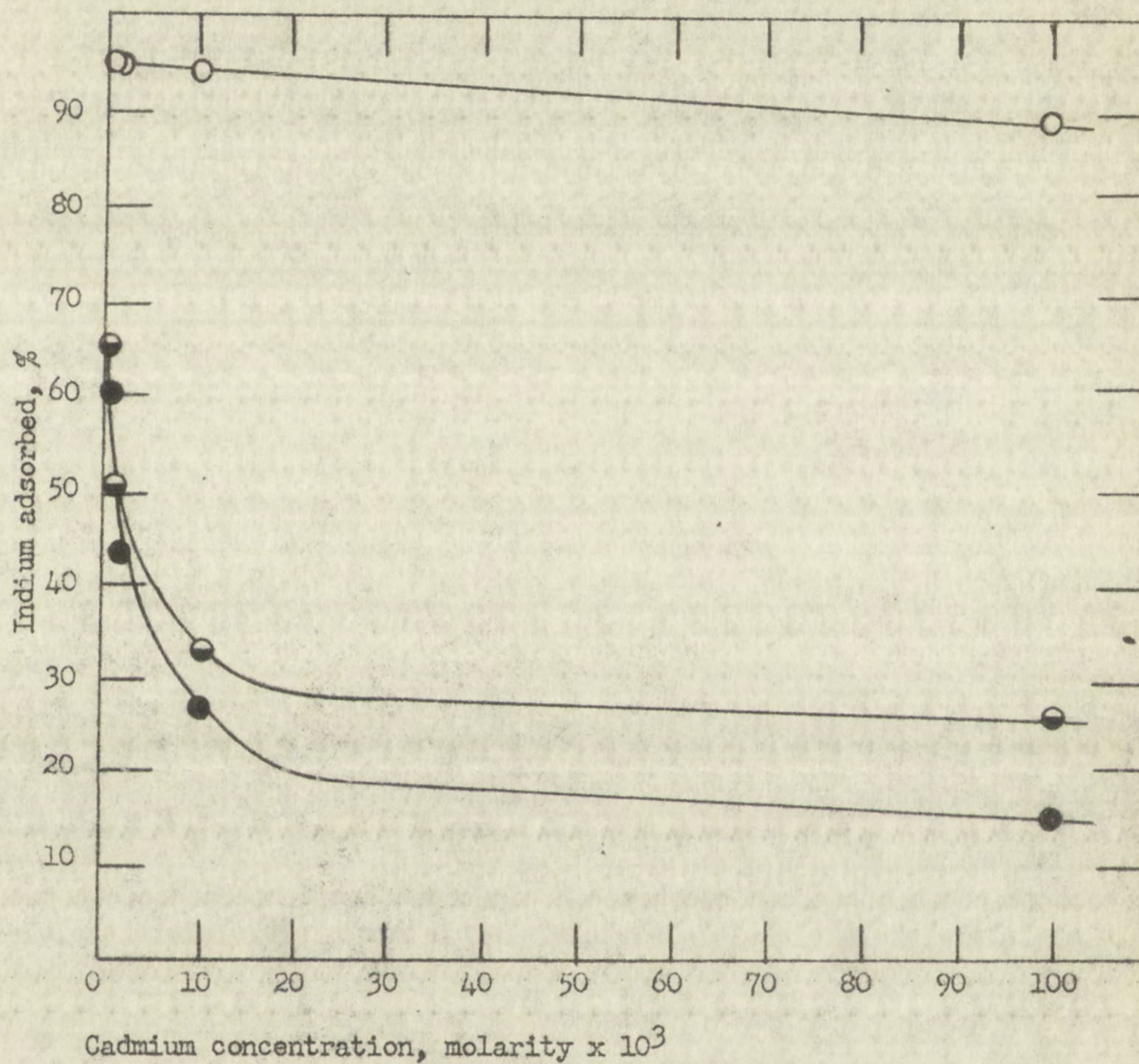


Figure 5. Adsorption of carrier-free indium at room temperature from 5.33M ammonium hydroxide as a function of cadmium concentration.

Adsorbents: ○ Pyrex cone + 1.000 gram powdered glass.  
 ◐ Pyrex cone + 0.69 milliliter paper mash.  
 ● Pyrex cone



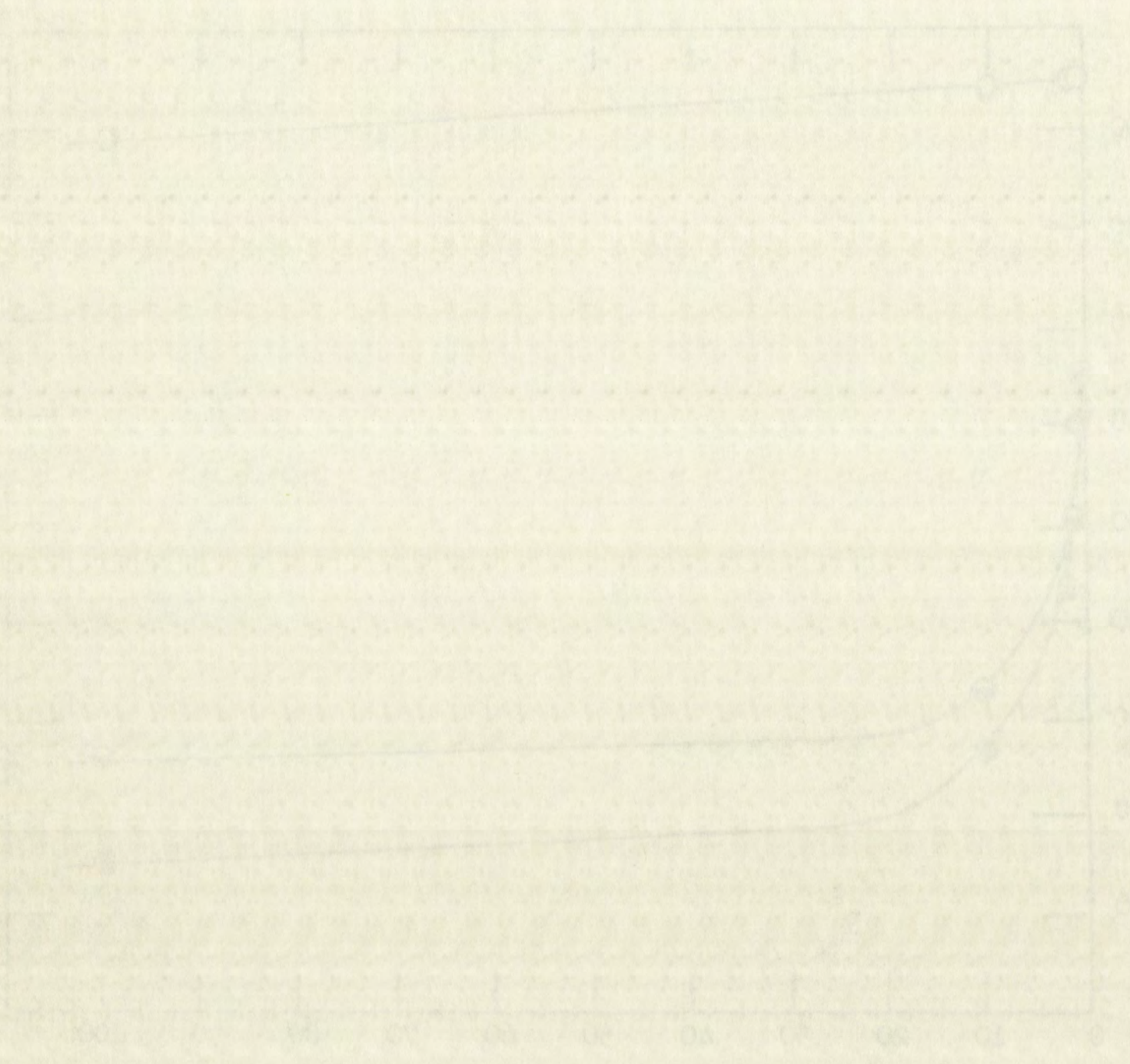


Figure 1. Relationship of relative humidity and air temperature. The curves represent the theoretical limits of relative humidity for a given air temperature.

Legend:  $\circ$  Open circle = 1.0 g/m<sup>3</sup> of water vapor  
 $\square$  Filled square = 0.5 g/m<sup>3</sup> of water vapor  
 $\triangle$  Filled triangle = 0.2 g/m<sup>3</sup> of water vapor



A summary of the results of Type II adsorption experiments is given in Table IV. The amount of indium adsorbed on the fritted-glass disc is a function of both the flow rate of the solution and the porosity of the disc. Essentially quantitative adsorption was effected on discs of fine porosity, whereas discs of medium and coarse porosities yielded 30-90% adsorption in 10-50 seconds. Increasing the cadmium concentration to 0.01 molar did not alter the percentage of indium removed. Consequently, these adsorbents may be used in effecting rapid separations of indium from cadmium. With Millipore filters, 15-30% carrier-free indium was adsorbed; however, from solutions which are 0.01 molar in cadmium, the indium adsorption was reduced to approximately 4%. Whatman filter papers adsorbed less than 4% carrier-free indium. Thus, under the conditions of these experiments, Millipore filters and Whatman filters proved to be much less effective for the separation of indium from cadmium. The purity of the separated activity from fritted-glass discs and Millipore filters was high; no detectable contamination was revealed by analysis of the decay curves and less than 0.002% cadmium was indicated by the hydrogen sulfide color tests. No tests for cadmium contamination were made in the case of the Whatman filter papers.

Extraction procedure. The selective extraction of indium as 8-hydroxyquinolate with chloroform has been developed by Moeller<sup>(44)</sup> as a satisfactory means of separating indium in macro quantities from cadmium and other elements. This procedure has been applied in the present work to the separation of tracer amounts of indium from cadmium. In the pH range 3.4-6.4 the extraction of indium from aqueous solution







TABLE IV

Adsorption of Indium on Fritted-glass Discs, Millipore Filters,  
and Whatman Filter Papers

Type of adsorbent	Porosity	Flow rate, ml./sec.	Approximate time of single filtration, sec.	Approximate time to complete experiment, min.	Indium adsorbed, %
Fritted-glass discs	Fine	0.09	90	5	94-99
		0.2	40-50	2.5	90
	Medium	0.3	35	2.5	30-50
	Coarse	0.8 0.3 <sup>(a)</sup>	<10 40	1.5 2.5	40 32-53
Millipore filters	300 mu	0.3	30-35	3	15
	10 mu	0.03	300	12	18
	10 mu	0.03 <sup>(b)</sup>	300	17	30
	10 mu	0.03 <sup>(c)</sup>	300	22	17
Whatman papers	No. 50	0.3	30	2.5	< 4
	No. 42	0.3	30	2.5	< 4

(a) Suction was not applied.

(b) The solution was allowed to stand on the filter 5 minutes, with stirring, prior to the filtration.

(c) The solution was allowed to stand on the filter 10 minutes, with stirring, prior to the filtration.



TABLE IV

Summary of the results of the analysis of variance for the effect of the treatment on the yield of the crop

and the effect of the treatment on the yield of the crop

Source of variation

Sum of squares

D.F.

Mean square

F-value

Probability

Significance

Level of significance

Level of significance

Level of significance

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is essentially quantitative. Varying the cadmium concentration from  $10^{-1}$  to  $10^{-3}$  molar or the indium concentration from tracer amounts (about  $10^{-12}$  molar) to  $5 \times 10^{-5}$  molar, at a pH of 3.85, had no detectable effect on the percentage of indium extracted. No detectable amounts of radiocadmium were found in the carrier-free indium separated from solutions which were 0.01 molar in cadmium and at a pH of 3.85. However, the gross cadmium contamination determined by the hydrogen sulfide method was about 0.5% after one aqueous extraction of the chloroform layer and less than 0.002% after a second extraction.

#### Quantitative Studies of the Adsorption of Carrier-free Indium

The rate of adsorption. The percentage of indium adsorbed on Pyrex and quartz as a function of time was determined at various ionic strengths and pH values. The data are tabulated in Tables V and VI and plotted in Figures 6 and 7. It can be seen that the adsorption rate, though considerably influenced initially by pH and ionic strength, is essentially constant after three hours. The data for the adsorption on Pyrex at pH 11.1 and 11.2 (curves A, B, and C of Figure 6) were obtained using the sealed vessels which had a surface area approximately 20% larger than that of the vessels used in the other experiments. The rates of adsorption on quartz and Pyrex are essentially the same except for the effect of ionic strength. However, quartz was considered undesirable for most of the experiments to follow due to its low chemical resistance to the alkaline solutions used.

Adsorption-pH relationships. Studies of the adsorption of indium-115m as a function of pH were carried out to determine the







TABLE V

Adsorption of Carrier-free Indium on Pyrex as a Function of Time

Temp. =  $32.2 \pm 0.2^\circ\text{C}$ .

Time of agitation, hours	Indium adsorbed, %					
	pH $\mu$	11.2	11.2	11.1	9.8	8.1 7.5
		0.0039	0.038	0.315	0.10	0.10 0.10
0.083		70	74	57	-	- -
0.25		80	82	67	-	- -
0.50		89	85	71	66	28 31
0.75		91	-	-	-	- -
1.50		93	87	80	-	- -
2.00		96	-	-	-	- -
3.00		95	88	89	75	61 64
11.00		-	-	-	-	64 72 -
15.83		-	-	-	79	75 71







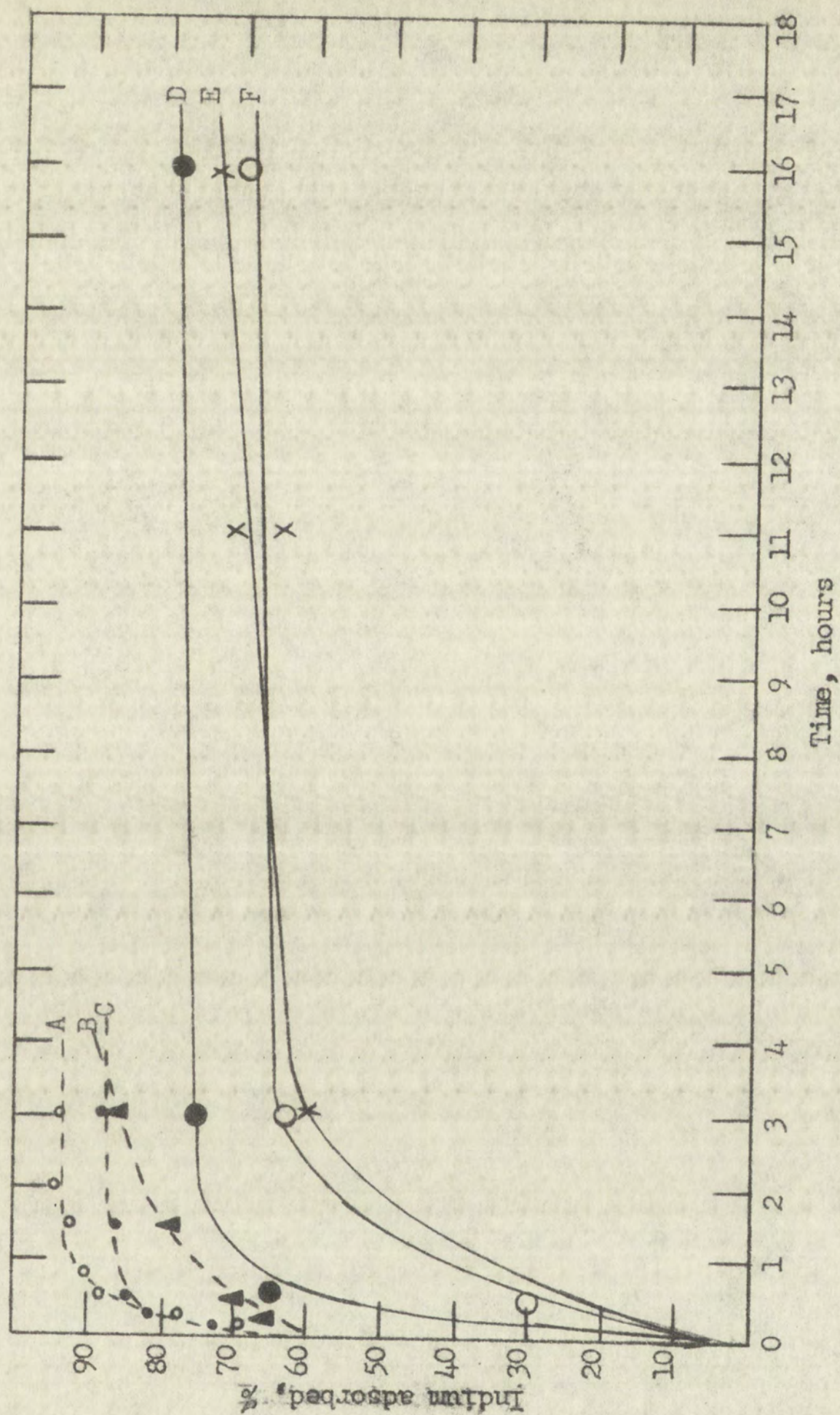


Figure 6. Adsorption of carrier-free indium on Pyrex as a function of time.

	pH	$\mu$	Method of agitation	
A	11.2	0.0039	Rotation	
B	11.1	0.315	Rotation	
C	11.2	0.038	Rotation	
D	9.8	0.10	N <sub>2</sub> stirring	
E	8.1	0.10	N <sub>2</sub> stirring	
F	7.5	0.10	N <sub>2</sub> stirring	







TABLE VI

Adsorption of Carrier-free Indium on Quartz as a Function of Time

Temp. =  $32.2 \pm 0.2^\circ\text{C}$ .

