RADIATION EFFECTS ON ION EXCHANGE MATERIALS

A Report on Radiation Effects Program
for
Oak Ridge National Laboratory
Oak Ridge, Tennessee

T.E. Gangwer, M. Goldstein, and K.K.S. Pillay

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T.E. Gangwer, M. Goldstein*, and K.K.S. Pillay**

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*Present address: Institute for Environment and Policy, East-West Center,
1717 East-West Rd., Honolulu, Hawaii 96822

**Associate Professor of Nuclear Engineering, The Pennsylvania State
University, University Park, PA 16802

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FORWARD

This study is part of the Actinide Partitioning and Transmutation Program which is a multisite effort coordinated at the Oak Ridge National Laboratory. The overall program objective is to evaluate the feasibility and incentives for partitioning the long-lived biologically significant isotopes found in fuel wastes and transmuting them to shorter-lived or stable isotopes in power reactors. The BNL contribution to this program is the examination of the formation of radiation products in waste streams encountered in fuel reprocessing and refabrication plants which operate with a high degree of stream recycle.

We would like to acknowledge the valuable services of Pennsylvania State University, the University of Notre Dame Radiation Laboratory and Data Center, and the various U.S. ion exchange resin manufacturers for supplying information and materials necessary to prepare this report.

We are thankful to the ORNL and ERDA for their support of this literature study. Our special thanks to the IAEA, Vienna, and KETER Publishing House Ltd., Jerusalem for allowing us the use of the materials from their publications as appendices to this report. One of us (KKSP) wishes to express his gratitude to Brookhaven National Laboratory for the opportunity to participate in this study.

ABSTRACT

An extensive literature review and data compilation has been completed on the radiation-damage of ion exchange resins. The primary goal of the study has been to review the available literature on ion exchange materials used in, as well as those with potential for use in, the nuclear fuel and waste reprocessing areas. The physical and chemical properties of ion exchangers are reviewed. Experimental parameters useful in characterizing the effects of radiation on synthetic ion exchange resins are identified or defined. In compiling the diverse types of data, an effort was made to present the experimental data or experimentally based parameters in a format that would be useful for inter-comparing radiation effects on resins. When subject to radiation there are various general trends or qualitative effects displayed by the different types of resins. These radiation-trends and effects have been formulated into qualitative statements. The present day level of understanding of the behavior of resins under ionizing radiation is too limited to justify quantitative predictive modeling. The limitations and difficiencies of the literature are discussed and the experimentation needed to achieve quantitative modeling are outlined.

I. INTRODUCTION

During the past century, a very large number of natural and synthetic materials have been identified as having ion exchange properties and today their applications in science and industry are rather extensive. Ever since the first synthesis of organic ion exchangers forty years ago, hundreds of different types of ion exchange materials, both organic and inorganic have been synthesized. From this bewildering assortment of synthetic ion exchangers, only a few types have emerged as materials of commercial value. Of these, a selected few have found vital applications in the nuclear process industry. The last three decades saw rapid growth in the applications of ion exchange materials in several areas of nuclear power generation, radioisotope processing, nuclear fuel reprocessing and radioactive waste treatment. Although the number of ion exchangers identified as potentially useful in nuclear process industry include many inorganic materials, the vast majority of the ion exchangers used today are the synthetic organic resins. One of the serious limitations of these ion exchange materials is their radiation chemical decomposition as a consequence of their exposure to ionizing radiations. Since inorganic ion exchangers show considerable superiority in this one respect, there have been renewed interest in developing inorganic ion exchangers to replace the functions of synthetic organic resins. While this effort is still maturing, synthetic organic ion exchangers dominate the process related applications in the nuclear industry.

This literature survey was undertaken to review the present knowledge on the radiation effects on ion exchange materials. It is part of an overall effort to examine the present knowledge of the effects of intense ionizing radiation on the degradation of process materials, with the objective of predicting potential problems in the process streams. This survey is limited to the

radiation induced chemical changes and the resultant changes in the properties of ion exchange materials. No detailed discussion of ion exchange technology and its applications are considered appropriate here. The basic principles of processing aqueous radioactive wastes and spent fuel materials using ion exchangers are reviewed in two recent monographs [77,78]. Brief reviews of the chemical nature and properties of ion exchange materials are included here to orient the reader to the terminology used in this report and to show the relevance of estimating radiation effects on ion exchangers through a study of measurable properties that are of significance to process applications.

This literature survey has attempted to identify all published materials on the radiation effects on ion exchange materials. We have used the computerized literature search facilities of ERDA's RECON abstracts (from 1967 to mid-1977) and the chemical abstracts condensates called DIALOG (from 1972-1976). However, one unique source which became most valuable to this survey was the compilations of the Radiation Chemistry Data Center of the University of Notre Dame. It was also identified that significant omissions exist in all these three compilations and therefore a major portion of the material used in this survey were derived from routine search done by the investigators.

Among the publications identified, the book by Egorov and Novikow [1] is the only publication of significance on the subject to date. This book covers the progress on the subject up to 1963-64 period and would be a valuable source for further examination. While Egorov's and Novikov's book has extensively surveyed the Soviet literature and publications from Poland, Yugoslavia, Rumania, Hungary and Czechoslovakia, there are some significant omissions in the book on some of the experimental work done in the west. These publications have been identified and incorporated in the present survey.

Since the publication of Egorov's and Novikov's book, there has been considerable amount of experimental work done. Although this survey has attempted to gather as much of the published experimental data on radiation effects on ion exchange materials, it cannot claim to be all inclusive. For example, we have not been able to translate all the identified publications in non-English languages. A few publications recognized as significant to this effort were translated for the purpose of this survey.

During this literature survey, we have found that almost all the published literature on radiation effects on ion exchangers deal with synthetic organic materials that are of importance to the present day process industry. There is little or no quantitative experimental data on the radiation effects on inorganic ion exchangers that are considered of potential value in processing radioactive materials. It is, however, recognized that the inorganic ion exchangers in general are considerably more resistant to radiation damage and therefore they can be of significant value to nuclear fuel reprocessing and radioactive waste management. Since the necessary experimental work to study the effects of ionizing radiation would require exposures of materials to considerably higher radiation doses, investigators studying the radiation effects on organic materials have not yet actively undertaken these studies.

Our present knowledge on the radiation effects on synthetic organic ion exchangers is better than that of inorganic exchangers. However, the information available today on organic ion exchangers are not adequate to provide meaningful mechanistic interpretations of many of the recognized problems resulting from radiation damages in ion exchangers during process applications. For the present survey, we have assigned major importance to synthetic organic

exchangers, which are indeed the materials used in the present-day process industry.

This survey has attempted to present objectively all the available facts in an extensive tabulation of experimental data (Tables III and IV) with adequate bibliographical records. Appendices I and II of this report contain general information on the chemical nature of ion exchange resins and the trade names of both organic and inorganic ion exchange materials that are marketed by various manufacturers. In addition, the present knowledge on radiation effects on ion exchange material is summarized as general rules applicable to most organic ion exchangers. These generalizations should be regarded only as present knowledge. While this survey can definitely add to our present knowledge regarding the radiation chemical changes in ion exchange process materials, it is felt that considerable additional work needs to be done to reliably explain and accurately predict many of the phenomenological observations of experimental studies and process related incidents.

II. GENERAL CHARACTERISTICS OF ION EXCHANGE MATERIALS

The characteristics of ion exchange materials that are of importance in discussing radiation effects are considered here. An attempt will be made in the following section to further elaborate on the influence of radiation-induced chemical changes on these characteristics of ion exchangers.

II.1 Organic and Inorganic Exchangers

Most of the ion exchange materials that are used (and have the potentials to be used) in radiochemical process applications are synthetic materials. One of the reasons for the preferential use of synthetic materials is the relative ease with which the characteristics of the exchangers can be controlled by appropriate changes in composition and preparative methods. This, in turn, allows for the evaluation and prediction of process characteristics in the use of these materials.

Synthetic organic ion exchangers are high molecular weight polyacids or bases which are virtually insoluble in most aqueous and nonaqueous media. In general, they are cross-linked polymer tridimensional networks to which is attached large polar exchange groups. Since these materials are not individual compounds, their composition and properties are dependent on the nature and purity of the original chemicals from which they are synthesized, and their treatment prior to process applications. Some of the major differences in the properties of synthetic organic ion exchangers produced by various manufacturers as well as the differences between different batches of materials produced by the same manufacturer are accountable by these variations. Radiation effects on these materials can also be influenced, to a limited degree, by the potentials for variability in different synthetic preparations. In general, radiation effects on synthetic organic ion exchangers can cause irreversible chemical changes

in their macromolecules due to the rupture of single bonds and the resultant of degradation processes. Also, synthetic cation exchangers contain bonds between functional groups and the polymer matrix which are relatively unstable. It is these weak linkages that are more liable to succumb to the influence of radiation.