Time of agitation, hours	Indium adsorbed, %							
	pH	11.0	10.0	11.3	10.1	7.5	6.1	3.8
	$\mu$	0.0039	0.0039	0.10	0.10	0.10	0.10	0.10
0.083		44	7	48	57	23	-	9
0.25		-	-	-	61	-	-	-
0.50		57	11	47	66	37	59	6
1.00		-	14	47	71	47	-	22
1.17		66	-	-	-	-	-	-
1.67		-	-	-	75	60	-	-
2.00		-	14	-	-	-	-	-
2.50		69	-	-	-	-	-	-
2.83		-	-	54	-	-	-	-
3.00		-	-	-	80	66	73	-
4.75		-	-	-	-	-	-	29
12.00		-	-	-	-	-	73	28
15.25		-	-	-	75	62	-	-







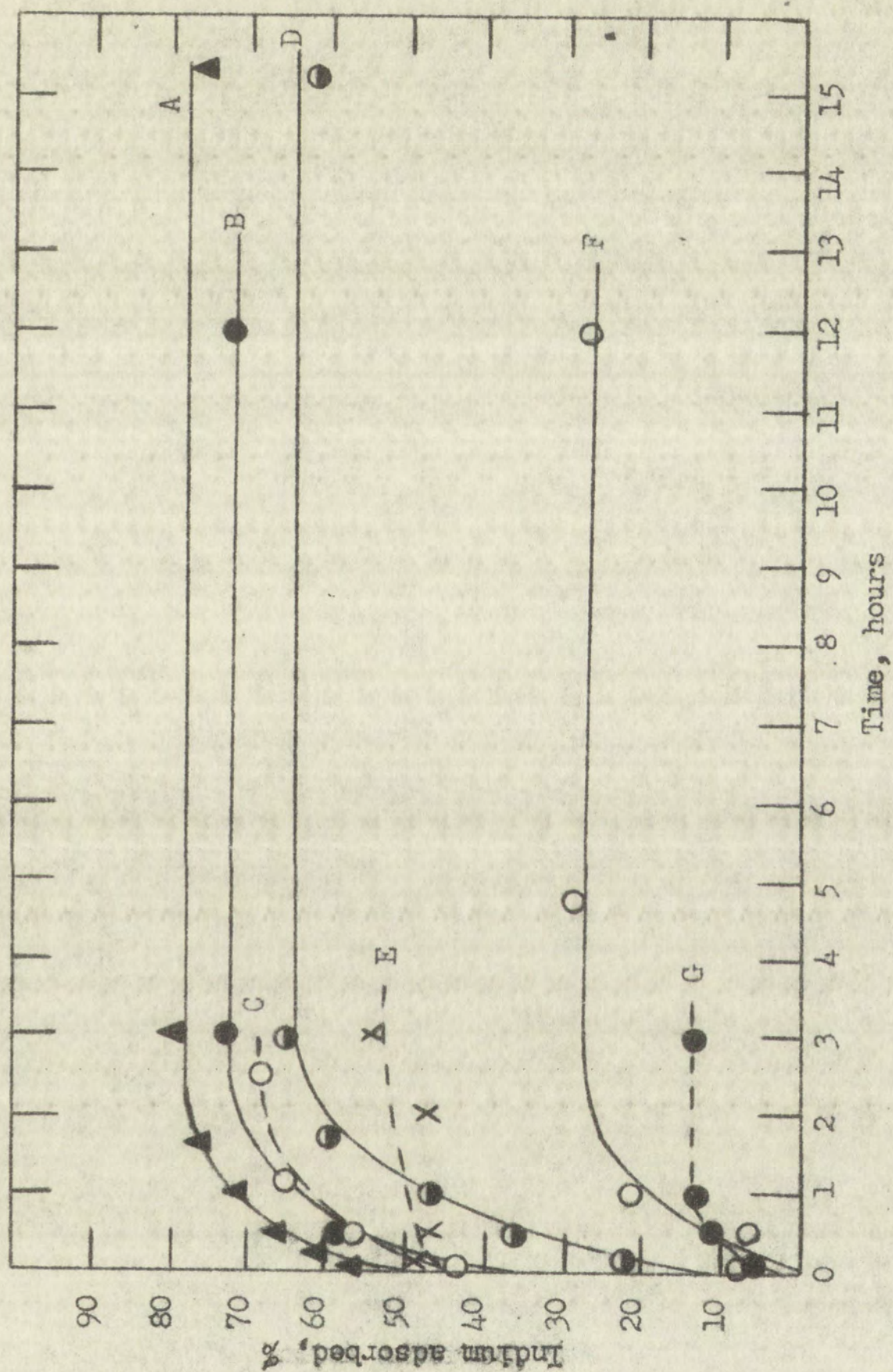


Figure 7. Adsorption of carrier-free indium on quartz as a function of time.

	pH	$\mu$	Method of agitation		pH	$\mu$	Method of agitation
A	10.1	0.10	N <sub>2</sub> stirring	E	11.3	0.10	N <sub>2</sub> stirring
B	6.1	0.10	N <sub>2</sub> stirring	F	3.8	0.10	N <sub>2</sub> stirring
C	11.3	0.0039	N <sub>2</sub> stirring	G	10.0	0.0039	N <sub>2</sub> stirring
D	7.5	0.10	N <sub>2</sub> stirring				





Time	Temperature	Symbol
0	0	
1	1	x
2	2	x
3	3	x
4	4	x
5	5	x
6	6	x
7	7	x
8	8	x
9	9	x
10	10	x
11	11	x
12	12	x
13	13	x
14	14	x
15	15	x
16	16	x
17	17	x
18	18	x
19	19	x
20	20	x
21	21	x
22	22	x
23	23	x
24	24	x
25	25	x
26	26	x
27	27	x
28	28	x
29	29	x
30	30	x
31	31	x
32	32	x
33	33	x
34	34	x
35	35	x
36	36	x
37	37	x
38	38	x
39	39	x
40	40	x
41	41	x
42	42	x
43	43	x
44	44	x
45	45	x
46	46	x
47	47	x
48	48	x
49	49	x
50	50	x
51	51	x
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88	88	x
89	89	x
90	90	x
91	91	x
92	92	x
93	93	x
94	94	x
95	95	x
96	96	x
97	97	x
98	98	x
99	99	x
100	100	x



influence on ionic strength, temperature, surface material, and added electrolytes. The results shown in Figures 8 and 9 and Tables VII and VIII were obtained by measuring the adsorption of indium from perchloric acid solutions after adjusting to the proper pH with ammonium hydroxide and mixing for 0.5 or 3 hours. The solutions of highest ionic strength, 0.10, were prepared by the addition of ammonium perchlorate solution.

Table IX and Figure 10 show the effect of adjusting the ionic strength of the solutions to 0.34 with different ammonium salts on the % adsorption-pH curves. The experiments were carried out in sealed Pyrex vessels which were rotated for 0.5 hour at constant temperature. No appreciable difference was noted when ammonium chromate was substituted for ammonium perchlorate. A slight shift in the adsorption curve was observed with ammonium iodide. However, when secondary ammonium phosphate was used, a marked decrease occurred in the adsorption.

Using ammonium chromate as the added electrolyte, the adsorption of indium-115m was measured as a function of pH on Pyrex, quartz, polyethylene, and paraffined walls. The data are given in Table X and represented graphically in Figure 11.

Ion-exchange resin studies. Studies of the adsorption of indium-115m on ion-exchange resins, Dowex-50 and Dowex-2, were conducted using Pyrex cones as containing vessels. The activity adsorbed by the resin and the glass walls of the vessel was determined separately by transferring the resin to a second vessel and displacing the activity with acid. The walls of the glass vessel initially used were washed







TABLE VII

Adsorption of Carrier-free Indium on Pyrex as a Function of  
pH at Different Ionic Strengths and Time of Agitation

$\mu$	0.0036	0.035		0.10	
Time	0.5 hr. rotation	0.5 hr. rotation		3 hrs. N <sub>2</sub> stirring	
pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %
2.00	1.2	1.00	1.1	1.55	0.2
3.54	13	2.11	1.1	4.93	45
4.12	29	3.11	6.1	5.95	65
4.19	36	3.40	4.3	6.37	71
4.78	45	4.17	15	7.00	68
5.00	62	4.39	27	7.08	72
6.00	56	4.78	42	7.32	71
6.28	48	5.52	69	7.47	63
7.03	29	6.21	66	8.25	60
7.86	28	6.28	49	8.35	67
8.19	19	6.55	52	8.98	72
8.35	22	6.67	34	9.78	78
9.21	21	7.45	27	10.75	67
10.01	21	7.98	24		
10.42	41	8.59	25		
11.21	86	9.40	30		
		10.65	63		
		11.17	88		



TABLE 1					
Summary of Data for 1950-1951					
Year	Jan	Feb	Mar	Apr	May
1950	10.5	11.2	12.1	13.0	14.5
1951	11.0	11.8	12.5	13.5	15.0
1952	11.5	12.2	13.0	14.0	15.5
1953	12.0	12.8	13.5	14.5	16.0
1954	12.5	13.2	14.0	15.0	16.5
1955	13.0	13.8	14.5	15.5	17.0
1956	13.5	14.2	15.0	16.0	17.5
1957	14.0	14.8	15.5	16.5	18.0
1958	14.5	15.2	16.0	17.0	18.5
1959	15.0	15.8	16.5	17.5	19.0
1960	15.5	16.2	17.0	18.0	19.5
1961	16.0	16.8	17.5	18.5	20.0
1962	16.5	17.2	18.0	19.0	20.5
1963	17.0	17.8	18.5	19.5	21.0
1964	17.5	18.2	19.0	20.0	21.5
1965	18.0	18.8	19.5	20.5	22.0
1966	18.5	19.2	20.0	21.0	22.5
1967	19.0	19.8	20.5	21.5	23.0
1968	19.5	20.2	21.0	22.0	23.5
1969	20.0	20.8	21.5	22.5	24.0
1970	20.5	21.2	22.0	23.0	24.5
1971	21.0	21.8	22.5	23.5	25.0
1972	21.5	22.2	23.0	24.0	25.5
1973	22.0	22.8	23.5	24.5	26.0
1974	22.5	23.2	24.0	25.0	26.5
1975	23.0	23.8	24.5	25.5	27.0
1976	23.5	24.2	25.0	26.0	27.5
1977	24.0	24.8	25.5	26.5	28.0
1978	24.5	25.2	26.0	27.0	28.5
1979	25.0	25.8	26.5	27.5	29.0
1980	25.5	26.2	27.0	28.0	29.5
1981	26.0	26.8	27.5	28.5	30.0
1982	26.5	27.2	28.0	29.0	30.5
1983	27.0	27.8	28.5	29.5	31.0
1984	27.5	28.2	29.0	30.0	31.5
1985	28.0	28.8	29.5	30.5	32.0
1986	28.5	29.2	30.0	31.0	32.5
1987	29.0	29.8	30.5	31.5	33.0
1988	29.5	30.2	31.0	32.0	33.5
1989	30.0	30.8	31.5	32.5	34.0
1990	30.5	31.2	32.0	33.0	34.5
1991	31.0	31.8	32.5	33.5	35.0
1992	31.5	32.2	33.0	34.0	35.5
1993	32.0	32.8	33.5	34.5	36.0
1994	32.5	33.2	34.0	35.0	36.5
1995	33.0	33.8	34.5	35.5	37.0
1996	33.5	34.2	35.0	36.0	37.5
1997	34.0	34.8	35.5	36.5	38.0
1998	34.5	35.2	36.0	37.0	38.5
1999	35.0	35.8	36.5	37.5	39.0
2000	35.5	36.2	37.0	38.0	39.5
2001	36.0	36.8	37.5	38.5	40.0
2002	36.5	37.2	38.0	39.0	40.5
2003	37.0	37.8	38.5	39.5	41.0
2004	37.5	38.2	39.0	40.0	41.5
2005	38.0	38.8	39.5	40.5	42.0
2006	38.5	39.2	40.0	41.0	42.5
2007	39.0	39.8	40.5	41.5	43.0
2008	39.5	40.2	41.0	42.0	43.5
2009	40.0	40.8	41.5	42.5	44.0
2010	40.5	41.2	42.0	43.0	44.5
2011	41.0	41.8	42.5	43.5	45.0
2012	41.5	42.2	43.0	44.0	45.5
2013	42.0	42.8	43.5	44.5	46.0
2014	42.5	43.2	44.0	45.0	46.5
2015	43.0	43.8	44.5	45.5	47.0
2016	43.5	44.2	45.0	46.0	47.5
2017	44.0	44.8	45.5	46.5	48.0
2018	44.5	45.2	46.0	47.0	48.5
2019	45.0	45.8	46.5	47.5	49.0
2020	45.5	46.2	47.0	48.0	49.5
2021	46.0	46.8	47.5	48.5	50.0
2022	46.5	47.2	48.0	49.0	50.5
2023	47.0	47.8	48.5	49.5	51.0
2024	47.5	48.2	49.0	50.0	51.5
2025	48.0	48.8	49.5	50.5	52.0
2026	48.5	49.2	50.0	51.0	52.5
2027	49.0	49.8	50.5	51.5	53.0
2028	49.5	50.2	51.0	52.0	53.5
2029	50.0	50.8	51.5	52.5	54.0
2030	50.5	51.2	52.0	53.0	54.5
2031	51.0	51.8	52.5	53.5	55.0
2032	51.5	52.2	53.0	54.0	55.5
2033	52.0	52.8	53.5	54.5	56.0
2034	52.5	53.2	54.0	55.0	56.5
2035	53.0	53.8	54.5	55.5	57.0
2036	53.5	54.2	55.0	56.0	57.5
2037	54.0	54.8	55.5	56.5	58.0
2038	54.5	55.2	56.0	57.0	58.5
2039	55.0	55.8	56.5	57.5	59.0
2040	55.5	56.2	57.0	58.0	59.5
2041	56.0	56.8	57.5	58.5	60.0
2042	56.5	57.2	58.0	59.0	60.5
2043	57.0	57.8	58.5	59.5	61.0
2044	57.5	58.2	59.0	60.0	61.5
2045	58.0	58.8	59.5	60.5	62.0
2046	58.5	59.2	60.0	61.0	62.5
2047	59.0	59.8	60.5	61.5	63.0
2048	59.5	60.2	61.0	62.0	63.5
2049	60.0	60.8	61.5	62.5	64.0
2050	60.5	61.2	62.0	63.0	64.5
2051	61.0	61.8	62.5	63.5	65.0
2052	61.5	62.2	63.0	64.0	65.5
2053	62.0	62.8	63.5	64.5	66.0
2054	62.5	63.2	64.0	65.0	66.5
2055	63.0	63.8	64.5	65.5	67.0
2056	63.5	64.2	65.0	66.0	67.5
2057	64.0	64.8	65.5	66.5	68.0
2058	64.5	65.2	66.0	67.0	68.5
2059	65.0	65.8	66.5	67.5	69.0
2060	65.5	66.2	67.0	68.0	69.5
2061	66.0	66.8	67.5	68.5	70.0
2062	66.5	67.2	68.0	69.0	70.5
2063	67.0	67.8	68.5	69.5	71.0
2064	67.5	68.2	69.0	70.0	71.5
2065	68.0	68.8	69.5	70.5	72.0
2066	68.5	69.2	70.0	71.0	72.5
2067	69.0	69.8	70.5	71.5	73.0
2068	69.5	70.2	71.0	72.0	73.5
2069	70.0	70.8	71.5	72.5	74.0
2070	70.5	71.2	72.0	73.0	74.5
2071	71.0	71.8	72.5	73.5	75.0
2072	71.5	72.2	73.0	74.0	75.5
2073	72.0	72.8	73.5	74.5	76.0
2074	72.5	73.2	74.0	75.0	76.5
2075	73.0	73.8	74.5	75.5	77.0
2076	73.5	74.2	75.0	76.0	77.5
2077	74.0	74.8	75.5	76.5	78.0
2078	74.5	75.2	76.0	77.0	78.5
2079	75.0	75.8	76.5	77.5	79.0
2080	75.5	76.2	77.0	78.0	79.5
2081	76.0	76.8	77.5	78.5	80.0
2082	76.5	77.2	78.0	79.0	80.5
2083	77.0	77.8	78.5	79.5	81.0
2084	77.5	78.2	79.0	80.0	81.5
2085	78.0	78.8	79.5	80.5	82.0
2086	78.5	79.2	80.0	81.0	82.5
2087	79.0	79.8	80.5	81.5	83.0
2088	79.5	80.2	81.0	82.0	83.5
2089	80.0	80.8	81.5	82.5	84.0
2090	80.5	81.2	82.0	83.0	84.5
2091	81.0	81.8	82.5	83.5	85.0
2092	81.5	82.2	83.0	84.0	85.5
2093	82.0	82.8	83.5	84.5	86.0
2094	82.5	83.2	84.0	85.0	86.5
2095	83.0	83.8	84.5	85.5	87.0
2096	83.5	84.2	85.0	86.0	87.5
2097	84.0	84.8	85.5	86.5	88.0
2098	84.5	85.2	86.0	87.0	88.5
2099	85.0	85.8	86.5	87.5	89.0
2100	85.5	86.2	87.0	88.0	89.5



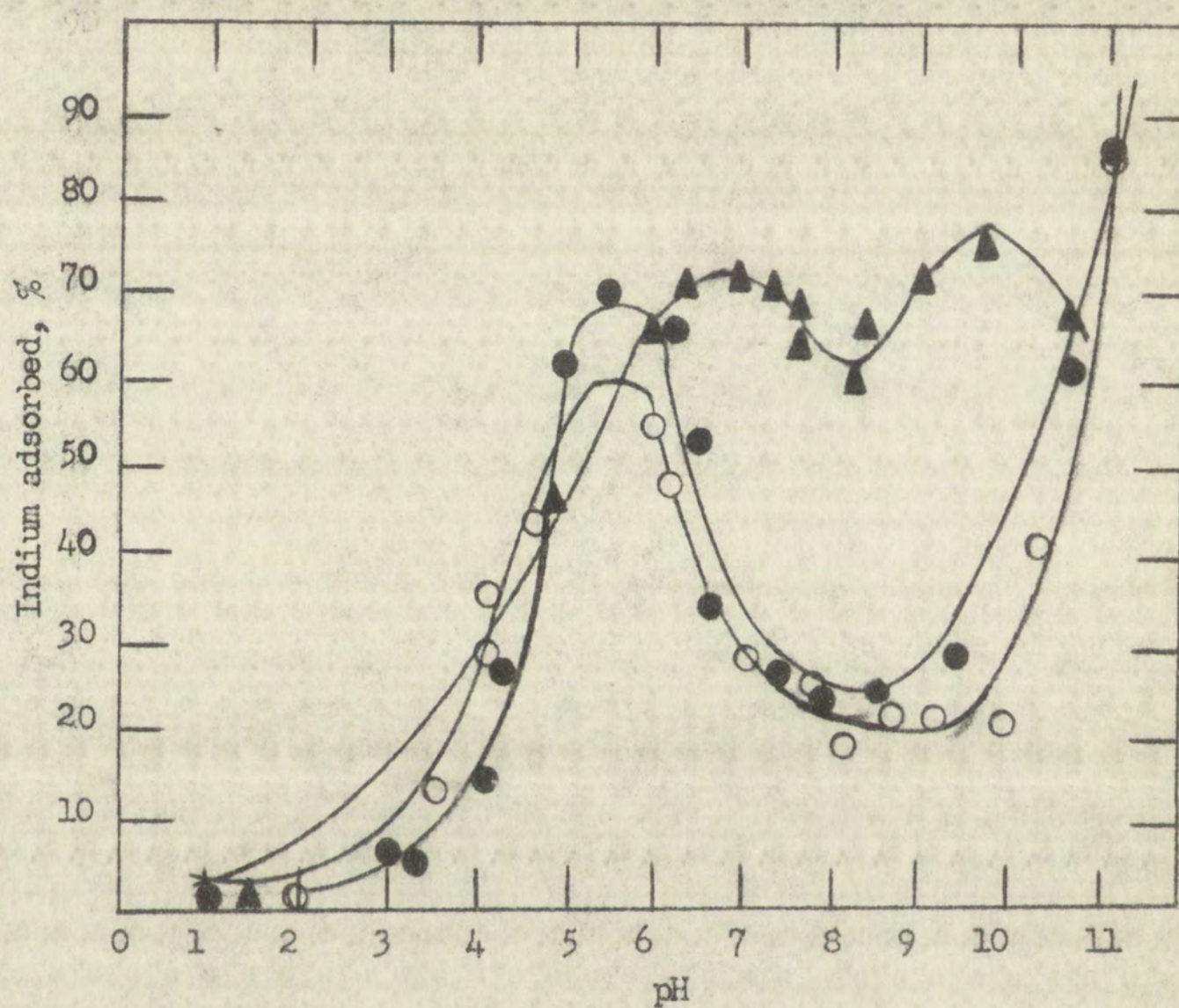


Figure 8. Adsorption of carrier-free indium on Pyrex as a function of pH at different ionic strengths and time of agitation.

	$\mu$	Time of agitation, hrs.	Method of agitation
○	0.0036	0.5	rotation
●	0.035	0.5	rotation
▲	0.10	3	N <sub>2</sub> stirring





Figure 2. Absorption of  $\text{H}_2\text{O}$  by  $\text{CaCl}_2$  in a desiccator. The curves show the change in concentration of  $\text{CaCl}_2$  as a function of time.

Time (min)	Concentration (g/l)	Concentration (g/l)	Concentration (g/l)
0	1.0	0.5	0.0
1	0.8	0.6	0.1
2	0.6	0.65	0.2
3	0.4	0.7	0.3
4	0.2	0.7	0.4
5	0.3	0.65	0.5
6	0.5	0.6	0.6
7	0.7	0.5	0.7
8	0.8	0.4	0.8
9	0.7	0.3	0.9
10	0.6	0.2	1.0



TABLE VIII

Adsorption of Carrier-free Indium on Quartz as a function of pH at Different Ionic Strengths and Time of Agitation\*

$\mu$	0.0036	0.10		0.10	
Time	0.5 hr.	0.5 hr.		3 hrs.	
pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %
2.55	2.6	3.68	8.6	3.21	16
3.05	4.6	4.63	43	6.03	73
4.33	31	5.62	61	6.82	72
4.61	28	6.24	59	7.58	66
5.10	50	7.50	37	8.48	50
6.20	45	8.55	25	8.65	62
7.31	18	9.08	53	10.11	80
8.65	11	10.11	66	10.71	62
9.98	11	10.71	56	11.30	55
11.03	57	11.30	47		

\* All solutions were agitated by stirring with nitrogen.







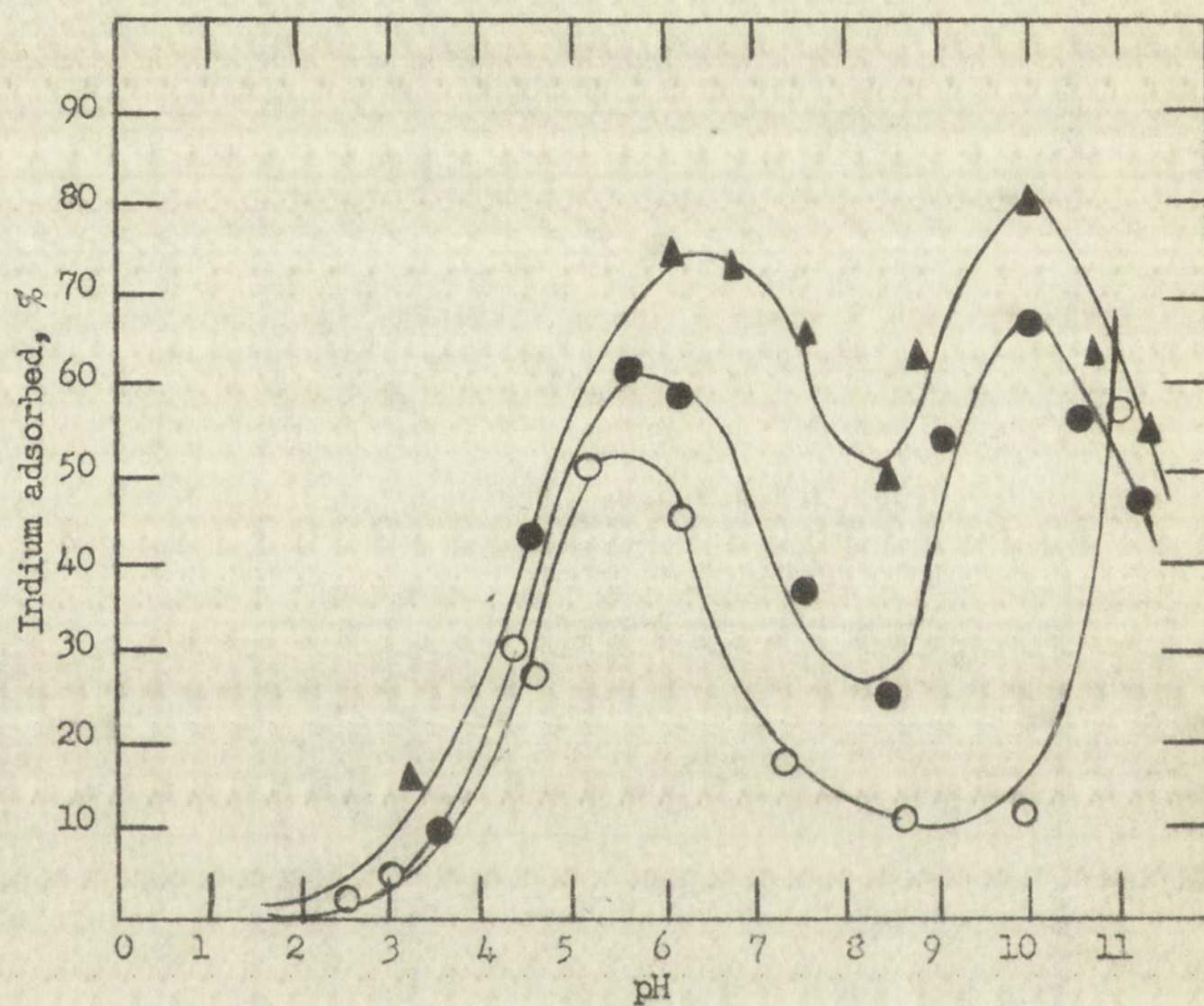


Figure 9. Adsorption of carrier-free indium on quartz as a function of pH at different ionic strengths and time of agitation.

$\mu$	Time of agitation, hrs.	Method of agitation
○ 0.0036	0.5	N <sub>2</sub> stirring
● 0.10	0.5	N <sub>2</sub> stirring
▲ 0.10	3	N <sub>2</sub> stirring



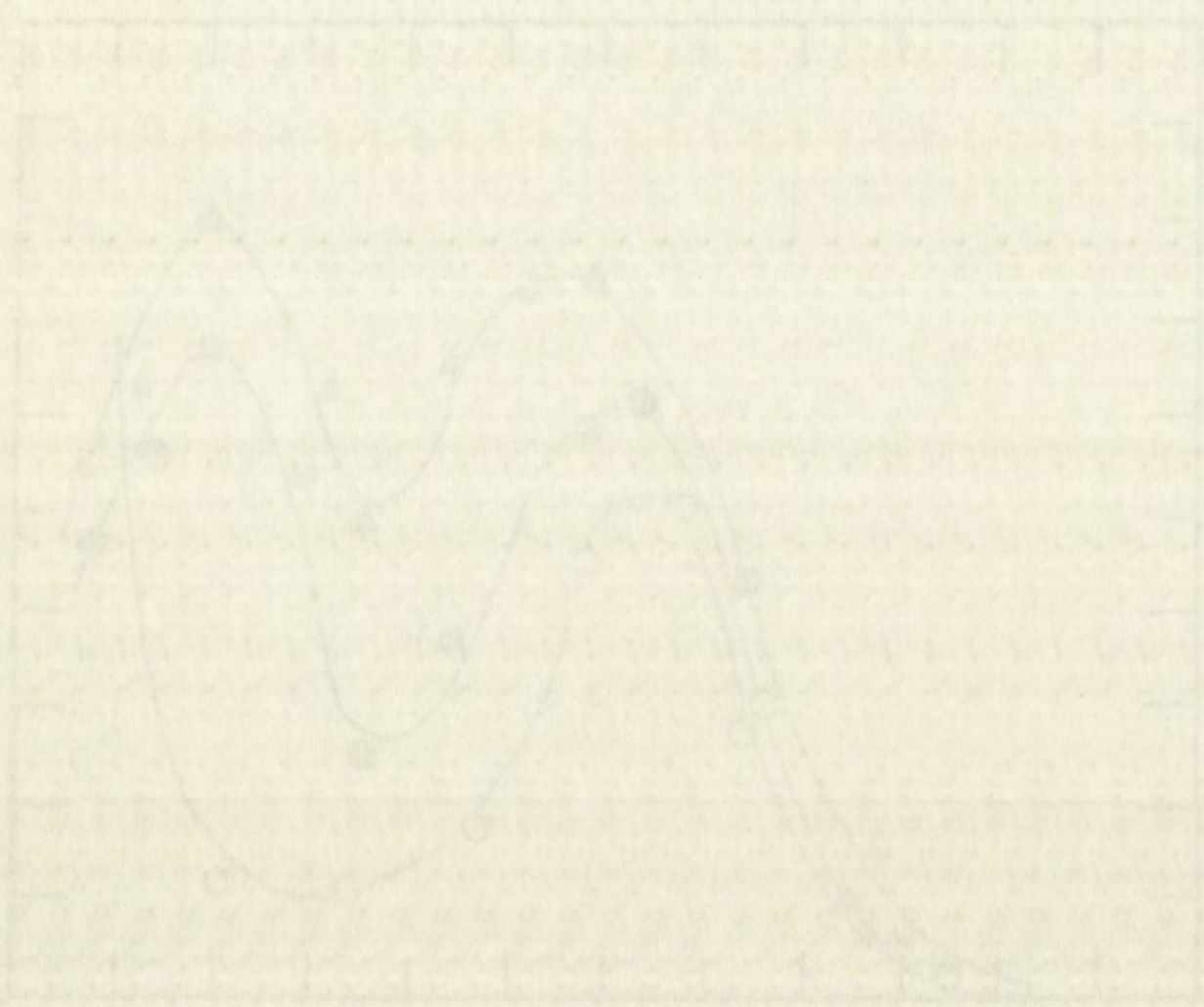


Figure 2. Comparison of experimental data and theoretical curve for the reaction of  $\text{H}_2$  and  $\text{O}_2$  at 25°C.

TABLE I. Rate constants for the reaction of  $\text{H}_2$  and  $\text{O}_2$  at 25°C.