Inorganic ion exchangers, unlike the organic materials, are well defined compounds. In general, they are hydrous oxides. Acidic salts of multivalent metals, salts of heteropolyacids, insoluble ferrodyanides, synthetic aluminosilicates or similar substances of well defined chemical composition. Unlike organic ion exchangers, these inorganic substrates are highly resistant to radiation exposure. This particular property can be of great value in the nuclear process industry. Two recent review articles [79,80] and a monograph by Amphlett [81] have extensively surveyed the very large number of materials that can be classified as synthetic inorganic ion exchangers. The increasing interest in these materials for potential application in radioactive waste processing is evidenced by several reviews [82-84] by organizations and groups interested in reactor coolant purification and radioactive waste management. However, one of the recognized limitations of inorganic ion exchangers is their relative instability in acid media and their high sensitivity to pH changes. Therefore, the widespread process applications of inorganic ion exchangers in nuclear fuel reprocessing, reactor coolant maintenance and radioactive waste separations are still awaiting further developments in materials of qualities comparable to the present day synthetic organic ion exchangers. Synthetic organic ion exchangers (resins) are the most widely used and highly developed exchange materials of the day.

II.2 Classification of Ion Exchangers

Ion exchangers are classified in several different ways. Some of the major classifications of importance are the following.

II.2.a Classification based on exchangeable species

One of the classifications of ion exchange materials is based on the electrical charge of the chemical species they are able to exchange from the aqueous or non-aqueous media. On this basis, ion exchangers are grouped as:

Cation exchangers,
Anion exchangers,
Ampholytes, and
Multifunctional exchangers.

While cation and anion exchangers only sort cations or anions respectively, the ampholytes can act as an anion exchanger or a cation exchanger depending on the conditions under which they are used. Also, there are some ion exchangers that have been synthesized with both cation and anion exchange groups. The number of ampholytes and multifunctional synthetic exchangers are extremely limited and they still remain laboratory curiosities.

II.2.b Classification based on functional groups

A second, rather arbitrary type, classification of ion exchangers is based on their functional groups and their degree of ionization (pK values). On this basis, ion exchangers are classified as strong, intermediate and weak acid/base type exchangers. Although this classification is fairly arbitrary, it is often used in the ion exchange vocabulary and does serve the purpose of quickly identifying functional groups. Table I summarizes this type of classification and some of the common functional groups of organic ion exchangers used in this grouping. Polyfunctional (distinct from "multifunctional") ion exchangers have more than one type of functional groups of the strong/intermediate/weak (acid/base) type.

Table I
FUNCTIONAL GROUPS OF SYNTHETIC ORGANIC RESINS

<u>Type of Resin</u>	<u>Functional Group</u>
Strongly Acid	Nuclear Sulfonic - SO_3H Methylene Sulfonic - $\text{CH}_2\text{SO}_3\text{H}$
Intermediate Acid	Phosphoric - O-P(O)(OH)_2 Phosphonic - P(O)(OH)_2 Phosphonous - P(O)H(OH) Arsonic - As(O)(OH)_2
Weakly Acid	Carboxylic - COOH Phenolic hydroxyl - $\text{C}_6\text{H}_4\text{OH}$ Sulphydryl - SH
Strongly Basic	Quarternary Ammonium - $\text{N}^+(\text{CH}_3)_3$ - $\text{N}^+(\text{CH}_2\text{CH}_2\text{OH})_3$ - $\text{N}^+(\text{CH}_3)_2\text{C}_2\text{H}_4\text{OH}$ Pyridine - $\text{N}^+\text{C}_5\text{H}_5$ t-Sulfonium $\equiv \text{S}^+$ Quartenary phosphonium $\equiv \text{P}^+$
Intermediate Base	(Multi-functional consisting of combinations of strongly basic and weakly basic groups)
Weakly Basic	p-amino - NH_2 s-amino = NH t-amino $\equiv \text{N}$

Note: A brief summary of the structural features of ion exchange resins along with descriptions of their chemical make up is included as Appendix I of this report.

II.2.c Classification based on preparative processes

Another type of classification for synthetic organic ion exchangers is based on the preparative processes used in the synthesis of the basic macromolecular structure. This classification is considered of significance to radiation induced chemical changes of these ion exchangers. On this basis, the synthetic organic resins are broadly classified as:

Polymerization type, and
Condensation type.

These polymerization and condensation products are resinous materials from which the popular name "resins" for synthetic ion exchangers originate. Polymerization type resins are prepared from several molecules of similar (or same) material combining to form larger molecules, while the condensation type of resins are prepared by the combination of several constituents to form a larger molecule with the elimination of smaller molecules like water.

II.2.d Classification based on physical state

While almost all the ion exchangers considered here are solids, there are a few substances (synthetic organic types) that are classified as ion exchangers in the liquid form. Functionally, the use of these ion exchangers resemble liquid-liquid partitioning processes, even though the mechanism of ion partition is considered as ion exchange [85]. At the present time, these liquid ion exchangers are seldom used in fuel reprocessing or radioactive waste separations.

II.2.e Classification based on granulation

Ion exchangers are also identified as granular solids and membrane types. Most of the commercially used resins are the granular types. The membrane type resins are increasingly gaining prominence in several applications. Ion exchange membranes are mechanically rigid films, discs, plates, strips or tubes made of either cation or anion exchange resins. Again, these ion exchange membranes

have not yet found significant applications in processing involving high level radioactive materials.

II.2.f Classification based on the rigidity of porous structure

Synthetic polymerization type ion exchangers are distinguished as gel-type and macroporous (or macrorecticular)-type on the basis of the rigidity of the porous structure of the macromolecule. The macroporous resins are prepared by specialized polymerization techniques with a high degree of cross-linkage. Macroporous resins have an average pore size of 300-700 Å in diameter which are extremely rigid. The conventional gel-type resins have pore structure that are flexible and collapsible [86]. The average surface area per unit weight of macroporous resins is about 400-600 times greater than that of gel-type resins, [87,88]. Unlike gel-type resins, the macroporous resins do not change volume with change in ionic strength of the solutions. At the present time the macroporous resins are primarily used in organic solvent systems.

II.3 Properties of Ion Exchangers

The physicochemical properties of relevance to process applications of commercially important ion exchange materials are usually found in manufacturer's brochures. An extensive compilation of such data available from manufacturers and presented in an IAEA monograph [2] has been adapted as Appendix II of this report. In addition, manufacturer's literature often contains recommendations for column operations and regeneration of the ion exchangers. However, singularly lacking from these sources is any information regarding the radiation stability of these commercially used products.

Some of the important properties of ion exchange materials that are of significance to radiation effect studies are described below.

II.3.a Exchange capacity

One of the most important characteristics of ion exchangers is their exchange capacity, which indicates the amount of ions the material is capable of exchanging under given conditions. By convention [89], it is expressed as milligram equivalent per gram of dry ion exchanger (meq/g). In general, the exchange capacities of strong acid and strong base exchangers remain practically constant over a wide range of pH values. The exchange capacities of weakly acidic and weakly basic ion exchangers vary greatly depending on the pH of the media - the weak acid exchangers showing high exchange capacities at higher pH, while the weakly basic exchangers exhibiting higher exchange capacities in solutions of low pH values.

Since the ion exchange reactions are a result of electrostatic forces, the capacity of ions to be exchanged depends on the relative size of the charge and the radii of the hydrated ions. In dilute solutions, ions with higher valency and higher atomic number (or lower radius of hydration) have greater tendencies for exchange with the solid exchanger. However, this generalization has its limitations, because it is also known that the ability of ions to exchange is dependent on the structure (cross-linkage) of the sorbent, the pH of the medium, the ionic concentration of the solution and the temperature of the system.

The effect of ionizing radiations on ion exchangers are often measured in terms of the change in exchange capacity of the material at various exposure rates and under a variety of environmental conditions. This provides a quantitative measure of the rupture of functional groups as a result of radiation induced chemical changes.

II.3.b Degree of cross-linking

Another important characteristic property of organic ion exchangers that has a direct influence on its radiation stability is the degree of cross-linking. This term is used to describe the porosity of an ion exchange particle. Highly cross linked resin can be impermeable to ions of high molecular weight, whereas resins of lower cross-linkage can be quite permeable to the same ions. For synthetic polymerization type resins, cross-linkage is arbitrarily defined as the percentage of divinylbenzene which is used in the preparation of the macromolecular base. Chemicals other than divinylbenzene can also be used to produce cross-linkage in the resin matrix. For synthetic condensation type resins, the cross-linkage is determined by the ratio of phenol to substituted phenols used to produce condensation reaction with an aldehyde. It is a common practice to indicate the cross-linkage of the resin by an "x" number following the trade name of the resin.

Cross-linkage of synthetic organic exchangers are related to their exchange capacities. In general, on a dry weight basis, the exchange capacity of the resin decreases with increasing cross-linkage. On the other hand, the radiation stability of the resins, in general, tend to increase with increasing cross-linkage. In practice, it is not desirable to increase the cross-linkage of the resins beyond 10 to 15% because of the increased rate of diminution in exchange capacity beyond this degree of cross-linkage.

The influence of ionizing radiation on resins is to create further cross-linkages in certain instances, while in other cases, radiation exposure causes rupture of cross-linkage resulting in degradation of the ion exchanger.

II.3.c Swelling and Moisture Content

When ion exchange sorbents are immersed in water or in aqueous solutions of an electrolyte, they swell owing to the diffusion of water molecules to the sorbent phase. The tendency of ion exchangers to swell depends on several factors, such as the mesh size of the particle, the degree of cross-linkage of the macromolecule, the rigidity of the spatial network and the degree of dissociation of the functional group. In general, swelling is favored by polar solvents, low degree of cross-linkage of the resin, high capacity of the resin, and low concentration of the external solution.

Ion exchangers placed in liquids continue to swell until an equilibrium condition is reached. The polar and ionic constituents of the resin tend to surround themselves with the solvent and the framework continues to yield until its elastic forces balances the dissolution tendency. The osmotic pressure difference (or "swelling pressure") between the interior and exterior of the resin is often very large, at times greater than a thousand atmospheres [2].

Moisture content of the ion exchanger furnishes a measure of its water-holding capacity or swelling. Commercially available ion exchangers always contains a significant amount of moisture. A full elimination of all the water, especially the hydration layer on the polar groups is very difficult without the destruction of the ion exchanger itself.

Radiation chemical effects on ion exchangers are significantly influenced by the presence of moisture within and external to the ion exchanger. The radiolytic products of water often changes the degree and the mechanism of decomposition of the ion exchanger.

II.4 Ion Exchange Process

The ion exchange process is considered a combination of absorption, adsorption and diffusion processes, which is also termed as "sorption" and is similar to chemical double decomposition. Typical ion exchange reactions may be represented as follows:

where R represents the insoluble matrix of the ion exchanger and X^{+} and Y^{-} represent ionic species in solution. The reversal of these processes are employed during the regeneration of depleted ion exchangers. Many factors seem to influence the sorption equilibrium. These include: exchange capacity, degree of cross-linking, concentration of ionic species in solution, ionic valencies, ionic sizes, swelling pressure, rate of diffusion of ions in solution and within the resin, solution temperature and the interactions between mobile and fixed ions in the exchanger. Among these, the most important rate determining factor is the rate of diffusion of ions both in solution and in the resin matrix. A general rule states that ion exchangers tend to exclude strong electrolytes with counter ions (mobile ions) identical to the exchanger counter ions. The degree of this exclusion is enhanced by the low valence of counter ions and high valence of the co-ions.

Radiation effects on ion exchangers and the immediate surroundings of the sorbents influences several of the above mentioned factors, which in turn affect the kinetics of the ion exchange process itself.

II.5 Chemical Composition of Synthetic Organic Ion Exchangers

Many of the ion exchangers that are often discussed in experimental studies involving radiation chemical effects are synthetic resins of importance to process industry. Resins on which there are meaningful experimental studies reported in the open literature are grouped as cation exchangers and anion exchangers in the tabulations presented in Tables II-A and II-B respectively. These tabulations include a listing of the major constituents of the matrix and the type of process used in their preparation along with the functional groups of the resin. This tabulation uses the trade names of these ion exchangers and these are arranged in alphabetical order to facilitate cross reference with the radiation effects data presented in the later sections of this report. Further details of the chemical structure of these resins are described in various references following the radiation effects data [see Tables III and IV].

TABLE IIA
SOME OF THE TYPICAL SYNTHETIC ORGANIC RESINS
(CATION EXCHANGERS)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
Amberlite IR-120	Nuclear Sulfonic	Copolymer of styrene and divinyl-benzene (DVB)
Amberlite IR-112	"	"
Amberlite IR-105	Methylene-sulfonic and phenolic hydroxyl	Condensation type phenol and formaldehyde
Amberlite IRC-150	Carboxylic	Copolymer of Methyl Methacra- late (or methacrylic acid and DVB)
Catex S	Nuclear sulfonic	Copolymer of styrene and DVB
Catex F	Methylene-sulfonic and phenolic hydroxyl	Condensation type phenol and formaldehyde
Catex FN	Nuclear sulfonic	Condensation type phenol, formaldehyde and naphthalene
Dienon SK-1	Nuclear sulfonic	Copolymer of styrene and DVB
Dienon SK-100	"	"
Dowex 50	"	"
Dowex 50W	"	"
Dowex 30	Methylene sulfonic and phenolic hydroxyl	Condensation type phenol and formaldehyde
Duolite C-3	Methylene sulfonic and phenolic hydroxyl	Condensation type phenol and formaldehyde
Duolite C-10	Nuclear sulfonic	Condensation type phenol, formaldehyde and naphthalene
Duolite CS-101	Carboxylic	Copolymer of acrylic acid and DVB

TABLE IIA (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
EO-7	Nuclear sulfonic and phenolic hydroxyl	Condensation type phenol, formaldehyde and hydroquinone
Imac C-12	Nuclear sulfonic	Copolymer of styrene and DVB
KB-6	Carboxylic	"
KB-4	"	Copolymer of methylmethacrylate and DVB
KB-4P-2	"	"
KF-1	Phosphonic	Copolymer of styrene and DVB
KFU	Carboxylic	Condensation type penoxy-acetic acid, formaldehyde and phenol
KS	Carboxylic	Copolymer of styrene and DVB
KU-2	Nuclear sulfonic	Copolymer of styrene and DVB
KU-4	"	Copolymer of acenaphthalene and DVB
KU-5	Nuclear sulfonic	Condensation type formaldehyde, and naphthalene sulfonic acid
KU-6	Nuclear sulfonic	Condensation type acenaphthalene sulfonic acid and formaldehyde
KU-160	"	Condensation type carbazole and formaldehyde
KU-1	"	Condensation type phenol and formaldehyde
KU-1g	"	"
Nalcite HCR	"	Copolymer of styrene and DVB

TABLE IIA (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
Permutit Q	Nuclear sulfonic	Copolymer of styrene and DVB
Permutit H-70	Carboxylic	Copolymer of methylmethacralate and DVB
P ₃	Nuclear sulfonic	Condensation type, benzoquinone, benzidine disulfonic 2,2' or stilbene disulfonic 2,2' acids
P ₄	"	"
PS ₃	"	"
RF	Phosphonic and phenolic hydroxyl	Condensation type phenol, resorcinol and formaldehyde or monohydroxy phenyl phosphate and formaldehyde
R ₅ C	Carboxylic and phenolic hydroxyl	Condensation type resorcylic acid and formaldehyde
SBS-1	Nuclear sulfonic	Copolymer of styrene and butadiene
SBS-2	"	"
SDV-3	"	Copolymer of styrene and DVB
SF	Phosphonic	"
SG-1	Carboxylic	Copolymer of methylmethacralate and ethylene glycol dimethacralate
Wolfatit KPS	Nuclear sulfonic	Copolymer of styrene and DVB
Wolfatit F	"	Condensation type phenol and formaldehyde
Wolfatit F ₂ S	"	"
Wolfatit F ₄ S	"	"
Wolfatit FF ₂ S	"	"

TABLE IIA (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
Wolfatit P	Methylene sulfonic and phenolic hydroxyl	"
Wolfatit CP	Carboxylic	Copolymer of acrylic acid and DVB
Wolfatit C	Carboxylic and phenolic hydroxyl	Condensation type resor-cyclic acid and formalde-hyde
Wolfatit CN	"	Condensation type resor-cyclic acid, phenol and formaldehyde
Zeocarb-225	Nuclear sulfonic	Copolymer of styrene and DVB
Zeolex SA	Nuclear sulfonic	Copolymer of styrene and DVB
ZeoRex	Methylene sulfonic and phenolic hydroxyl	Condensation type phenol and formaldehyde
Zeolex WA	Carboxylic	Copolymer of methylmethac-rate and DVB
Zerolitt-225	Nuclear sulfonic	Copolymer of styrene and DVB

TABLE IIB
SOME OF THE TYPICAL SYNTHETIC ORGANIC RESINS
(ANION EXCHANGERS)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
AM	Trimethyl benzyl ammonium	Copolymer of styrene and divinylbenzene (DVB)
Amberlite IRA-400	"	"
Amberlite IRA-401	"	"
Amberlite IRA-410	Dimethyl hydroxyethyl ammonium	"
Amberlite IRA-411	"	"
Amberlite XE-114	"	Condensation type polyethylene, polyamines and epichlorhydrin
Amberlite IR-45	P-, S- and t- amino	Copolymer of styrene and DVB
Amberlite IR-4B	S- and t- amino	Condensation type polyethylene, polyamines and phenol
Amberlite XE-58	"	"
AMP	Pyridine	Copolymer of styrene, pyridine and DVB
AN-1	P- and S- amino	Condensation type melamine and formaldehyde
AN-9	S- and t- amino	Condensation type ammonium sulfate, phenol and formaldehyde
AN-2F	"	Condensation type polyethylene, polyamines and phenol
AN-21	Trimethyl benzylammonium	Copolymer of acenaphthalene and DVB

TABLE IIB (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
AN-25	Pyridine derivative	Copolymer of 2,5 methyl-vinyl pyridine with DVB
AN-25A	Pyridine derivative	Copolymer of 2,5 methyl-vinyl pyridine with DVB (methylated derivative)
ASD-2	Trimethyl benzyl ammonium	Copolymer of styrene and DVB
ASD-4	Dimethyl hydroxyethyl ammonium	"
ASD-3	Pyridine	Copolymer of styrene, pyridine and DVB
AV-16	Pyridine and S- and t-amino	Condensation type pyridine, polyethylene, polyamines and epichlorohydrin
AV-17	Trimethyl benzyl ammonium	Copolymer of styrene and DVB
AV-27	Dimethyl hydroxyethyl ammonium	"
AV-18	Pyridine	Copolymer of pyridine, styrene and DVB
AV-19	Trimethyl benzyl ammonium	Copolymer of 2-vinyl naphthalene and DVB
AV-16	Pyridine and S- and t-amino	Condensation type pyridine, polyethylene, polyamines and epichlorohydrin
Deacidite FF	Trimethyl benzyl ammonium	Copolymer of styrene and DVB
Dienon SA-200	"	"
Dienon SA-100	Dimethyl hydroxyethyl ammonium	"
Dowex-1	Trimethyl benzyl ammonium	"
Dowex-21K	"	"
Dowex-2	Dimethyl hydroxyethyl ammonium	"