Run	$k_1$ (sec <sup>-1</sup> )	$k_2$ (sec <sup>-1</sup> )	$k_3$ (sec <sup>-1</sup> )
1	0.001	0.01	0.001
2	0.002	0.02	0.002
3	0.003	0.03	0.003
4	0.004	0.04	0.004
5	0.005	0.05	0.005



TABLE IX

Adsorption of Carrier-free Indium on Pyrex as a Function of  
pH for Different Electrolyte Systems

$\mu = 0.34$

Time and method of agitation—rotated 0.5 hour in sealed Pyrex vessels.

Ammonium perchlorate		Ammonium chromate (neutral)		Ammonium iodide		Diammonium hydrogen phosphate	
pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %
2.57	2.4	2.22	0.0	2.95	2.0	2.75	0.5
3.47	6.2	4.75	23	3.70	3.0	3.95	1.7
5.67	57	5.06	25	5.38	44	4.91	8.5
6.57	56	5.29	38	5.82	54	5.12	3.3
6.92	50	5.75	61	5.93	72	5.70	0.6
7.44	55	6.50	66	6.33	75	6.88	1.5
8.08	51	6.85	61	6.67	67	7.49	0.0
8.50	66	7.21	57	7.14	47	7.95	1.0
9.32	81	7.41	56	7.54	61	8.34	1.8
9.72	86	7.60	52	8.43	71	9.57	18
10.85	54	8.12	53	9.23	79	10.02	36
		8.59	53	9.65	85	10.55	19
		9.49	75	10.70	43		
		9.81	84				
		10.44	79				
		11.05	66				



No.	Name	Age	Sex	Religion	Marital Status	Occupation	Education	Income	Assets	Liabilities	Net Worth	Remarks
1	John Doe	35	M	Christian	Married	Teacher	High School	\$10,000	\$50,000	\$20,000	\$30,000	
2	Jane Smith	28	F	Buddhist	Single	Nurse	College	\$12,000	\$60,000	\$15,000	\$45,000	
3	Robert Johnson	45	M	Muslim	Married	Engineer	University	\$15,000	\$70,000	\$25,000	\$45,000	
4	Mary White	52	F	Hindu	Widowed	Homemaker	High School	\$8,000	\$30,000	\$10,000	\$20,000	
5	David Brown	30	M	Jewish	Married	Software Developer	College	\$18,000	\$80,000	\$30,000	\$50,000	
6	Sarah Green	25	F	Sikh	Single	Student	College	\$5,000	\$10,000	\$2,000	\$8,000	
7	Michael Black	40	M	Christian	Married	Manager	University	\$14,000	\$65,000	\$22,000	\$43,000	
8	Emily Davis	38	F	Buddhist	Married	Writer	College	\$9,000	\$40,000	\$12,000	\$28,000	
9	Christopher Lee	55	M	Muslim	Married	Retired	High School	\$6,000	\$25,000	\$8,000	\$17,000	
10	Amanda King	22	F	Hindu	Single	Intern	College	\$4,000	\$8,000	\$1,000	\$7,000	

This is a summary of the data collected from the survey. The data is organized into a table with columns for various demographic and socioeconomic factors. The table is sorted by age, with the youngest individuals at the top and the oldest at the bottom. The data shows a diverse population with varying levels of education, income, and assets. The majority of the respondents are married, and the majority are of the Christian faith. The data also shows that there is a positive correlation between education and income, with those who have a college degree or higher earning more than those who have a high school diploma or less.



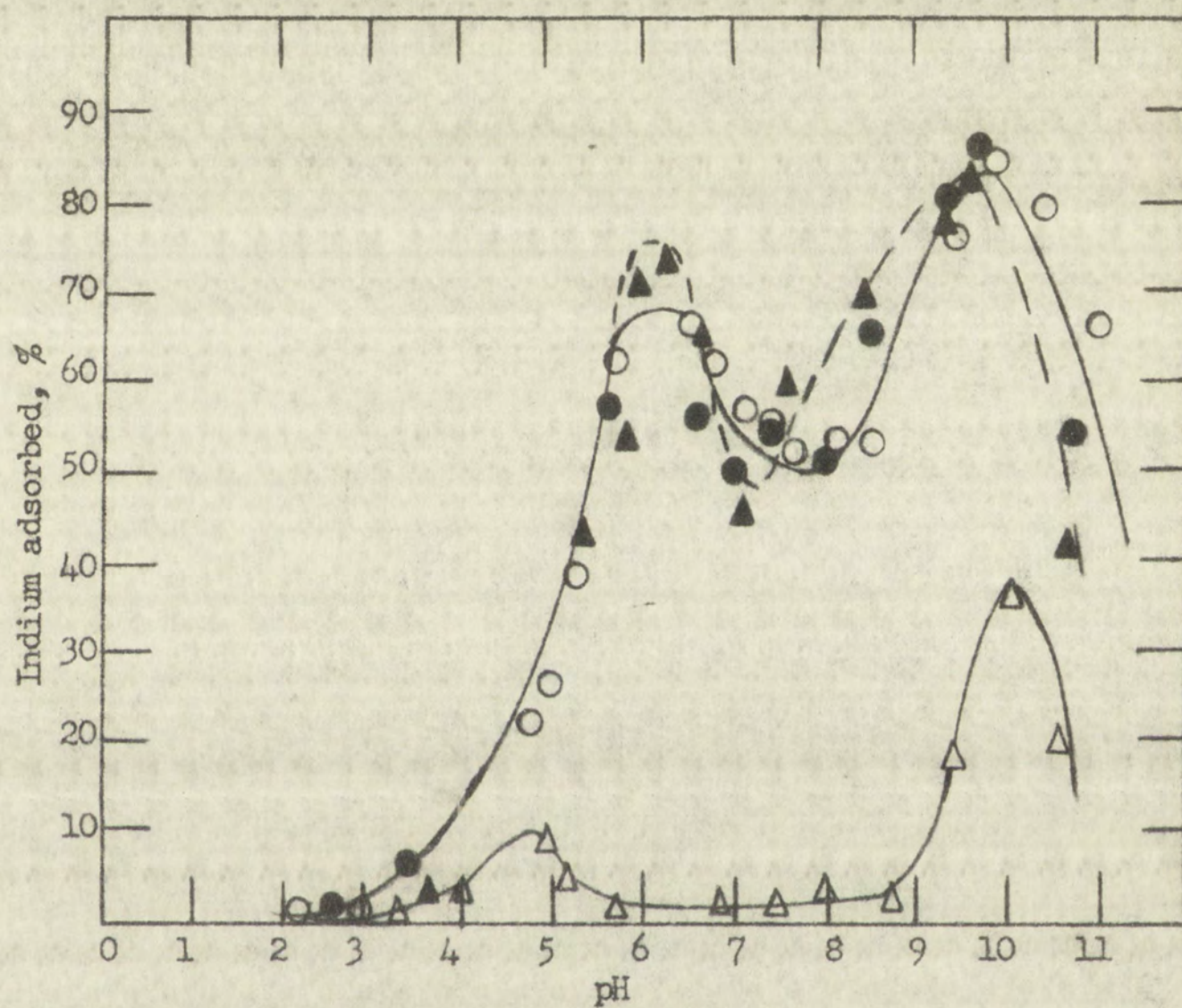


Figure 10. Adsorption of carrier-free indium on Pyrex as a function of pH for different electrolyte systems.

- - ammonium chromate (neutral)
- - ammonium perchlorate
- ▲ - ammonium iodide
- △ - diammonium hydrogen phosphate





Figure 10. Comparison of the two curves in Figure 9. The solid curve is the curve of Figure 9, and the dashed curve is the curve of Figure 9.

- - Curve of Figure 9
- - Curve of Figure 9
- △ - Curve of Figure 9
- ▽ - Curve of Figure 9



TABLE X

Adsorption of Carrier-free Indium on Different Surfaces as a Function of pH

$\mu = 0.34$

Time and method of agitation—stirred 0.5 hour with nitrogen.

Electrolyte added—ammonium chromate (neutral).

Paraffined Walls		Polyethylene		Quartz		Pyrex	
pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %
2.22	0.3	2.25	1.7	2.55	2.5	2.03	0.0
5.84	11	4.92	22	4.45	7.8	5.23	33
6.87	16	5.68	32	5.35	24	5.92	56
8.18	22	5.82	29	5.94	58	6.78	44
8.50	23	6.86	39	6.79	45	7.15	38
9.47	16	8.05	44	7.18	39	7.87	33
9.95	12	8.51	41	7.88	37	8.19	27
10.50	3.0	9.47	34	8.14	32	8.59	34
		9.89	24	8.55	41	9.46	57
		10.49	15	9.46	57	9.95	68
		11.00	5.2	9.95	60	11.03	43
				10.50	30		
				11.03	38		



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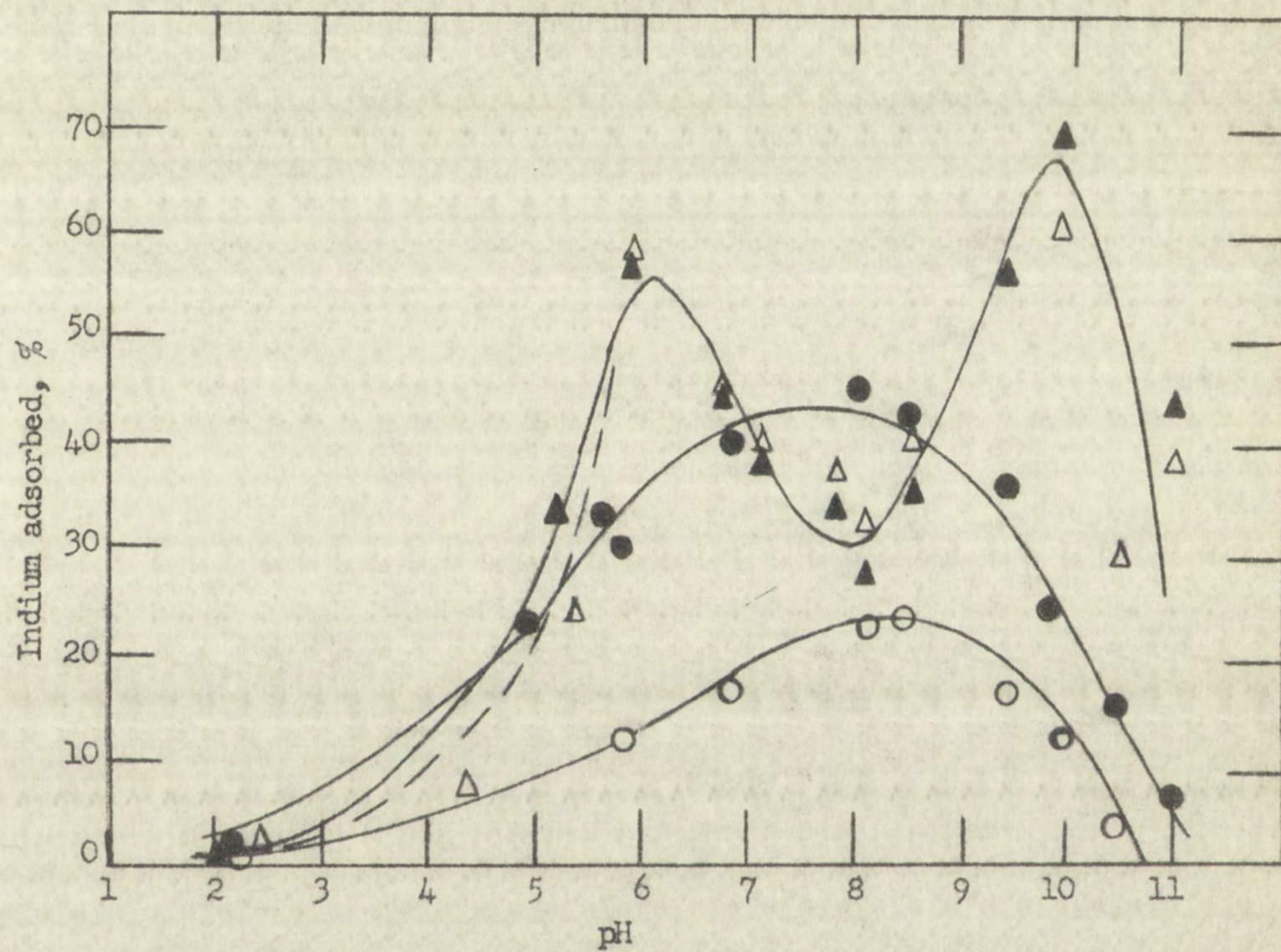


Figure 11. Adsorption of carrier-free indium on different surfaces as a function of pH; electrolyte-ammonium chromate.

- - paraffined walls
- - polyethylene
- ▲ - Pyrex
- △ - quartz





Figure 1. Comparison of the effect of different concentrations of the polymer on the rate of polymerization.

Curve A: 0.5% polymer  
 Curve B: 0.2% polymer  
 Curve C: 0.1% polymer



with acid and the activities of both acid washes determined. The results are given in Table XI and Figure 12.

Effect of temperature. The determination of the variation of adsorption with pH at  $32.2 \pm 0.2^\circ\text{C}$ . was carried out with sealed Pyrex adsorption vessels at ionic strengths of 0.035 and 0.33. The solutions were kept at the particular temperature without agitation for 45 minutes, then rotated at  $32.2 \pm 0.2^\circ\text{C}$  for 15 minutes and centrifuged. The data are tabulated in Table XII and plotted in Figures 13 and 14. For the pH range of approximately 1-12, adsorption was generally greater at the higher temperature; the only exception occurred between pH 10.5 and 11.3 with solutions of ionic strength of 0.035. In this case, adsorption was unaffected by the elevation of temperature.

Reformation and equilibrium studies. Some preliminary experiments showed that the amount of indium-115m adsorbed after a ten-minute centrifugation was always greater than the amount adsorbed without centrifugation in the pH range 7 to 11. This increased adsorption suggested the formation of radiocolloidal aggregates of indium. To test this possibility, reformation and equilibrium studies were conducted. In the reformation studies, adsorption of indium-115m on Pyrex was measured after a three-hour agitation period; the solution was then transferred to a second Pyrex vessel and the adsorption determined after three hours of agitation. The procedure was repeated with the exception that the solution was centrifuged for ten minutes after each three-hour period. The percentage of indium



with the same results as in the case of the other two series.

The results of the analysis of the variance are given in Table I.

Table I. Analysis of variance. The results of the analysis of variance are given in Table I.

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TABLE XI

Adsorption of Carrier-free Indium on Dowex-2 Anion-exchange Resin and Dowex-50 Cation-exchange Resin Contained in Pyrex Vessels as a Function of pH

$\mu = 0.10$

Time and method of agitation--stirred three hours with nitrogen.

Weight of resin-- $23.8 \pm 0.2$  milligrams.

pH	Indium adsorbed, %		pH	Indium adsorbed, %	
	Dowex-2	Pyrex		Dowex-50	Pyrex
2.12	0.7	0.4	2.08	100	0.2
3.71	6.3	5.1	3.00	95	0.2
6.52	33	38	3.81	94	1.9
7.85	31	29	5.79	27	57
9.89	28	50	6.08	20	57
10.69	14	58	6.28	18	57
11.01	10	56	6.55	19	47
			7.82	19	55
			9.91	12	53
			10.74	21	34
			11.09	30	30







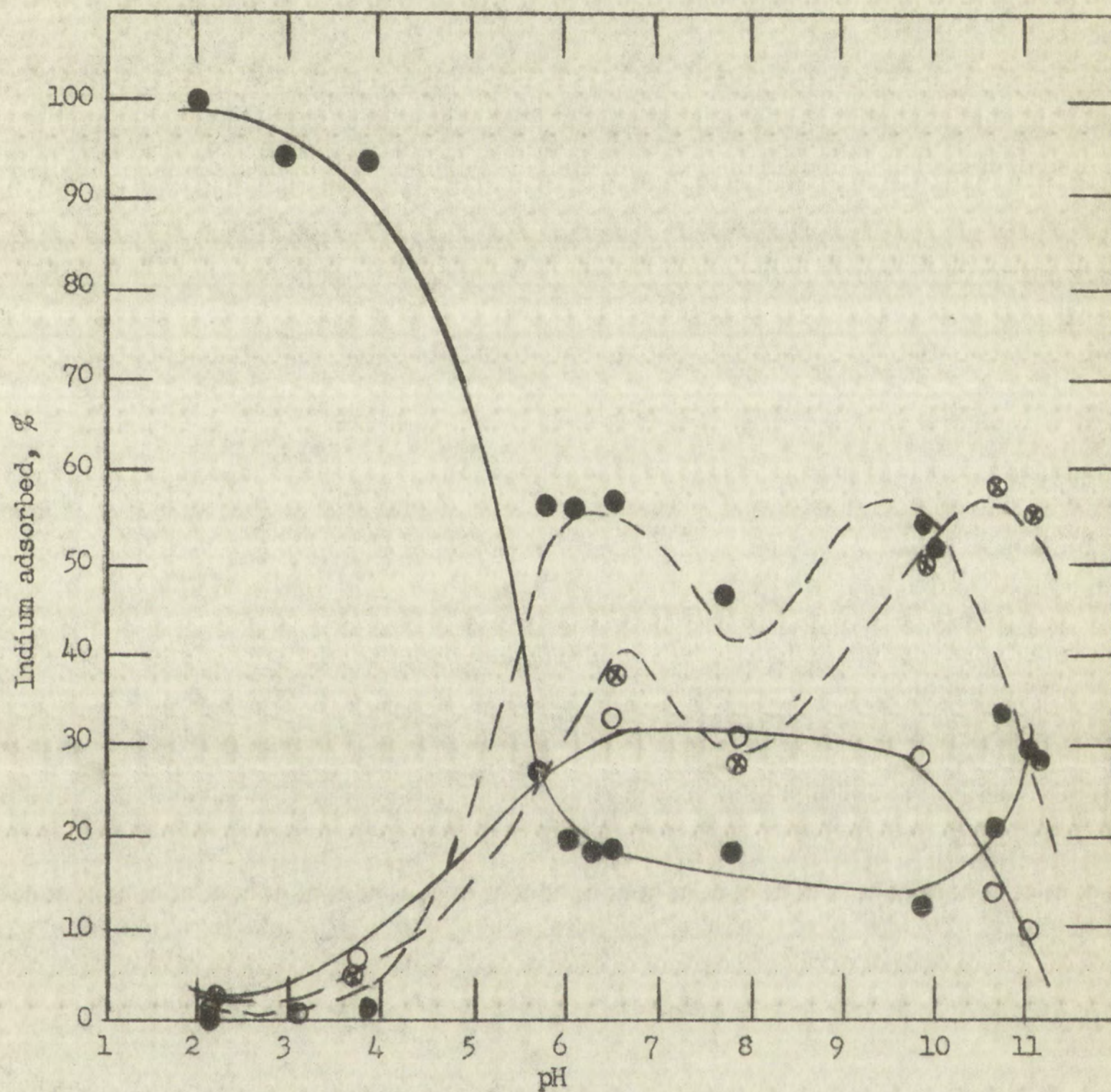


Figure 12. Adsorption of carrier-free indium on Dowex-2 and Dowex-50 contained in Pyrex vessels as a function of pH.

- - Dowex-2.
- - Dowex-50.
- — — ⊗ - Adsorption on Pyrex when Dowex-2 was used.
- — — ● - Adsorption on Pyrex when Dowex-50 was used.





Figure 1. Absorption of carbon dioxide by leaves of *Phaseolus vulgaris* L. (var. *Contender*) at 25°C. The leaves were exposed to a constant light intensity of 1000 foot-candles.

- - Series A
- - Series B
- △ - Series C
- ◇ - Series D



TABLE XII

Adsorption of Carrier-free Indium on Pyrex as a Function of pH at Different Ionic Strengths and Temperatures

Time and method of agitation—45 minutes standing in contact with sealed Pyrex vessels at the designated temperature, followed by 15 minutes rotation at  $32.2 \pm 0.2^\circ\text{C}$ .

Ionic strength = $0.035 \pm 0.003$				Ionic strength = $0.329 \pm 0.006$			
Temp. = $32.2 \pm 0.2^\circ\text{C}$ .		Temp. = $109 \pm 2^\circ\text{C}$ .		Temp. = $32.2 \pm 0.2^\circ\text{C}$ .		Temp. = $109 \pm 2^\circ\text{C}$ .	
pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %	pH	Indium adsorbed, %
1.00	1.1	1.04	1.4	0.84	0.7	0.82	0.1
2.11	1.1	2.08	1.1	1.89	0.0	1.95	2.3
3.11	6.1	3.20	16	1.90	1.6	1.98	0.3
3.40	4.3	3.32	16	2.48	2.3	2.05	2.0
4.17	15	3.88	36	6.58	15	2.85	0.2
4.39	27	4.48	61	6.71	54	6.39	81
4.78	42	4.85	80	6.85	51	6.70	73
5.52	69	5.69	82	6.99	40	7.50	38
6.21	66	6.19	73	7.39	16	8.59	63
6.28	49	6.49	63	8.59	49	9.58	75
6.55	53	6.61	59	9.59	51	10.37	79
6.67	34	7.38	57	10.37	59	10.95	71
7.45	27	8.07	45	10.95	55		
7.98	24	8.58	48				
8.59	25	9.37	49				
9.40	30	10.65	58				
10.65	63	11.17	88				
11.17	88						



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1906

1907

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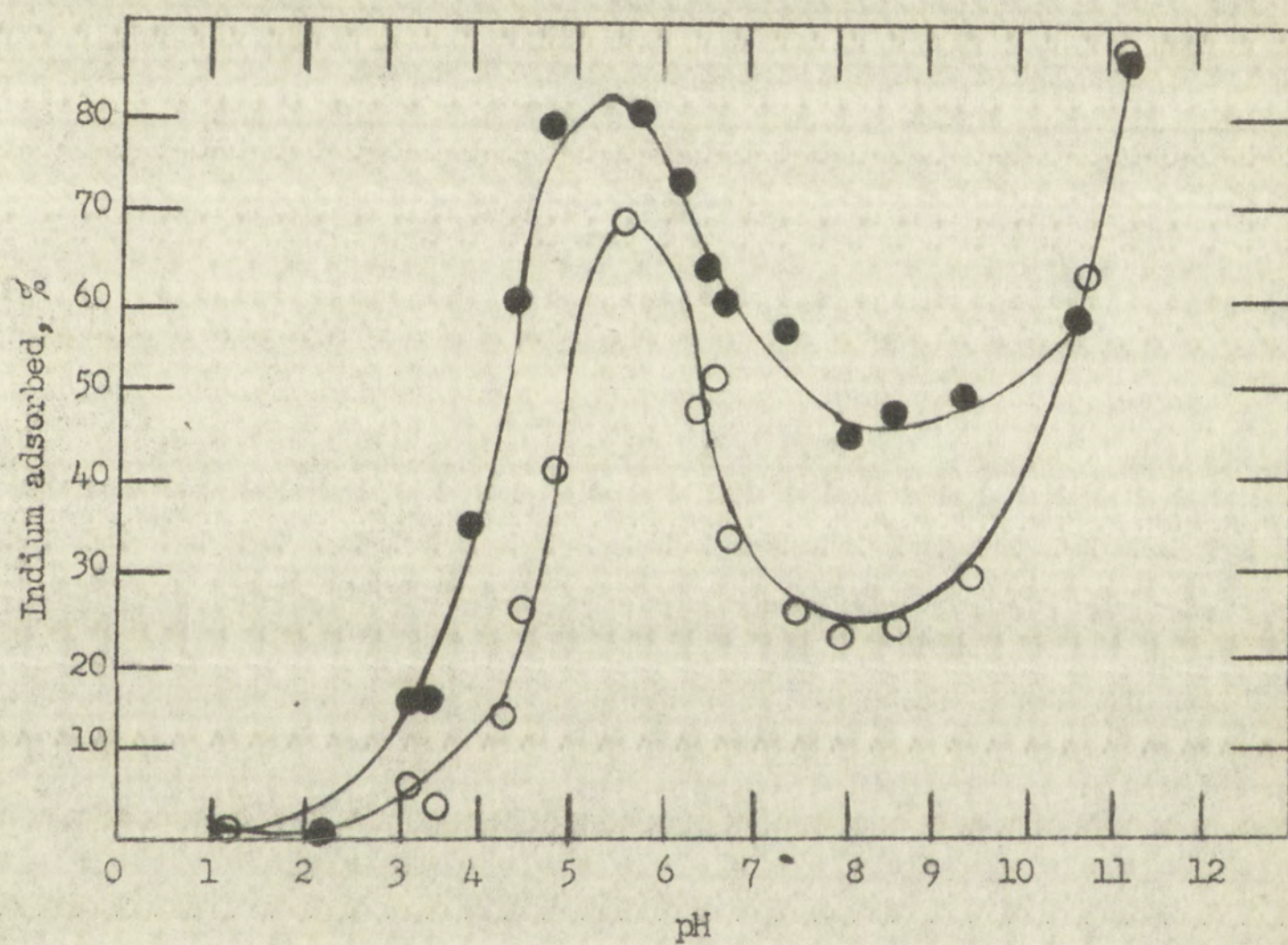
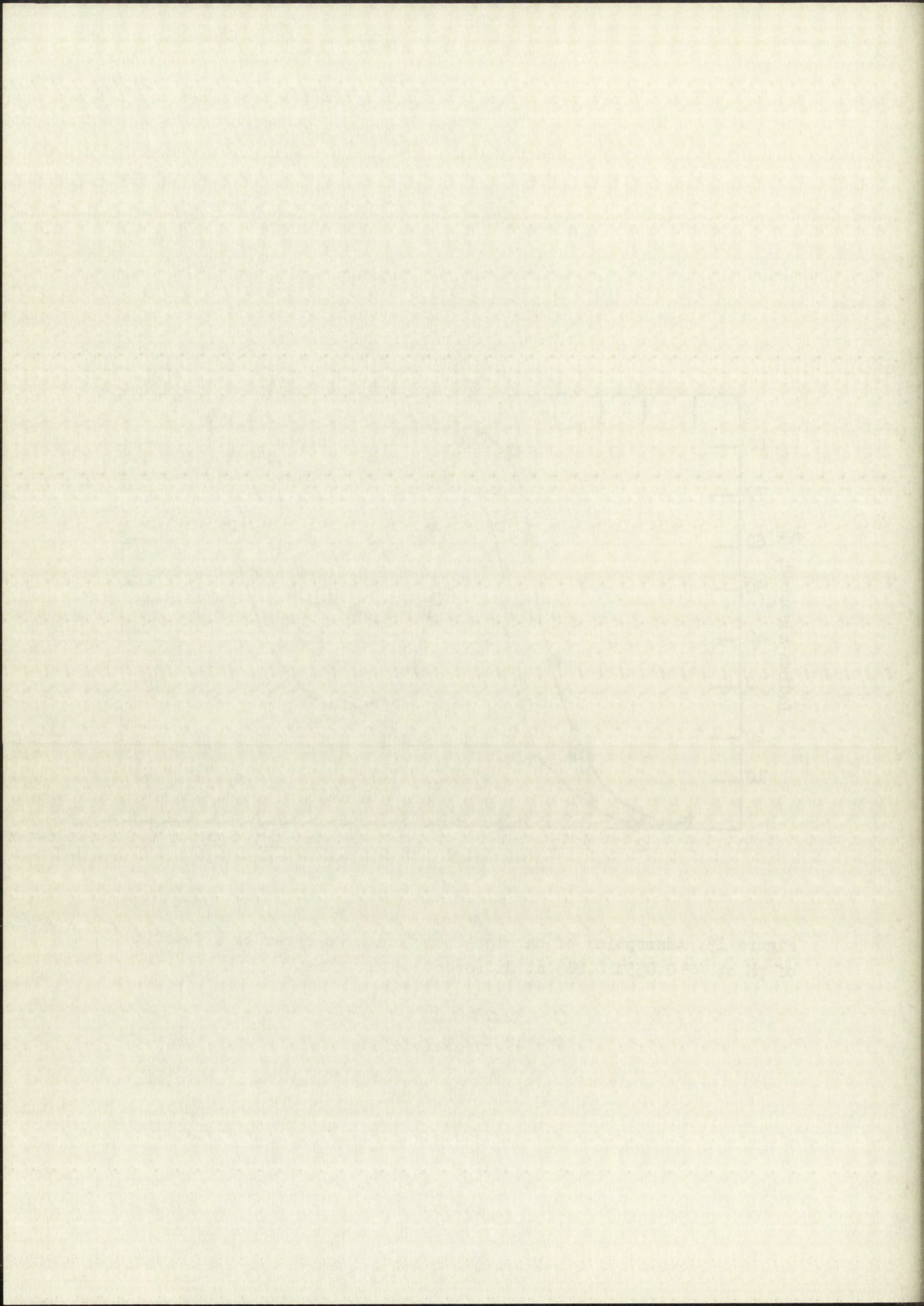


Figure 13. Adsorption of carrier-free indium on Pyrex as a function of pH at  $\mu = 0.035 \pm 0.003$  at different temperature.

○ -  $32.2 \pm 0.2^\circ\text{C}$   
 ● -  $109 \pm 2^\circ\text{C}$







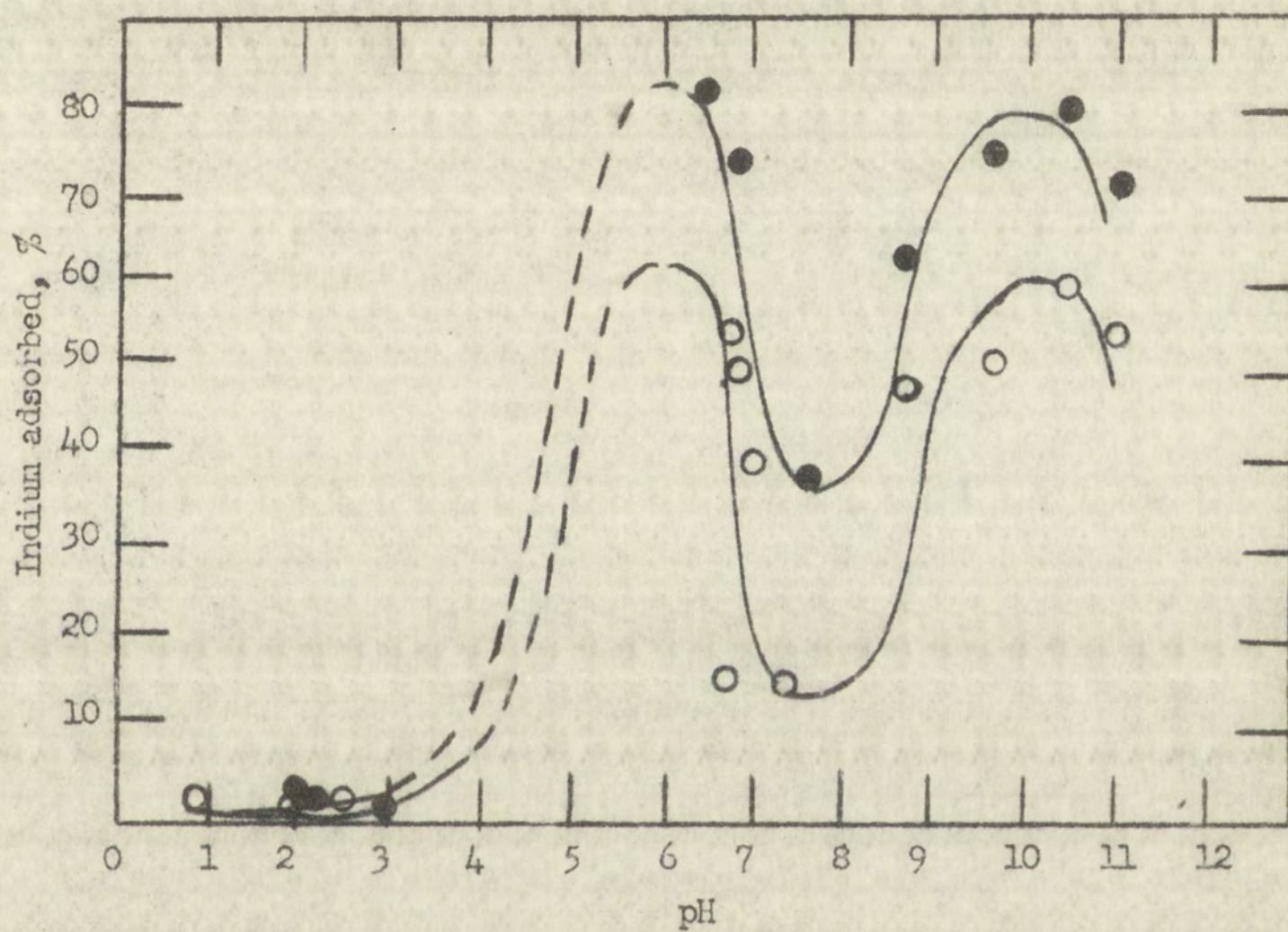


Figure 14. Adsorption of carrier-free indium on Pyrex as a function of pH at  $\mu = 0.329 \pm 0.006$  and different temperatures.