TABLE IIB (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
Dowex-3	P-, S- and t- amino	Copolymer of styrene and DVB
EDE-10	"	Condensation type polyethylene, polyamines and epichlorohydrin
EDE-10P	"	"
Imac S-4	Trimethyl benzyl ammonium	Polyxyalene from p-xylene
MMG-1	P- and S- amino	Condensation type urea, melamine, guanidine and formaldehyde
Nalcite SAR	Dimethyl hydroxyethyl ammonium	Copolymer of styrene and DVB
Nalcite WBR	P-, S- and t- amino	"
Permutit S-2	Dimethyl hydroxyethyl ammonium	"
Permutit SK	Pyridine	Copolymer of pyridine, styrene and DVB
Stamex S	t-sulfonium	Condensation type anisol and formaldehyde
Stamex S-44	"	"
VP-1	Pyridine (derivative)	Copolymer of 2-methyl-5-vinyl-pyridine and DVB
Wolfatit-SBW	Trimethyl benzyl ammonium	Copolymer of styrene and DVB
Wolfatit-SBS-400	Dimethyl hydroxyethyl ammonium	"
Wolfatit L	P-, S- and t- amino	Condensation type polyethylene, polyamines and epichlorhydrin
Wolfatit-L-150	"	"

TABLE IIB (Cont'd)

<u>Trade Name</u>	<u>Functional Group(s)</u>	<u>Type of Preparation</u>
Wolfatit MD	S- and t- amino	Condensation type poly-ethylene, polyamines and phenol
Zeolex SB-I	Trimethyl benzyl ammonium	Copolymer of styrene and DVB
Zeolex SB-II	Dimethyl hydroxyethyl ammonium	"
Zeolex WB	P-, S- and t- amino	"
Zerolitt FF-IP	Trimethyl benzyl ammonium	(Macroporous resin) co-polymer of styrene and DVB

III. EXPERIMENTAL DATA ON THE EFFECT OF RADIATION ON SYNTHETIC ION EXCHANGERS

Because of the prevailing importance of synthetic ion exchangers in nuclear process applications, most of the published papers deal with experimental studies using organic resins. At the present time, there are very few studies reporting quantitative data on the effects of radiation on inorganic ion exchange materials. Most of the published material on the effects of ionizing radiation on ion exchangers resins are the results of experiments conducted using miniature scale resin bands exposed to irradiation sources such as x-ray machines, ^{60}Co γ -facilities, electron accelerators and in a few instances, research reactors. There have been few reports on direct contact irradiation where radioactive nuclides are sorbed on the resin matrix. These latter types of studies include the use of both β, γ emitters and α -emitters. The available data also include irradiations performed under a variety of environmental conditions on both polymerization and polycondensation type resins. Many of the findings of the radiation degradation studies of resins have been confirmed by others on similar types of resins of different origin. However, disagreements do exist in several areas and some of the reported conclusions remain debatable. The data presented here and in the discussions in the following sections should be viewed with this limitation in mind.

Some of the discrepancies in the reported experimental observations are attributable to insufficiently defined irradiation conditions, difficulties in radiation dosimetry and the existing variations in the overall qualities of similar type of resins from different batches and those produced by different manufacturers. The difficulties in dosimetries is particularly evident in some of the experimental results using reactor irradiations [see Table III].

The tabulation presented here is a summary of experimental data from numerous sources. Most of the quantitative data of relevance are from the first fifty references grouped at the beginning of the reference section of this report. Some of the other references cited in this report also contain similar data and the gist of these findings have been incorporated in the discussions in the following sections.

The choice of the format for their tabulation was primarily dictated by the kind of data available from most of the experimental studies. Some of the important experimental parameters and quantitative data that are generally measured with reliability are tabulated. Along with this, appropriate notations have been included to indicate other details presented in each of the original studies. The tabulation is broadly divided into two groups - Table III summarizing the data on synthetic organic cation exchangers and Table IV contains similar data on anion exchanger resins.

The following subsections are brief descriptions of terms and abbreviations used in Tables III and IV. These descriptions are presented to further define these experimental parameters and results more accurately and to bring out the modifications made, if any, in the original data for brevity and consistency.

III.1 Resin (Trade name)

Here, the word "resin" is used synonymous with organic amorphous materials, which are not true compounds. Synthetic organic ion exchangers are variously referred to as "resins," "ion exchange resins," or as "synthetic organic resins" in the published literature.

The trade names of commercially produced ion exchangers are a combination of letters, numbers and words and in general they have no logical relationship

to the chemical characteristics of the resin. However, these trade names are the only way a particular commercial product is clearly identified and therefore they are part of the vocabulary in the literature. Another puzzling feature of the trade names is that without any substantiable reason, the trade name of particular resin is often changed and several trade names are used to describe the same resin. Adding to the confusion in trade names is the existing practice of resins manufactured by a few major manufacturers being sold under a variety of trade names by the distributors. It is often difficult to get accurate information on these cross-listings from either the manufacturer or the distributor.

The trade names used in the tabulations are the same identifications used by the authors of these publications. Some of these names are not found in the most recent literature available from U.S. manufacturers, although the same resin is available under a different trade name. The manufacturer's pamphlets also contain additional information to identify the trade names with the type of resin, although very few of these brochures provide detailed information on the chemical constituents of the preparation or the structural formula of the product.

III.2 Ionic Form

The chemical symbols used here refer to the forms in which the ion exchangers were used in the experimental studies. It is generally known that the salt forms of the ion exchangers are more resistant to radiation damage than the H^+ or OH^- forms. In most of the process applications, the ion exchangers are used in the hydrogen and hydroxyl forms. However, during their use, the ion exchanger changes to salt forms and constitute significant part of a column

by the time the resin bed accumulates increased radiation doses. Salt forms of the resin generally provide a radiation protection effect.

III.3 Exchange Capacity

This important property of ion exchangers has been described earlier (see Section II.3.a). There are several different ways in which the exchange capacities of ion exchangers are presented in the literature. The exchange capacity of resins tabulated here is the "TOTAL EXCHANGE CAPACITY," also referred to as the "ultimate capacity" [90].

The total exchange capacity (TEC) is the number of chemical equivalents which the resin has available for exchange per unit weight of the dry form of the ion exchanger. The recommendations of the IUPAC Commission on Analytical Nomenclature is to express the exchange capacity of an ion exchanger as milliequivalent per dry gram of resin (meq/g).

The total exchange capacity (TEC) listed in Tables III and IV is different from other exchange capacities mentioned in the literature. TEC should be distinguished from:

- Dynamic capacity
- Breakthrough capacity
- Salt-Splitting capacity
- Static exchange capacity
- Apparent capacity
- Operating capacity and
- Sorption capacity, among others.

Unlike the various types of exchange capacities mentioned here, the total exchange capacity (TEC) is a constant for a particular exchange material, which shows the number of fixed ionic sites that can enter into an ion exchanger reaction. In Tables III and IV, some of the TEC values reported are in terms of the weight of the matrix (not dry resin).

III.4 Radiation Source (Dose rate: Rad/Hr)

A variety of radiation sources were used during the experimental studies surveyed here. These include sources of different linear energy transfer (LET) values: amount of energy deposited per unit distance, and sources which are both external and internal to the resin sample. These sources are briefly identified and where known, the dose rates of the ionizing sources are included. All the reported data have been converted to dose rate as rad/hr for uniformity of presentation.

III.5 Irradiation Condition(s)

A variety of irradiation conditions have been used in the experimental studies reported because the environmental conditions and the moisture (or electrolyte) content of the resin significantly influences the nature and the extent of radiation chemical changes in the ion exchange material. This diverse information is presented in abbreviated form. Further details regarding irradiation conditions are described in the original publication(s).

III.6 Integral Dose (Rads)

This is the total dose the resin is reported to have accumulated before its change in properties were measured during the experimental study. Again, for uniformity of presentation, this data has been converted into rad units - one rad being equivalent to 100 erg of absorbed energy/g or 6.24×10^{13} ev/g or 10^{-5} watt-second/g.

In estimating absorbed radiation doses, most of the experimenters have assumed that the mass absorption coefficients of x-rays and γ -radiations and the LET values for accelerated electrons and radioactive sources emitting β -particles in the resins are approximately equal to those values in water. This is generally considered a reasonable assumption.

III.7 Loss of Exchange Capacity (%)

Most of the reported experimental studies have used the measurement of total exchange capacity of the resin after irradiation as a quantitative measure to determine the changes in ion exchange properties of the resin. This is experimentally achieved by measuring the exchange capacity of the irradiated resin using procedures used to determine total exchange capacity. The difference in exchange capacities are expressed as the percentage of initial capacity (TEC) of the resin. In most instances, on radiation exposure, the exchange capacities of the resins decrease as a result of the rupture of functional groups. However, in certain instances, the TEC has shown net increases due to the formation of new functional groups as a consequence of oxidation of the resin matrix. These gains are reported with a negative sign before the number.