- -  $32.2 \pm 0.2^\circ\text{C}$
- -  $109 \pm 2^\circ\text{C}$



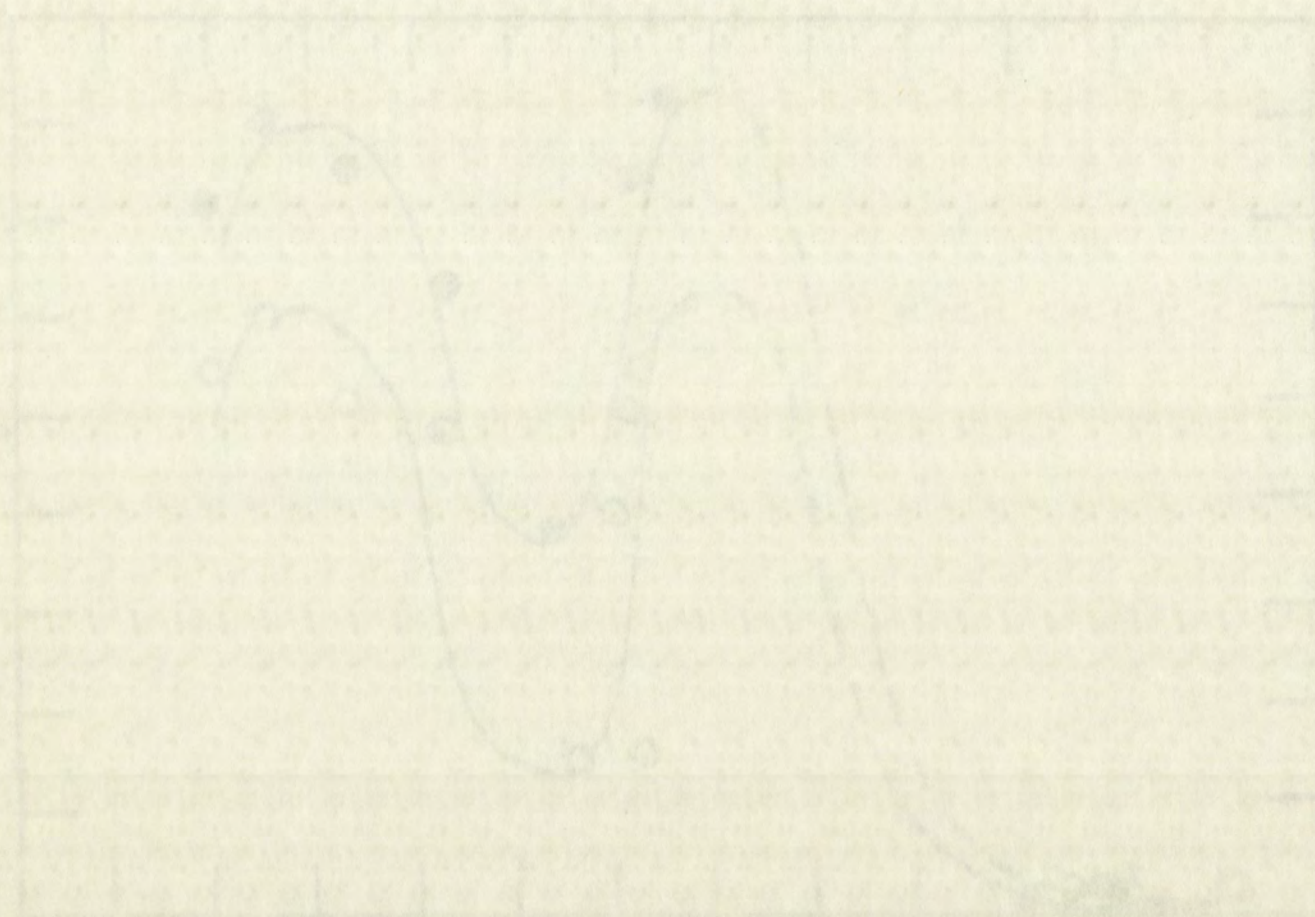


Figure 1. A graph of the function  $f(x) = \frac{1}{x}$  for  $x > 0$ . The solid curve represents the function  $f(x)$  and the dashed curve represents the function  $f(x) + \frac{1}{x^2}$ .



adsorbed was calculated on basis of the amount of activity present in each vessel. The results are shown in Table XIII.

In the equilibrium studies, solutions of appropriate ionic strength and pH were agitated in Pyrex vessels for definite time intervals. After removal of the supernatant liquid, successive portions of a solution identical in composition except for the presence of indium-115m were added to the vessel and the agitation repeated for similar time intervals. The amount of activity removed from the walls of the vessel each time was calculated on basis of the activity remaining on the walls from the previous step. At the low ionic strength, 0.038, and at pH 11.1, an agitation period of 30 minutes seemed adequate from a study of the rate curves for these conditions. As shown in Table XIV, centrifuging increased the amount of indium adsorbed at pH  $10.38 \pm 0.02$  and ionic strength of 0.038 from 19% to 46%. However, a considerable amount of the indium adsorbed was removed in only one treatment with inactive solution.

The reformation studies indicate an ion-exchange adsorption because the extent of adsorption on a new vessel was, in all instances, of the same magnitude as that initially observed. However, the strong influence of centrifuging and the fact that the equilibrium studies indicate an irreversible adsorption suggest that some other type of mechanism is operative.

Effect of indium concentration. It has been suggested<sup>(45)</sup> that the Langmuir isotherm can be used to differentiate between ion-exchange and colloidal adsorption. Adsorption by ion-exchange follows the isotherm, while adsorption as a result of colloidal formation may



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TABLE XIII

## Reformation Studies

 $\mu = 0.10$ Temp.  $32.2 \pm 0.2^\circ\text{C}$ .

Time and method of agitation—stirred 3 hours with nitrogen in 15 milliliter Pyrex cones.

pH	Indium adsorbed, %			
	Solutions centrifuged		Solutions not centrifuged	
	Vessel #1	Vessel #2	Vessel #1	Vessel #2
6.98	70	74	27	17
7.47	64	54	43	34
8.35	67	58	31	20
9.00	73	66	12	9
9.78	78	65	66	48



# TABLE I

PERCENTAGE OF CRYSTALLINITY

TEMPERATURE, °C.

CRYSTALLINITY, %

TEMPERATURE, °C.	CRYSTALLINITY, %
100	30.0
110	25.0
120	20.0
130	15.0
140	10.0
150	5.0
160	0.0



TABLE XIV

## Equilibrium Studies

Temp. =  $32.2 \pm 0.2^\circ\text{C}$ .

Method of agitation—stirred with nitrogen in 15 milliliter Pyrex cones.

Ionic strength, $\mu$	pH	Time of agitation, hours	Indium initially adsorbed, %	Indium removed, %			Indium remaining on walls, %
				1	2	3	
0.10	8.32	3	33	25	7	5	22
0.10	9.68	3	60	8	6	2	51
0.038	10.37	0.5	19	5	1	1	18
0.038	10.40	0.5	46 <sup>(a)</sup>	25	—	—	35

(a) The solution was centrifuged for 10 minutes after the agitation period.



1911					1912				
1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100



or may not follow the isotherm. The adsorption of indium-115m as a function of inactive indium concentration was determined at pH 9.8 and 7.4 over an indium concentration range of  $2 \times 10^{-5}$  molar to tracer concentrations (about  $10^{-12}$  molar). As shown in table XV, the Langmuir isotherm was followed regardless of whether the solutions were centrifuged.

Effect of varying electrolyte concentration. According to Schubert<sup>(46)</sup> the addition of an electrolyte brings about a decreased adsorption in the case of ion-exchange, but in radiocolloidal adsorption either has no effect at all or results in an increased adsorption. The effect of varying electrolyte concentration at pH 9.8 and 7.4 on the adsorption of indium-115m was observed. The extent of indium adsorption on Pyrex cones was measured after stirring solutions of the appropriate composition with nitrogen for three hours. Sodium perchlorate and cadmium chloride were used as electrolytes. The solutions were not centrifuged. The results, recorded in Table XVI, indicate essentially no effect on the adsorption as the electrolyte concentration is increased.

Reproducibility. For similar samples run under the same conditions in the adsorption and extraction procedures of this work, reproducibility was quite good. Typical results of identical experiments showed that the average deviation was approximately 3%. For the graphical representations, the majority of the points represents the average of two or more values. The adsorption curves were sufficiently reproducible in all cases to conclusively establish the trend.







TABLE XV

Adsorption of Carrier-free Indium as a Function of Indium Concentration

$\mu = 0.10$

Temp. =  $32.2 \pm 0.2^\circ\text{C}$

Time and method of agitation—stirred 3 hours with nitrogen in 15 milliliter Pyrex cones.

Indium (III) concentration, molar	Indium-115m adsorbed, %			
	pH = $9.80 \pm 0.04$		pH = $7.44 \pm 0.06$	
	Solutions centrifuged	Solutions not centrifuged	Solutions centrifuged	Solutions not centrifuged
$2 \times 10^{-5}$	41	28	—	—
$8 \times 10^{-7}$	77	78	69	34
$8 \times 10^{-8}$	81	81	61	38
$8 \times 10^{-9}$	74	70	60	40
$8 \times 10^{-10}$	79	73	62	43
$8 \times 10^{-11}$	80	69	63	49
Tracer ( $\sim 10^{-12}$ )	78	68	64	43



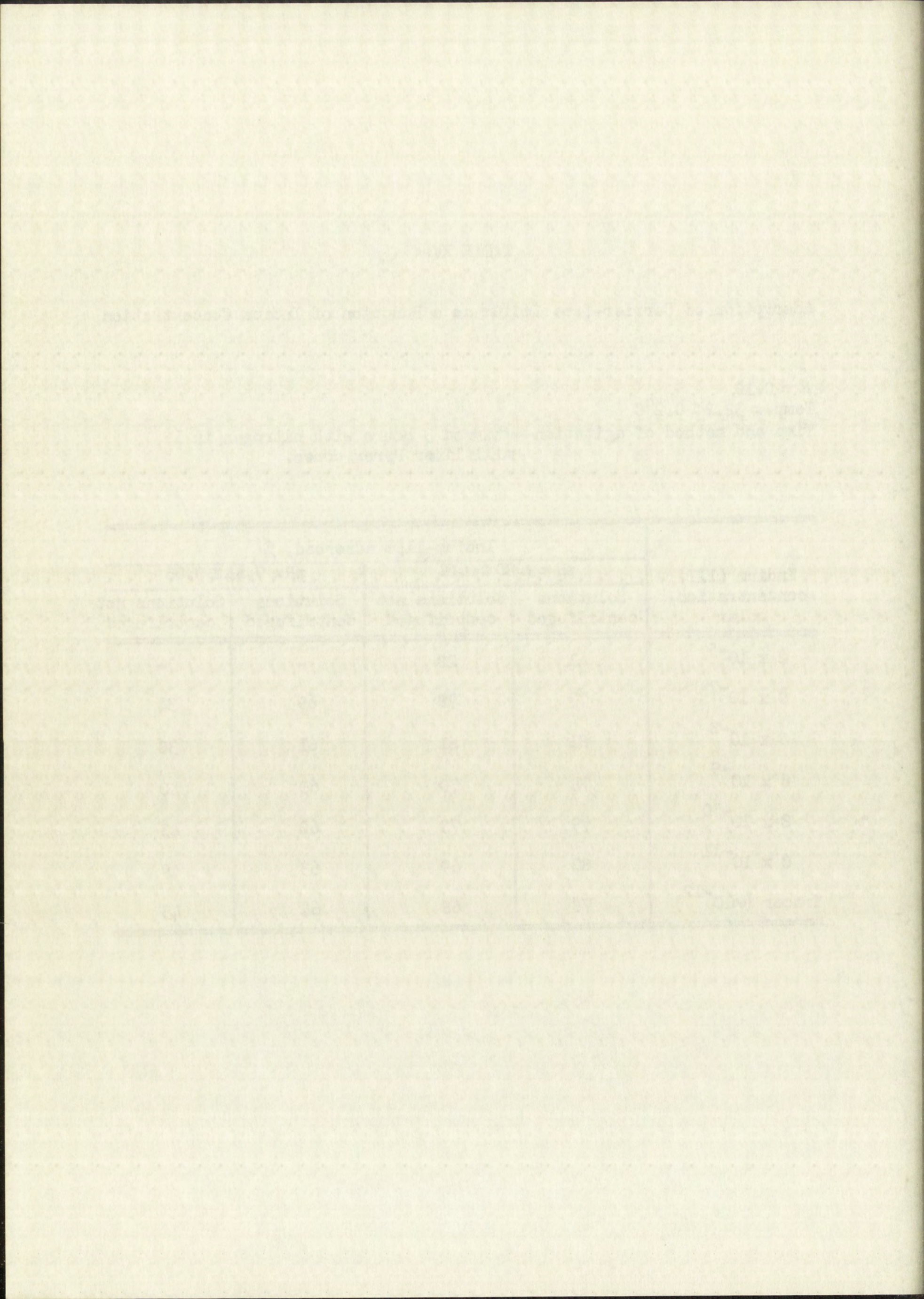




TABLE XVI

Adsorption of Carrier-free Indium as a Function of Concentration of  
Added Electrolyte

Concentration of sodium perchlo- rate, molar	Indium adsorbed, %		Concentration of cadmium chloride, molar	Indium ad- sorbed, % pH 9.8
	pH 7.4	pH 9.8		
0.00	43	68	0.00	68
0.01	49	70	0.001	66
0.10	34	67	0.010	65
0.50	42	72		



# TABLE I

Summary of experimental results for the reaction of  $\text{C}_2\text{H}_5\text{MgBr}$  with  $\text{C}_6\text{H}_5\text{MgBr}$  in the presence of  $\text{C}_6\text{H}_5\text{MgBr}$

Reaction conditions:  $\text{C}_2\text{H}_5\text{MgBr}$  (1.0 mole),  $\text{C}_6\text{H}_5\text{MgBr}$  (1.0 mole),  $\text{C}_6\text{H}_5\text{MgBr}$  (1.0 mole)

Reaction time (hr)	Yield of $\text{C}_6\text{H}_5\text{MgBr}$ (mole)	Yield of $\text{C}_6\text{H}_5\text{MgBr}$ (mole)	Yield of $\text{C}_6\text{H}_5\text{MgBr}$ (mole)
0.5	0.00	0.00	0.00
1.0	0.00	0.00	0.00
1.5	0.00	0.00	0.00
2.0	0.00	0.00	0.00
2.5	0.00	0.00	0.00
3.0	0.00	0.00	0.00
3.5	0.00	0.00	0.00
4.0	0.00	0.00	0.00
4.5	0.00	0.00	0.00
5.0	0.00	0.00	0.00
5.5	0.00	0.00	0.00
6.0	0.00	0.00	0.00
6.5	0.00	0.00	0.00
7.0	0.00	0.00	0.00
7.5	0.00	0.00	0.00
8.0	0.00	0.00	0.00
8.5	0.00	0.00	0.00
9.0	0.00	0.00	0.00
9.5	0.00	0.00	0.00
10.0	0.00	0.00	0.00



## DISCUSSION

The graphs representing the variation of percentage of indium adsorbed with pH generally show three distinct regions; regions A, B, and C, which include pH values up to approximately 5.5, between 5.5 and 9.5, and above 9.5 respectively. These regions will be discussed separately.