Not all of the experimental studies included here report results similarly. The changes in total exchange capacities are calculated from available data wherever possible. At times, the experimenters have chosen to report these changes in exchange capacities using the dry weight of the irradiated specimen. Since radiation chemical changes also result in weight changes of the resin, an attempt was made to identify this type of data and when adequate information on weight changes were available, these results were recalculated in terms of the initial weight of the resin. Thus all of the data reported here are with respect to the initial capacity and the initial weight of the resin.

III.8 G-Value

By definition, G-value, the radiation chemical yield, is the number of species formed as a result of the absorption of 100 ev of ionizing radiation. In the experimental studies surveyed, G-values have been reported for a variety of different radiation produced species. The different G-values that have

been tabulated without further change in this work are the following:

(i) A term G_0 is used in some of the data reported by Egorov and Novikov [1]. This denotes the value of G calculated from the initial part of the kinetic curve. The G_0 value represents the total amount of the initial functional groups lost per 100ev of radiation energy absorbed by the ion exchange medium. This parameter indicates that the same resin may have varying radiation chemical resistance which has been confirmed by experimental findings of other workers. The data from Tables 70 and 77 (identified in the last column of the tabulation) from reference [1] are G_0 values as described above. Most of the other reported values of G are the average value of G considering the integral dose and the net radiation chemical change. If the dependence between radiation chemical change and the dose is linear, G_0 is proportional to G .

(ii) Some of the G -values tabulated are radiation chemical yields estimated during this work from the data provided in the original papers.

(iii) The tabulation also includes G -values reported by the authors for the formation of gases such as H_2 , O_2 , SO_2 , CO_2 and CO and G -values for the formation of sulfate and sulfide ions found in aqueous extracts of irradiated resins. Other forms of G -values reported are for the formation of basic products such as ammonia and p-, S- and/or t-amine. An attempt has been made to identify these different forms of reported G -values in the tabulated data.

III.9 Other Parameters Measured

Because of the limitations of space, this tabulation could not include all the experimental data from original papers. Therefore a summary of various other parameters studied during the experimental investigations are indicated by letter symbols. It should be added that these notations do not necessarily

mean that the original work provided quantitative data on these various parameters. Often, they are qualitative discussions and sometimes pure speculations. The letter designations used in this column of Tables III and IV refers to:

- a. weight change
- b. swelling/shrinkage or volume change
- c. water content
- d. solubility
- e. oxidizability
- f. gas evolution
- g. thermal stability
- h. products of decomposition
- i. formation of ionic species such as SO_4^{--} , H^+ , Cl^- etc.
- j. use of scavenger
- k. exchange capacity measurements other than TEC
- l. attempt to propose mechanism(s)
- m. study of water soluble products, and
- n. microscopic examination of resin beads.

III.10 Reference Number and Notes

The reference numbers indicated are as listed in the reference section of this report. In addition, when it was found necessary, additional notes have been added to further assist the understanding of the tabulated data.

TABLE III
SUMMARY OF EXPERIMENTAL DATA ON THE EFFECT
OF IONIZING RADIATION ON SYNTHETIC CATION EXCHANGERS

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Dowex-50	H ⁺	5.0	γ-radiation (⁶⁰ Co) (0.25-0.6)x10 ⁶	Air-dry	Max. 1.4x10 ⁹	-	2.7-5.3	-	[1] Table 70
Dowex-50	H ⁺	3.55	γ-radiation (⁶⁰ Co) (0.19)x10 ⁶	Air-dry	3.3x10 ⁷	-	10	-	[1] Table 70
Dowex-50	Na ⁺	3.55	γ-radiation (⁶⁰ Co) (0.19)x10 ⁶	Air-dry	3.3x10 ⁷	-	7	-	[1] Table 70
Dowex-50	H ⁺	5.0	γ-radiation (⁶⁰ Co) and ¹⁴⁴ Ce-Pr (0.25 0.6)	Air-dry	Max. 9x10 ⁸	-	1.5-3	-	[1] Table 70
Dowex-50	H ⁺	5.0	x-rays (1.12x10 ⁸)	Air-dry	2.2x10 ⁹	-	3	-	[1] Table 70
Dowex-50Wx12	H ⁺	5.17	γ-radiation (isotonic)	Dry	2.7x10 ⁸	-	1.4	k	[1] Table 70
Dowex-50Wx12	H ⁺	5.17	γ-emitter	Swollen in water	8x10 ⁷	-	1.4	k	[1] Table 77
Dowex-50Wx12	H ⁺	-	γ-emitter	Swollen in water	9x10 ⁷	-	0.6	k	[1] Table 78
Dowex 50x8	H ⁺	4.80	γ-radiation (⁶⁰ Co)	Moist, Flowing Water	0.76x10 ⁹	33.8	1.0	c,k	"
Dowex 50x12	H ⁺	4.85	"	"	0.77x10 ⁹	30.3	1.1	"	"
Dowex 50x16	H ⁺	4.81	"	"	0.75x10 ⁹	27.9	1.2	"	[4][5]
Dowex 50x20	H ⁺	4.59	"	"	0.77x10 ⁹	28.8	1.6	"	"
Dowex 50x8	H ⁺	4.97	"	"	3.9x10 ⁹	62.2	-	"	[4][5]
Dowex 50x8	H ⁺ , Na ⁺ , K ⁺ , NH ₄ ⁺ , Ca ²⁺ , Mg ²⁺ , Mn ²⁺ , Cu ²⁺ , Fe ³⁺ , UO ₂ ²⁺	-	γ-radiation (⁶⁰ Co) (1.3x10 ⁵)	Varying moisture contents and ad- sorbed ions	0 to 1.9x10 ⁸	0-18	-	b,c,i,k,l	[10]
Dowex 50x2	H ⁺	-	γ-radiation (⁶⁰ Co) (1.3x10 ⁵)	In contact with water	3.6x10 ⁷	15.7	-	b,c,i,k,l	[10]
Dowex 50x2	H ⁺	-	"	"	"	17.1	-	"	"
Dowex 50x4	H ⁺	-	"	"	"	6.0	-	"	"
Dowex 50x4	H ⁺	-	"	"	"	6.5	-	"	"
Dowex 50x8	H ⁺	5.0	"	"	"	4.0	-	"	"
Dowex 50x8	H ⁺	5.0	"	"	"	4.2	-	"	"
Dowex 50x8	H ⁺	-	γ-radiation (⁶⁰ Co) (1.3x10 ⁵)	Moist (in distilled water)	6.1x10 ⁷	6.8	-	b,c,i,k,l	[10]
Dowex 50x8	Na ⁺	-	"	"	"	6.7	-	"	"
Dowex 50x8	K ⁺	-	"	"	"	6.8	-	"	"
Dowex 50x8	NH ₄ ⁺	-	"	"	"	6.7	-	"	"
Dowex 50x8	Ca ²⁺	-	"	"	"	6.9	-	"	"
Dowex 50x8	Mg ²⁺	-	"	"	"	7.2	-	"	"
Dowex 50x8	Mn ²⁺	-	"	"	"	7.3	-	"	"
Dowex 50x8	Cu ²⁺	-	"	"	"	0.7	-	"	"
Dowex 50x8	Fe ³⁺	-	"	"	"	0.6	-	"	"
Dowex 50x8	UO ₂ ²⁺	-	"	"	"	0.7	-	"	"
Dowex 50x8	H ⁺	5.0	-	Unhydrous resin and varying moisture con- tent (1-305 H ₂ O/ meq. resin)	3.6x10 ⁷	1.5 to 4.2	-	b,c,i,k,l	[10]
Dowex 50	Na ⁺	3.55	γ-radiation (⁶⁰ Co) (2x10 ⁵)	Dry resin (Dried Ar 60°C)	2x10 ⁵	-0.5	-	i,k	[12]
Dowex 50	Na ⁺	3.55	"	"	3x10 ⁶	2.3	-	"	"
Dowex 50	Na ⁺	3.55	"	"	4x10 ⁶	1.7	-	"	"
Dowex 50	Na ⁺	3.55	"	"	3.54x10 ⁷	6.5	-	"	"
Dowex 50	H ⁺	3.55	γ-radiation (⁶⁰ Co) (2x10 ⁵)	Dry resin	0.02 to 3.5x10 ⁷	-3.1 to 10.4	-	i,k	[12]