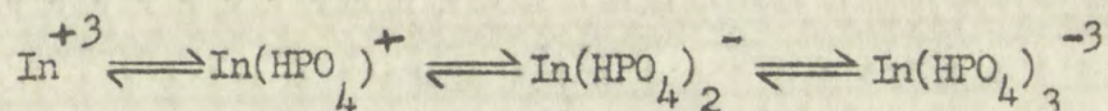
Region A (pH less than 5.5). A reasonable explanation for the increase in adsorption on Pyrex up to pH values of 5.5 is based on the assumption that an ion-exchange mechanism is operative in this pH range. The surface of glass is covered with weakly acidic  $\equiv\text{Si-OH}$  groups which dissociate, thus providing negatively charged sites where positively charged species of indium can adsorb. With increasing pH, the adsorption of indium increases presumably due to the larger number of available sites. The results obtained on ion-exchange resins, Dowex-2 and Dowex-50, strongly suggest that a cation exchange process is in effect at least in the pH range 2 to 5. On cation-exchanger Dowex-50, from pH 2 to 4, adsorption is equal to or greater than 94%, whereas adsorption on Pyrex or anion exchanger, Dowex-2, is 6% or less for the range. Similarly, adsorption on polyethylene and paraffined walls is extremely low in this pH range. This result is to be expected because such surfaces would tend to adsorb only neutral molecules rather than charged particles. Further evidence for ion-exchange adsorption in Region A is revealed upon analysis of the % adsorbed-pH curves for different electrolyte systems (Figure 10). With ammonium chromate, ammonium iodide, and ammonium perchlorate as electrolytes,







the curves are superimposable in this region. However, with secondary phosphate ion, which is known to complex with indium,<sup>(47)</sup> a small peak occurs between pH 3.5 and 5.5; the maximum adsorption being less than 9%. The small peak may be partly attributed to the adsorption of the positive intermediate proposed by Holroyd and Salmon for the equilibrium between indium and the secondary phosphate ion:



Thus, since indium forms principally anionic phosphate complexes in this pH region, the adsorption on Pyrex would be expected to decrease.

Although ion-exchange appears to be the principal mode of adsorption in this region, there is evidence to show that the last pH unit of the region (about pH 4.5-5.5) represents a transitory stage from ion-exchange adsorption to radiocolloidal adsorption. The sharp decline in adsorption of indium by cation-exchanger Dowex-50, in the pH range 4 to 6 is indicative of the decrease in positively charged indium species. Indium hydrolysis begins at a pH of approximately 3.0-4.6 and is complete between the pH range of 4.8 and 9.6, depending on the solution composition.<sup>(48)</sup> Thus, as the pH is increased, low valency hydrolysis products such as  $\text{In}(\text{OH})^{+2}$ ,  $\text{In}(\text{OH})_2^+$ , or  $\text{In}(\text{OH})_3^0$  replace  $\text{In}^{+3}$ . Because these products are less strongly adsorbed a decrease in adsorption on the cation exchanger occurs. Further inspection of Figure 12 shows that in this same pH region (4 to 6) adsorption on the glass containing vessel increases, presumably due to the fact that the colloidal particles favor glass to the cation exchanger.



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The curves of Figure 12 also reveal that Dowex-2 anion exchanger and Pyrex are equally effective in this pH range.

In Region A, the effects of ionic strength and time of the % adsorbed-pH curves for Pyrex and quartz suggest an ion exchange adsorption mechanism which gradually changes over to a radiocolloidal mechanism. Thus, at low pH (less than 4), the amount of indium adsorbed is slightly higher for low ionic strengths, perhaps because the cationic species of indium can compete more favorably for the available sites. Increasing the time of contact tends to increase the amount of indium adsorbed. This effect is more important as the pH is increased from approximately 4 to 6. It is reasonable to assume that largely ion-exchange adsorption predominates initially, followed by preliminary stages of radiocolloidal formation as the pH assume higher values. The adsorption maximum for low ionic strengths occurs slightly to the left of that obtained for higher ionic strengths perhaps due to less coagulation. The foregoing explanation of the adsorptive behavior of indium in this range is consistent with the theory proposed by Rydberg and Rydberg for the adsorption of thorium on glass.<sup>(49)</sup>

Region B (pH 5.5 to 9.5). Between pH 5.5 and 9.5, there is strong support for the existence of colloidal or polymeric forms of indium. Within this pH region, the adsorptive behavior of indium may be attributed to its tendency to polymerize as a result of repeated hydrolyses. Schubert<sup>(50)</sup> lists indium as one of the elements which probably forms colloidal aggregates above a pH of about 7.2. He



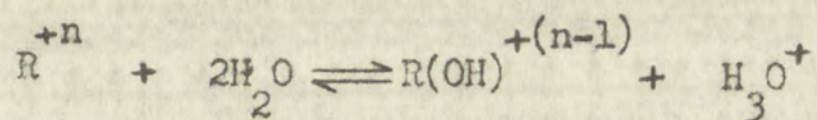




suggested that the colloidal tendencies are related to the acid or hydrolysis constant,  $k$ , defined as:

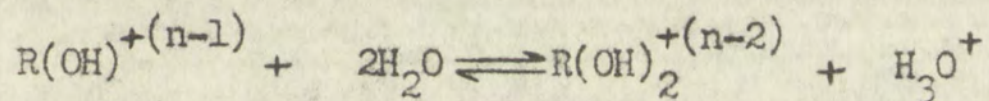
$$k = \frac{(\text{H}_3\text{O}^+)^+ [\text{R}(\text{OH})]^{+(n-1)}}{(\text{R}^{+n})}$$

which is the mass action equilibrium expression for the reaction

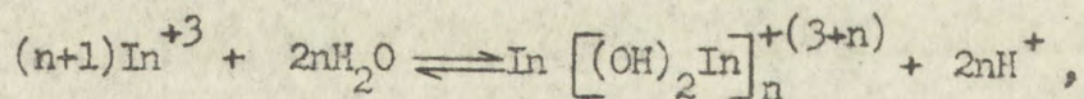


Depending on the basicity of the cation  $\text{R}^{+n}$ , the process can continue.

For example,



As the pH increases the reactions proceed to a point where a colloidal solution is formed, presumably because of polymerization of the hydroxylated compound which occurs through the binding of various numbers of atoms of the cations by R-O-R linkages and with varying numbers of hydroxyl groups attached. Biedermann<sup>(51)</sup> investigated the hydrolysis of indium(III) and found that, in solutions of pH less than 4, polynuclear complexes of indium are formed according to the equilibrium:



where  $n$  assumes a number of values. In solutions of 0.1 molar total indium concentration, complexes of the type  $\text{In} \left[ (\text{OH})_2\text{In} \right]_n^{+(3+n)}$  and  $\text{In}(\text{OIn})_n^{+(3+n)}$ , where  $n$  assumes values up to and including 5, predominate over mononuclear complexes. Even at total indium concentrations of  $10^{-3}$  molar, appreciable amounts of polynuclear complexes with  $n$



1. The first part of the paper is devoted to a general discussion of the problem.

2. In the second part, we shall consider the case of a single particle.

3. The third part is devoted to the case of a system of particles.

4. In the fourth part, we shall discuss the results of our calculations.

5. The fifth part is devoted to a discussion of the experimental results.

6. In the sixth part, we shall discuss the conclusions of our work.

7. The seventh part is devoted to a discussion of the prospects of our work.

8. In the eighth part, we shall discuss the bibliography.

9. The ninth part is devoted to a discussion of the references.

10. In the tenth part, we shall discuss the acknowledgments.

11. The eleventh part is devoted to a discussion of the conclusions.

12. In the twelfth part, we shall discuss the references.

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24. In the twenty-fourth part, we shall discuss the references.

25. The twenty-fifth part is devoted to a discussion of the conclusions.

26. In the twenty-sixth part, we shall discuss the references.

27. The twenty-seventh part is devoted to a discussion of the conclusions.

28. In the twenty-eighth part, we shall discuss the references.

29. The twenty-ninth part is devoted to a discussion of the conclusions.



equal to 2 were predicted from the experimental data. These complex ions may be considered as fragments of the sheets present in crystals of the basic salts of indium and as hydrolysis proceeds these fragments attain a critical size and the result is precipitation.

Although the pH range was lower and the total indium concentration higher in Biedermann's work than in the present work, the likely possibility of such complex formation cannot be overlooked. If as a result of increased pH, fragments of this type polymerized, a wide variety of hydrolysis products conceivably might result. These products may remain suspended in solution until removed through centrifugation or adsorption on the walls of the containing vessel.

In the pH range of 5.5 to 9.5 adsorption occurs on polyethylene and paraffined walls. This adsorption behavior suggests the presence of radiocolloids because it is unlikely that adsorption on these surfaces would proceed via ion-exchange. The results obtained by the addition of various anions substantiate further the assumption that colloidal aggregates are formed between pH 5.5 and 9.5. Anions such as iodide, perchlorate, and chromate do not form complexes with indium and consequently as the pH is increased, solutions containing these anions and indium undergo hydrolysis. The result is little change in the corresponding adsorption curves. However, secondary phosphate ion complexes with indium to a considerable degree within this range and the adsorption is reduced to practically zero.

The appreciable increase in adsorption with centrifugation of solutions and the small effect of increasing the concentration







of added electrolytes on adsorption also suggest the presence of radiocolloids. Furthermore, a detailed analysis of the reformation and equilibrium studies, assuming an ion-exchange mechanism, failed to yield reproducible values for the distribution coefficient,  $K_D$ , defined as:

$$K_D = \frac{\text{activity adsorbed on glass}}{\text{activity remaining in solution}}$$

The minimum observed in the adsorption curves for Pyrex and quartz may be the result of rate effects. The time factor can be considered on the basis of the following qualitative picture. Assume that although a true adsorption equilibrium is not attained, the radiocolloidal particles which adsorb do not necessarily stick. This assumption is supported by the reformation and equilibrium studies. Thus, in the reformation studies activity was adsorbed on the second vessel and in the equilibrium studies initially adsorbed activity was partially removed.

Consider the following four curves which are shown in Figure 15. Curve I would be obtained if the surface had many available sites and there was no desorption of particles. Diffusion would be the rate-determining step. Curves II and III would be obtained by either of two processes. First, the activity could adsorb and remain, but if the surface had only a limited number of available sites, the maximum value (100%) would not be attained. Secondly, the number of available sites could be adequate but the maximum adsorption would not be reached because of desorption. Curve IV would be obtained where there are limited surface sites accompanied by desorption of the







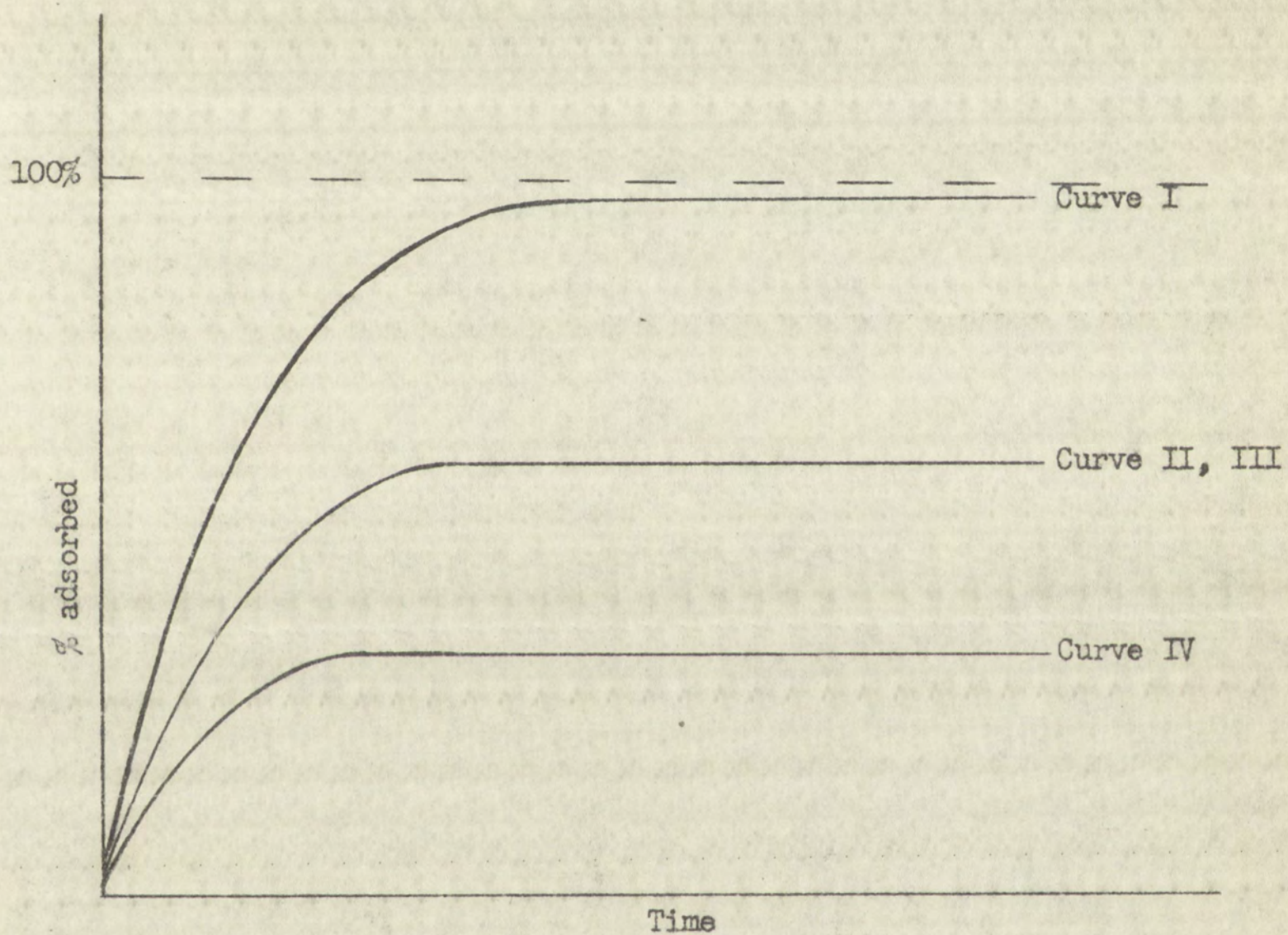


Figure 15. Percentage adsorbed--time curves.



Figure 15

Figure 15. Percentage adsorption vs. time



particles. The experimental rate curves eliminate Curve I but do not allow an unambiguous choice among the other three. However, reformation and equilibrium studies eliminate the mechanism associated with Curve II. From the following discussion it seems reasonable to favor the mechanism associated with Curve IV.

It is clear that the rate of adsorption is dependent not only on the number of available sites but also on the particle size. The size of the particle becomes important because the larger particle is associated with a slower diffusion rate. At about pH 7.5 or 8.0, the number of available sites increase, but it is assumed that the particle size increases also. These two opposing effects result in a minimum in the rate curves.

Region C (pH greater than 9.5). Most of the data obtained in this work suggested colloidal adsorption at pH values above 9.5. Equilibrium studies conducted above pH 9.5 showed that the indium was irreversibly adsorbed. The amount of indium adsorbed depended considerably on whether centrifugation was used, although the effect of centrifugation was less pronounced at pH 9.78 than at other pH values studied. The reformation studies indicated an ion-exchange mechanism regardless of whether centrifugation was used. Similarly, the effect of increasing the indium concentration followed the Langmuir isotherm. However, the fact that the Langmuir isotherm was followed does not eliminate colloidal adsorption, because colloidal adsorption may or may not follow the isotherm.



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It is interesting to note that the effect of decreased ionic strength in this pH region is to increase the rate of adsorption. This observation, assuming smaller size particles at the low ionic strength, is consistent with the rate mechanism proposed for Region B.

A rise was noticed in the % adsorbed-pH curve for the secondary phosphate system. This suggested the existence of a charged species of indium which would adsorb on the glass surface. However, it seems more reasonable to suspect that the adsorption was due to colloidal phenomena; the complexing power of the secondary phosphate ion becoming considerably less at the high pH.

The adsorption on Dowex-2 anion exchanger, paraffin, polyethylene, Pyrex, and quartz (at ionic strength equal to or greater than 0.10) dropped at pH values greater than 10. Presumably the colloidal aggregates became negatively charged due to the excess hydroxyl ions and the result was reduced adsorption. A similar drop in adsorption of thorium on polyethylene was noticed by Rydberg and Rydberg at pH values greater than 9.