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Dowex 50Wx12	H ⁺	5.17	γ-radiation (Mixed fission products from spent reactor fuels) (3x10 ⁵)	Immersed in water (44.4% water)	0.88x10 ⁸	1.5	-	a,b,c,h,i, k,m	[22]
Dowex 50Wx2	H ⁺	5.17	"	Dry (44.6% water) (Dried at 110°C)	0.76x10 ⁸	3.3	-	"	"
Dowex 50Wx12	H ⁺	5.17	"	Dry (48% water)	1.10x10 ⁸	-0.3	-	"	"
Dowex 50Wx12	H ⁺	5.17	"	Dry (55.9% water)	2.67x10 ⁸	-0.3	-	"	"
Dowex 50Wx4	H ⁺	5.35	γ-radiation (⁶⁰ Co) (1.25x10 ⁶)	Air-dried (67.9% water)	0.88x10 ⁸	5.4	-	a,b,c,f,i, k,n	[23]
"	"	"	"	" (68% ")	1.17x10 ⁸	10.8	-	"	"
"	"	"	"	" (68.4% ")	2.93x10 ⁸	21.1	-	"	"
"	"	"	"	" (68.0% ")	3.59x10 ⁸	24.1	-	"	"
"	"	"	"	" (66.3% ")	5.12x10 ⁸	29.5	-	"	"
"	"	"	"	" (61.8% ")	7.15x10 ⁸	37.7	-	"	"
Dowex 50Wx4	H ⁺	5.35	γ-radiation (⁶⁰ Co) (1.25x10 ⁶)	In 0.1N HCl (68.6% water)	1.17x10 ⁸	9.4	-	a,b,c,f,i, k,n	[23]
"	"	"	"	" (69.6% ")	1.77x10 ⁸	12.5	-	"	"
"	"	"	"	" (70.3% ")	2.11x10 ⁸	16.6	-	"	"
"	"	"	"	" (69.4% ")	3.00x10 ⁸	21.9	-	"	"
"	"	"	"	" (69.6% ")	3.59x10 ⁸	25.2	-	"	"
"	"	"	"	" (67.9% ")	5.12x10 ⁸	30.5	-	"	"
Dowex 50Wx4	Na ⁺	5.35	γ-radiation (⁶⁰ Co) (1.25x10 ⁶)	Air-dried State (69.4% water)	1.77x10 ⁸	12.2	-	a,b,c,f,i, k,n	[23]
"	"	"	"	" (68.3% ")	3.85x10 ⁸	21.5	-	"	"
"	"	"	"	" (65.5% ")	6.32x10 ⁸	27.5	-	"	"
Dowex 50Wx4	Na ⁺	5.35	γ-radiation (⁶⁰ Co) (1.25x10 ⁶)	In 0.1N HCl (70.2% water)	1.77x10 ⁸	14.0	-	a,b,c,f,i, k,n	[23]
"	"	"	"	" (69.4% ")	3.85x10 ⁸	21.9	-	"	"
"	"	"	"	" (71.3% ")	6.32x10 ⁸	26.9	-	"	"
Dowex 50Wx4	"	"	α-radiation (²⁴¹ Am adsorbed on the resin) (3.85x10 ⁵)	In 0.1N HCl (69.5% water)	1.29x10 ⁸	27.1	-	b,c,k,m	[25][27]
"	"	"	"	" (76.3% ")	1.94x10 ⁸	33.8	-	"	"
"	"	"	"	" (92.0% ")	3.79x10 ⁸	81.3	-	"	Resin loaded to 10% capacity during these irradiations
"	"	"	"	" (93.5% ")	4.34x10 ⁸	84.4	-	"	"
"	"	"	"	" (94.8% ")	4.80x10 ⁸	88.8	-	"	"
"	"	"	"	" (94.6% ")	5.45x10 ⁸	88.0	-	"	"
"	"	"	"	" (92.5% ")	6.47x10 ⁸	83.0	-	"	"
Dowex 50Wx4	H ⁺	5.35	α-radiation (²⁴¹ Am adsorbed on the resin) (3.65x10 ⁶)	In 0.1N HCl (63.4% water)	0.88x10 ⁸	28.8	-	b,c,k,m	[25][27]
"	"	"	"	" (61.3% ")	1.76x10 ⁸	-6.4	-	"	"
"	"	"	"	" (69.9% ")	2.63x10 ⁸	18.7	-	"	Resin loaded to 100% capacity during these irradiations
"	"	"	"	" (69.7% ")	4.25x10 ⁸	15.1	-	"	"
"	"	"	"	" (58.6% ")	5.27x10 ⁸	-4.2	-	"	"
"	"	"	"	" (71.9% ")	6.18x10 ⁸	22.3	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Dowex 50Wx10	H ⁺	5.25	γ-radiation (⁶⁰ Co)	Vacuum-dried resin mixed with tritiated water (12.6% water)	(57 to 250)x10 ⁶	-	(Org. ³ H) 2.7x10 ⁻⁵	b,f,k,l	[33] G value of organically bound tritium measured
"	"	"	"	" (24.2% water)	(58 to 255)x10 ⁶	-	(Org. ³ H) 2.9x10 ⁻⁵	"	"
"	"	"	"	" (40.4% water)	(58 to 255)x10 ⁶	-	(Org. ³ H) 2.9x10 ⁻⁵	"	"
"	"	"	"	" (46.7% water)	(59 to 256)x10 ⁶	-	(Org. ³ H) 3.4x10 ⁻⁵	"	"
Dowex 50Wx10	H ⁺	5.25	γ-radiation (⁶⁰ Co)	Swollen resin vacuum dried (12.6% water)	(57 to 170)x10 ⁶	-	(H ₂) 3.9x10 ⁻²	b,f,k,l	[33]
"	"	"	"	"	"	-	(CO ₂) 3.4x10 ⁻²	"	"
"	"	"	"	"	"	-	(CO) 2.4x10 ⁻²	"	"
"	"	"	"	"	"	-	(SO ₂) 0.06-0.22	"	"
"	"	"	"	"	"	-	(H ₂ SO ₄) 0.67-0.72	"	"
Dowex 50Wx10	H ⁺	5.25	γ-radiation (⁶⁰ Co)	Swollen resin vacuum dried (24.2% water)	(58 to 171)x10 ⁶	-	(H ₂) 5.9x10 ⁻²	b,f,k,l	[33]
"	"	"	"	"	"	-	(CO ₂) 2.0x10 ⁻²	"	"
"	"	"	"	"	"	-	(CO) 2.9x10 ⁻²	"	"
"	"	"	"	"	"	-	(H ₂ SO ₄) 1.32	"	"
Dowex 50Wx10	H ⁺	5.25	γ-radiation (⁶⁰ Co)	Swollen resin vacuum dried (40.4% water)	(58 to 174)x10 ⁶	-	(H ₂) 8.2x10 ⁻²	b,f,k,l	[33]
"	"	"	"	"	"	-	(CO ₂) 1.5x10 ⁻²	"	"
"	"	"	"	"	"	-	(CO) 1.8x10 ⁻²	"	"
"	"	"	"	"	"	-	(H ₂ SO ₄) 1.27	"	"
Dowex 50Wx10	H ⁺	5.25	γ-radiation (⁶⁰ Co)	Swollen resin vacuum dried (46.7% water)	(59 to 175)x10 ⁶	-	(H ₂) 1.2x10 ⁻¹	b,f,k,l	[33]
"	"	"	"	"	"	-	(CO ₂) 2.2x10 ⁻²	"	"
"	"	"	"	"	"	-	(CO ₂) 1.5x10 ⁻²	"	"
"	"	"	"	"	"	-	(H ₂ SO ₄) 1.21	"	"
Dowex 50x12	H ⁺ /Na ⁺	4.40	X-ray machine (~10 ⁶)	Air-dry	~1.10 ⁹	22.6	-	a,d,g,i,k	[37]
Dowex 50x8	H ⁺	5.03	⁶⁰ Co γ-radiations (2.9x10 ⁵)	Moist	9.1x10 ⁷	7.7	-	a,b,c,k	[46]
"	H ⁺	5.03	"	"	9.2x10 ⁷	7.5	-	"	"
"	H ⁺	5.03	"	"	1.82x10 ⁸	11.5	-	"	"
"	H ⁺	5.03	"	"	1.90x10 ⁸	11.9	-	"	"
Dowex 50x8	H ⁺	5.03	"	Dry in the absence of oxygen	8.8x10 ⁷	4.6	-	a,b,c,k	[46]
"	H ⁺	5.03	"	"	8.9x10 ⁷	4.6	-	"	"
"	H ⁺	5.03	"	"	1.73x10 ⁸	5.7	-	"	"
"	H ⁺	5.03	"	"	1.75x10 ⁸	6.2	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Dowex 50Wx10	H ⁺	5.25	⁶⁰ Co γ-radiations (2.5x10 ⁵)	Dry	(0.5 to 2.0)x10 ⁸	-	(H ₂) 0.026	c, f, h, k	[47]
"	"	"	"	"	"	-	(CO ₂) .035	"	"
"	"	"	"	"	"	-	(CO) 0.009	"	"
"	"	"	"	"	"	-	(SO ₂) 0.87	"	G(SO ₂ is the initial G value for lowest dose
Dowex 50Wx10	Li ⁺	5.25	"	Dry	"	-	(H ₂) 0.001	"	"
"	"	"	"	"	"	-	(CO ₂) 0.007	"	"
"	"	"	"	"	"	-	(CO) 0.002	"	"
"	"	"	"	"	"	-	(SO ₂) 0.26	"	"
Dowex 50Wx10	H ⁺	5.25	"	6 moles of H ₂ O/eq. of resin	"	-	(H ₂) 0.095	"	"
"	"	"	"	"	"	-	(CO ₂) 0.019	"	"
"	"	"	"	"	"	-	(CO) 0.027	"	"
"	"	"	"	"	"	-	(SO ₂) 0.006	"	"
Dowex 50Wx10	Li ⁺	5.25	"	5.1 moles of H ₂ O/eq. of resin	"	-	(H ₂) 0.11	"	"
"	"	"	"	"	"	-	(CO ₂) 0.008	"	"
"	"	"	"	"	"	-	(CO) 0.019	"	"
"	"	"	"	"	"	-	(SO ₂) 0.50	"	"
Dowex 50Wx10	H ⁺	5.25	"	41 moles of H ₂ O/eq. of resin	"	-	(H ₂) 1.7	"	"
							(CO ₂) 0.41	"	"
Dowex 50Wx10	Li	5.25	"	24 moles of H ₂ O/eq. of resin	"	-	(H ₂) 1.3	"	"
							(CO ₂) 0.16	"	"
Dowex 50x4	H ⁺	5.0	⁶⁰ Co γ-radiations (2.5x10 ⁵)	Wet	9.1x10 ⁷	5.0	-	a, b, c, k	[46]
"	H ⁺	5.0	"	"	1.82x10 ⁸	10.0	-	"	"
Dowex 50x4	H ⁺	5.0	"	Dry	8.5x10 ⁷	2.4	-	"	"
"	H ⁺	5.0	"	"	1.66x10 ⁸	4.6	-	"	"
Amberlite IR-120	H ⁺	5.0	¹⁸² Ta and ⁶⁰ Co radiations	Air-dry	1.9x10 ⁸	-	1.6	-	[1] Table 70
Amberlite IR-120	H ⁺	5.0	X-rays (1.12x10 ⁸)	Air-dry	2.2x10 ⁹	-	1.2	-	[1] Table 70
Amberlite IR-120	H ⁺	5.0	¹⁸² Ta and ⁶⁰ Co radiations	Moist	1.9x10 ⁸	-	1.6	k	[1] Table 77
Amberlite IR-120	H ⁺	4.5	β and γ-radiations (activation and fis- sion products) (1.4x10 ⁷)	Moist (on-line use in D ₂ O moderator cleanup system)	up to 1.5x10 ⁸	~0.5 to 40	-	k, m	[13] [15]
Amberlite IR-112	H ⁺	5.0	¹⁸² Ta and ⁶⁰ Co radiations	Air-dry	1.9x10 ⁸	-	1.6	-	[1] Table 70
Amberlite IR-112	H ⁺	5.0	"	Moist	1.9x10 ⁸	-	1.6	-	[1] Table 77
Amberlite IR-105	H ⁺	2.7	"	Air-dry	9x10 ⁸	-	0.07	-	[1] Table 70
Amberlite IRC-50	H ⁺	10.0	X-ray unit (1.12x10 ⁸)	Air-dry	2.2x10 ⁹	-	2.7	-	[1] Table 70
Amberlite 200	H ⁺	5.00	"	Moist, flowing water	0.97x10 ⁹	34.0	1.2	c, k	[4] [5]

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Amberlite IR-120	-	4.97	^{182}Ta γ -radiation (4 to 4.2×10^5)	Dried at 60°C for 48 hrs	1.68×10^6	-3.2	-	c,h,i,k	[34][35][36]
Amberlite IR-120	-	4.97	"	"	1.72×10^7	8.0	-	"	"
Amberlite IR-120	-	4.97	"	Wet (filtered)	2.13×10^6	3.0	-	"	"
Amberlite IR-120	-	4.97	"	"	1.73×10^7	7.4	-	"	"
Amberlite IR-120	H^+/Na^+	4.15	X-ray machine	Air-dry	$\sim 1 \times 10^9$	9.4	-	s,d,g,i,k	[37]
Amberlite IR-112	-	5.19	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Dry	1.68×10^6	2.9	-	c,h,i,k	[34][35][36]
"	-	5.19	"	"	1.72×10^7	5.5	-	"	"
"	-	5.19	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	-2.1	-	"	"
Amberlite IR-112	-	5.19	^{182}Ta γ -radiation (4.0 to 4.2×10^5)	Wet (filtered)	2.13×10^6	1.3	-	"	"
"	-	5.19	"	"	1.73×10^7	0.8	-	"	"
Amberlite IR-112	-	5.19	^{60}Co γ -radiations (4.2×10^5)	"	1.83×10^8	-7.5	-	"	"
Amberlite IR-100	-	5.38	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Dry	1.68×10^6	2.8	-	c,h,i,k	[34][35][36]
"	-	5.38	"	"	1.72×10^7	0.6	-	"	"
"	-	5.38	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	12.3	-	"	"
Amberlite IR-100	-	5.38	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Wet (filtered)	2.13×10^6	2.4	-	"	"
"	-	5.38	"	"	1.73×10^7	1.7	-	"	"
"	-	5.38	^{60}Co γ -radiations (4.2×10^5)	"	1.83×10^8	15.8	-	"	"
Amberlite XE-111	-	6.03	^{182}Ta γ -radiations (4.0- 4.2×10^5)	Dry	1.68×10^6	-4.0	-	c,h,i,k	[34][35][36]
"	-	6.03	"	"	1.72×10^7	-1.2	-	"	"
"	-	6.03	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	-9.5	-	"	"
Amberlite XE-111	-	6.03	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Wet (filtered)	2.13×10^6	1.3	-	c,h,i,k	[34][35][36]
"	-	6.03	"	"	1.73×10^7	1.0	-	"	"
"	-	6.03	^{60}Co γ -radiations (4.2×10^5)	"	1.70×10^8	-11.1	-	"	"
Amberlite IRC-50	-	10.7	^{182}Ta γ -radiations (4 to 4.2×10^5)	Dry	1.68×10^6	2.8	-	c,h,i,k	[34][35][36]
"	-	10.7	"	"	1.72×10^7	1.7	-	"	"
"	-	10.7	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	8.9	-	"	"
"	-	10.7	^{182}Ta γ -radiations (4 to 4.2×10^5)	Wet (filtered)	2.13×10^6	4.2	-	"	"
"	-	10.7	"	"	1.73×10^7	0.9	-	"	"
"	-	10.7	(4.2×10^5)	"	1.83×10^8	5.6	-	"	"
Amberlite XE-89	-	12.1	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Dry	1.68×10^6	0	-	c,h,i,k	[34][35][36]
"	-	12.1	"	"	1.72×10^7	0.8	-	"	"
"	-	12.1	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	0	-	"	"
"	-	12.1	^{182}Ta γ -radiations (4.0 to 4.2×10^5)	Wet (filtered)	2.13×10^6	1.6	-	"	"
"	-	12.1	"	"	1.73×10^7	0.8	-	"	"
"	-	12.1	"	"	1.83×10^8	2.4	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Amberlite IRC-50	H ⁺	9.76	x-ray machine (~10 ⁵)	Air-dry	~1x10 ⁸	39	-	a,d,g,i,k	[37]
"	H ⁺	9.76	"	"	~2x10 ⁸	62	-	"	"
"	H ⁺	9.76	"	"	~4x10 ⁸	81	-	"	"
"	H ⁺	9.76	"	"	~7.6x10 ⁸	95	-	"	"
"	H ⁺	9.76	"	"	~1.5x10 ⁹	100	-	"	"
IMAC C-12x8	H ⁺	5.0	Reactor irradiation (2.6x10 ⁶)	Air-dry	2.0x10 ⁹	-	0.7	-	[1] Table 70
IMAC C-12x2	H ⁺	5.0	Reactor (2.6x10 ⁶)	Air-dry	2.0x10 ⁹	-	1	-	[1] Table 70
IMAC C-12	H ⁺	5.31	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Resin immersed in water	2x10 ⁷	1.9	2.5 (for highly acidic groups)	e,h,i,k,l, m	[21]
"	"	"	"	"	4x10 ⁷	1.9	-	"	"
"	"	"	"	"	7x10 ⁷	5.6	-	"	"
"	"	"	"	"	1x10 ⁸	5.5	-	"	"
"	"	"	"	"	1.5x10 ⁸	6.6	-	"	"
"	"	"	"	"	2.0x10 ⁸	5.3	-	"	"
"	"	"	"	"	3.0x10 ⁸	9.6	-	"	"
"	"	"	"	"	4.0x10 ⁸	12.6	-	"	"
"	"	"	"	"	5.0x10 ⁸	14.5	-	"	"
"	"	"	"	"	7.0x10 ⁸	19.2	-	"	"
"	"	"	"	"	1.7x10 ⁹	35.2	-	"	"
"	"	"	"	"	2.0x10 ⁹	37.2	-	"	"
"	"	"	"	"	3x10 ⁹	40.9	-	"	"
"	"	"	"	"	5x10 ⁹	51.4	-	"	"
Zeolex SA	H ⁺	3.48	⁶⁰ Co radiations (0.19x10 ⁶)	Air-dry	3.2x10 ⁷	-	5	-	[1] Table 70
Zoelex SA	H ⁺	3.48	γ-radiation (2x10 ⁵)	Dry resin	0.02 to 3.5x10 ⁷	0 to 4.9	-	i,k	[12]
Zeorex	H ⁺	1.96	⁶⁰ Co radiations (1.87x10 ⁵)	Air-dry	3.2x10 ⁷	-	1.5	-	[1] Table 70
Zeorex	H ⁺	1.96	γ-radiation (2x10 ⁵)	Dry resin	0.02 to 3.5x10 ⁷	-5.1 to 2.5	-	i,k	[12]
Dienon SK-1	H ⁺	3.52	⁶⁰ Co radiations (0.19x10 ⁶)	Air-dry	3.2x10 ⁷	-	9	-	[1] Table 70
Diaion SK#1	H ⁺	3.52	γ-radiation (2x10 ⁵)	Dry resin	0.02 to 3.5x10 ⁷	-2.2 to 9.1	-	i,k	[12]
Nalcite HCRx8	H ⁺	5.0	X-ray unit (1.12x10 ⁸)	Air-dry	2.2x10 ⁹	-	1	-	[1] Table 70
Nalcite HCR	H ⁺ /Na ⁺	4.81	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	8.3	-	a,d,g,i,k	[37]