At present no explanation can be afforded for the increase in adsorption of indium on Dowex-50 cation-exchanger or for the difference in the shape of the % adsorption-pH curves at low and high ionic strengths for quartz and Pyrex. It is believed, however, that these behaviors are associated with a colloidal rather than ionic phenomenon.







## SUMMARY

Procedures have been developed for the rapid separation of carrier-free indium from cadmium. The separations were effected by (1) the preferential adsorption of indium from ammoniacal solution on Pyrex glass, paper mash, and Millipore filters and (2) the selective extraction of indium from buffered acetate solutions by 8-hydroxyquinoline in chloroform. These rapid separations afford means for the detection of short-lived isotopes of indium.

The adsorptive behavior of carrier-free indium-115m has been studied as a function of pH. The observations made can be explained by the assumption that adsorption proceeds via ion-exchange for pH values up to approximately 5.5, followed by radiocolloidal adsorption at higher pH values.



It is found that the value of the

function  $f(x)$  is a continuous function of  $x$ .

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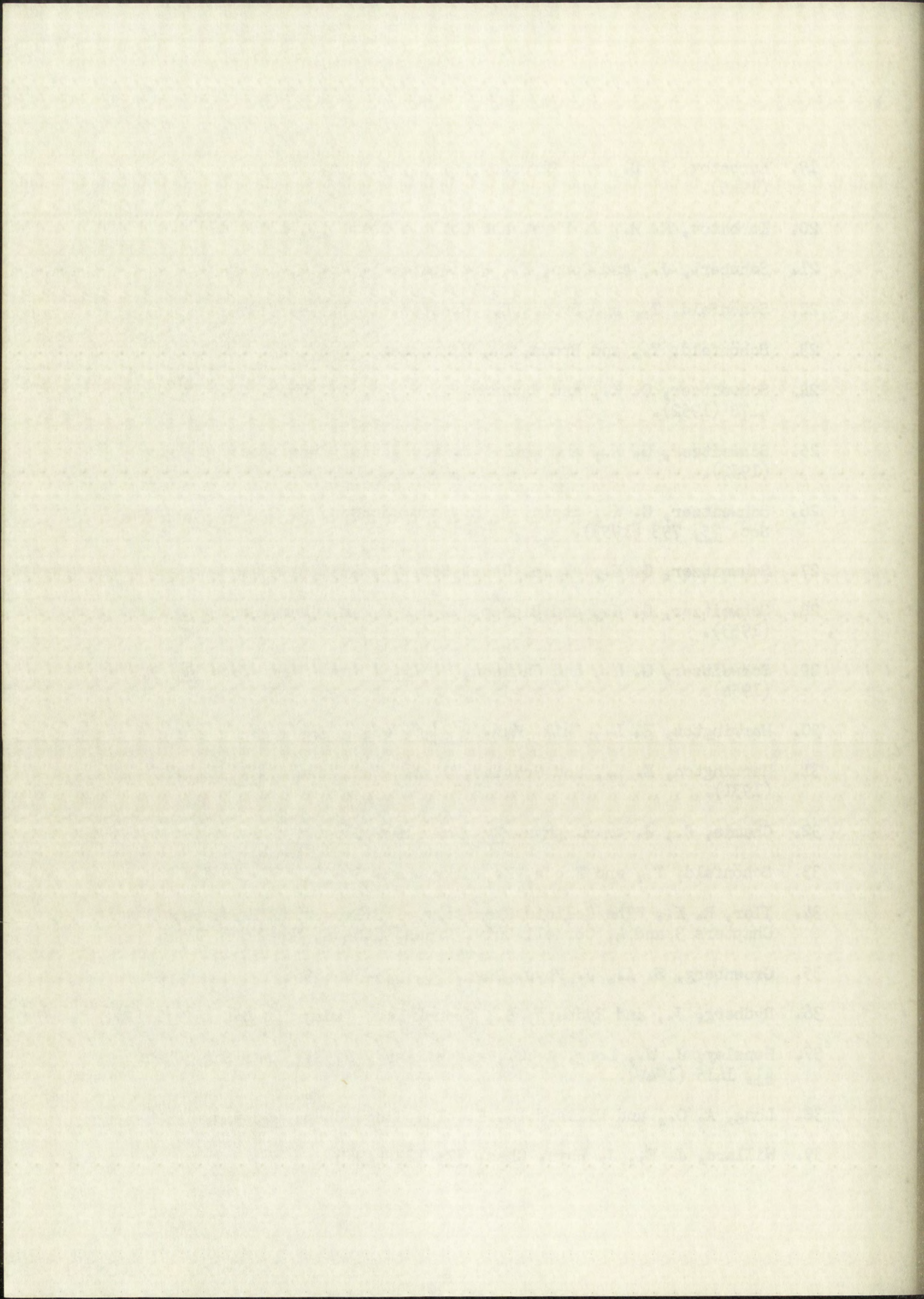
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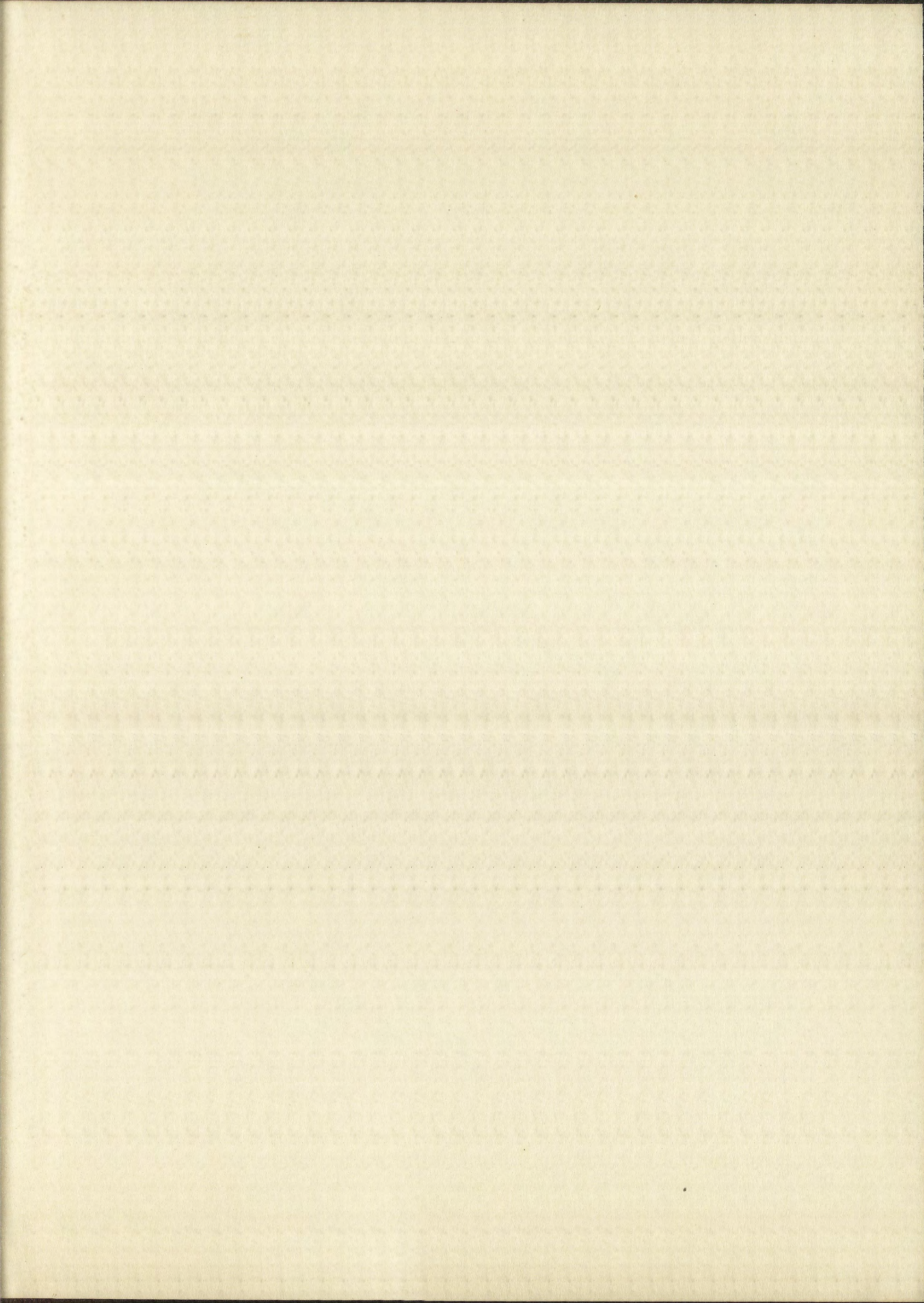


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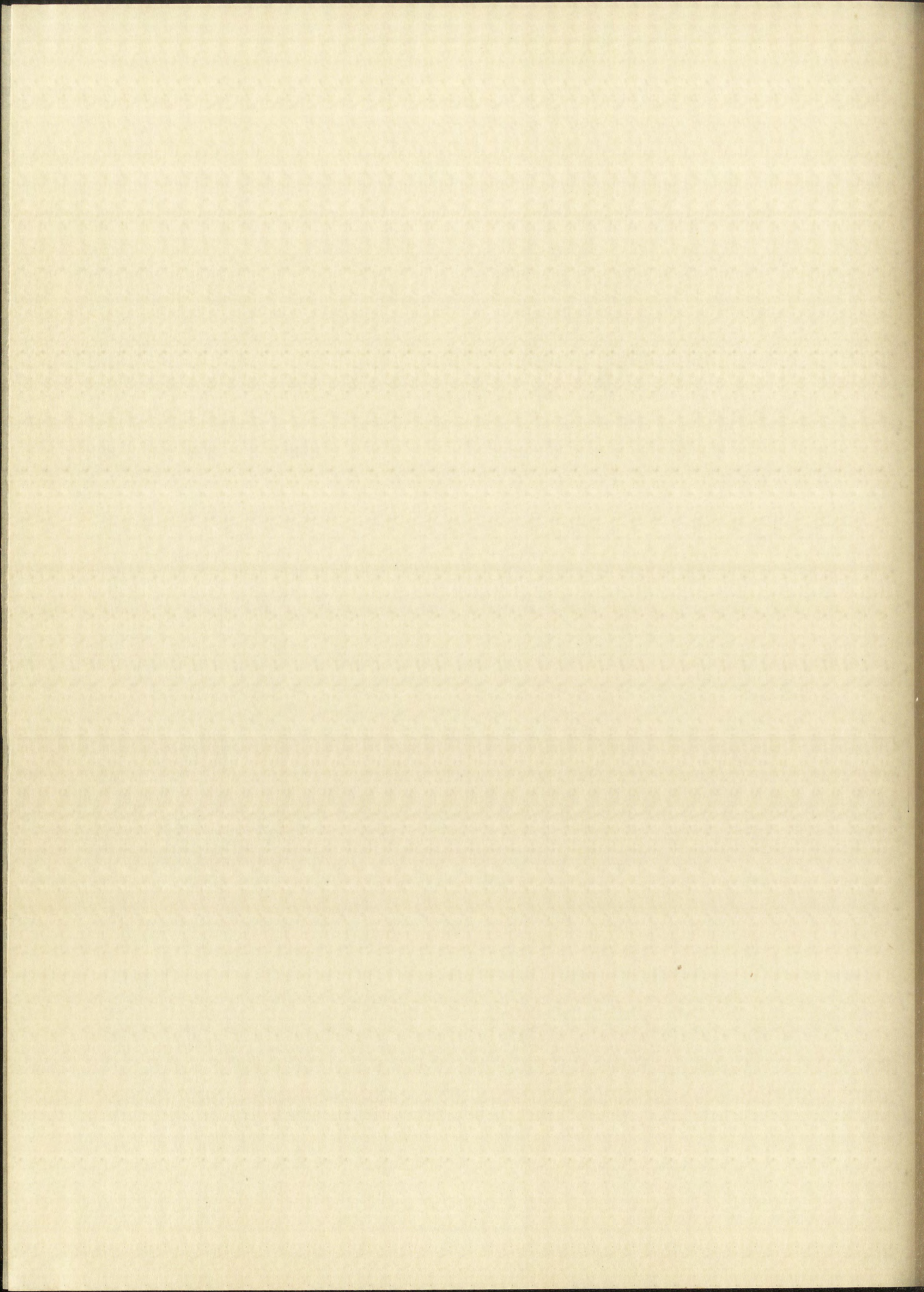
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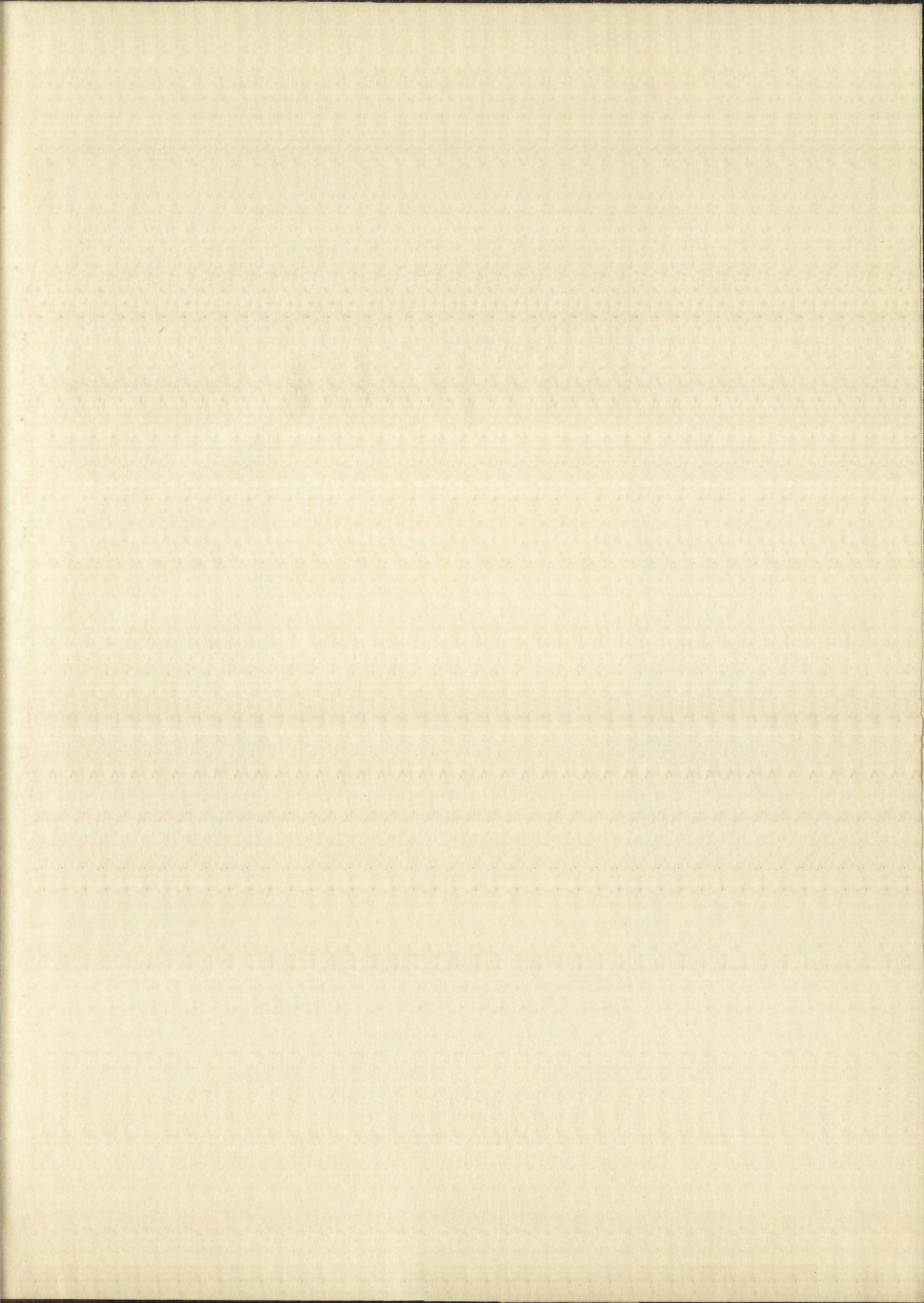














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