Nalcite HCRx1	H ⁺ /Na ⁺	5.53	X-ray machine (~10 ⁶)	Air-dry	~5x10 ⁸	12.4	-	a,d,g,i,k	[37]
Nalcite HCRx2	"	5.20	"	"	"	11.2	-	"	"
Nalcite HCRx4	"	4.90	"	"	"	7.1	-	"	"
Nalcite HCRx8	"	4.63	"	"	"	2.8	-	"	"
Nalcite HCRx12	"	4.40	"	"	"	2.8	-	"	"
Nalcite HCRx16	"	4.20	"	"	"	4.1	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Permutit O	H ⁺	5.0	X-ray unit	Air-dry	2.2x10 ⁹	-	0.03	-	[1] Table 70
Permutit O	H ⁺ /Na ⁺	4.49	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 1 \times 10^9$	2.0	-	a,d,g,i,k	[37]
Permutit H-70	H ⁺	10.0	X-ray unit (1.12x10 ⁸)	Air-dry	2.2x10 ⁹	-	2.7	-	[1] Table 70
Permutit H-70	H ⁺	10.05	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 2 \times 10^8$	54	-	a,d,g,i,k	[37]
Permutit H-70	H ⁺	10.05	"	"	$\sim 7.6 \times 10^8$	95	-	"	"
Catex S	H ⁺	3.7	⁶⁰ Co radiations (4.6 to 16.2)x10 ⁵	In water	2.10 ⁸	-	4.3	-	[1] Table 77
Ku-2	H ⁺	5.2	⁶⁰ Co radiations	Vacuum	3x10 ⁸	-	0.3	-	[1] Table 70
Ku-2	H ⁺	5.2	"	Air-dry	1x10 ⁸	-	1.9	-	"
Ku-2	H ⁺	5.0	Electron Accelerator	Vacuum	3x10 ⁸	-	0.06	-	[1] Table 70
Ku-2	H ⁺	5.0	"	"	3x10 ⁸	-	0.5	-	"
Ku-2	H ⁺	5.0	"	Air-dry	2x10 ⁹	-	0.04	-	"
Ku-2	H ⁺	5.0	Reactor	Air-dry	10 ¹¹	-	0.006	-	"
Ku-2	H ⁺	5.0	Reactor	Air-dry	10 ¹¹	-	0.005	-	"
Ku-2x8	H ⁺	5.0	⁶⁰ Co radiations	Absolutely dry (2.63 to 6.55)x10 ⁵	10 ⁸	-	0.5	-	[1] Table 70
Ku-2x8	H ⁺	4.9	Electron Accelerator (6.34x10 ⁸)	Air-dry	5x10 ⁹	-	1.0	-	[1] Table 70
Ku-2x8	H ⁺	4.8	Electron Accelerator (1.27x10 ⁹)	Air-dry	11x10 ¹⁰	-	1.0	-	"
Ku-2x2	H ⁺	5.0	Electron Accelerator (4.9x10 ⁸)	In distilled water	3.4x10 ⁹	-	3.5	-	[1] Table 77
Ku-2x12	H ⁺	4.75	"	"	3.4x10 ⁹	-	1.8	-	"
Ku-2	Cr ³⁺ , Fe ³⁺ , Cu ²⁺ , H ₂ O ₂	5.0	"	"	1.1x10 ⁹	-	0.75	-	"
Ku-2	H ⁺	5.0	"	"	1.1x10 ⁹	-	1.7	-	"
Ku-2	Ce ³⁺ , Ni ²⁺ , Mn ²⁺	5.0	"	"	1.1x10 ⁹	-	2.3	-	"
Ku-2	Na ⁺ , Co ²⁺ , Ca ²⁺ , La ³⁺ , Th ⁴⁺	5.0	Electron Accelerator (4.9x10 ⁸)	In distilled water	1.1x10 ⁹	-	1.6	k	[1] Table 77
Ku-2	NH ₄ ⁺	5.0	"	"	1.1x10 ⁹	-	1.5	k	"
Ku-2	Al ³⁺	5.0	"	"	1.1x10 ⁹	-	1.8	k	"
Ku-2x2	H ⁺	3.38	⁶⁰ Co radiations (2.63 to 6.55)x10 ⁵	In water	5.5x10 ⁸	-	2.5	-	[1] Table 77
Ku-2x8	H ⁺	3.38	"	"	5.5x10 ⁸	-	1.6	-	"
Ku-2x24	H ⁺	3.38	"	"	5.5x10 ⁸	-	1.4	-	"
Ku-2x8	Li ⁺ , NH ₄ ⁺ , Cs ⁺	3.38	⁶⁰ Co radiations (2.63 to 6.55)x10 ⁵	In water	9.3x10 ⁷	-	1.8	k	[1] Table 77
Ku-2x8	K ⁺ , Rb ⁺	3.38	"	"	9.3x10 ⁷	-	1.7	k	"
Ku-2x8	Na ⁺	3.38	"	"	9.3x10 ⁷	-	1.4	k	"
Ku-2x8	Mn ²⁺	3.38	"	"	2.7x10 ⁸	-	1.7	k	"
Ku-2x8	Ca ²⁺ , Sr ²⁺	3.38	"	"	2.7x10 ⁸	-	1.5	k	"
Ku-2x8	Ba ²⁺	3.38	"	"	2.7x10 ⁸	-	1.5	k	"
Ku-2x8	Co ²⁺	3.38	"	"	3.8x10 ⁸	-	1.2	k	"
Ku-2x8	Cu ²⁺	3.38	"	"	3.8x10 ⁸	-	0.2	k	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-2x8	Fe ³⁺ (~100%)	3.38	⁶⁰ Co radiations (2.63 to 6.55)x10 ⁵	In water	3.8x10 ⁸	-	0.05	k	[1] Table 77
Ku-2x8	Fe ³⁺ (~20%)	3.38	"	"	3.8x10 ⁸	-	0.63	k	"
Ku-2x8	Fe ³⁺ (~2%)	3.38	"	"	3.8x10 ⁸	-	2.8	k	"
Ku-2x8	H ⁺	5.0	"	Swollen in water	3.0x10 ⁸	-	2.8	k	[1] Table 77
Ku-2x8	H ⁺	5.0	"	Swollen (60% water)	10 ⁸	-	1.7	k	"
Ku-2x8	H ⁺	5.0	"	In water	3x10 ⁸	-	2.1	k	[1] Table 77
Ku-2x2	H ⁺	5.0	"	"	1.5x10 ⁸	-	3.0	-	"
Ku-2x24	H ⁺	5.0	"	"	1.5x10 ⁸	-	1.7	-	"
Ku-2x24	H ⁺	5.0	"	"	4.2x10 ⁷	-	1.4	-	[1] Table 77
Ku-2x8	H ⁺	5.0	"	"	1.2x10 ⁸	-	3.8	-	"
Ku-2x8	H ⁺	4.9	Electron accelerator (5.76x10 ⁸)	In water containing 0.25M CH ₃ COOH, COOH, 0.5M HNO ₃ and 0.5M CH ₃ COOH	2.3x10 ⁹	-	2.0	k	[1] Table 77
Ku-2x8	H ⁺	-	⁶⁰ Co radiations (2.63 to 6.55)x10 ⁵	In water	3x10 ⁸	-	0.5	-	[1] Table 78
Ku-2x2(4,8,12, 16)	H ⁺	-	Electron accelerator (5.04x10 ⁸)	In distilled water	1.8x10 ⁹	-	0.7	-	[1] Table 78
Ku-2	UO ₂ ²⁺ , Cu ²⁺ , Cr ³⁺ , Fe ³⁺	-	"	"	10 ⁹	-	0.9	-	"
Ku-2	UO ₂ ²⁺ , Cu ²⁺ , Ce ³⁺ , Cr ³⁺ , Fe ³⁺ , Th	-	"	"	1.1x10 ⁹	-	0.4	k	"
Ku-2	Ni ²⁺ , Mn ²⁺ , Al ³⁺ , La ³⁺	-	"	"	1.1x10 ⁹	-	0.3	k	"
Ku-2	Na ⁺ , NH ₄ ⁺	-	"	"	1.1x10 ⁹	-	0.2	k	"
Ku-2	H ⁺	-	"	In 0.54N HNO ₃	1.8x10 ⁹	-	1.3	k	"
Ku-2	H ⁺	-	"	In 0.5N CH ₃ COOH	2.3x10 ⁹	-	0.6	-	"
Ku-2x8	H ⁺ , Zn ²⁺	2.7	8, γ-radiations (Ad- sorbed ¹⁴⁴ Ce, ¹⁴⁷ Pm and/or ²² Na)	Processing, displace- ment chromatography	6x10 ⁸ 1x10 ⁹	26.0 48.0	-	a,b,k	[6]
Ku-2x8	H ⁺	2.7	8, γ-radiations (ad- sorbed radioisotopes of ¹⁴⁴ Ce, ¹⁵⁴ Eu and ¹⁵⁵ Eu)	Processing, displace- ment chromatography	6.0x10 ⁸ 1.0x10 ⁹	20.0 48.0	-	b,k	[8]
Ku-2	H ⁺	4.72	⁶⁰ Co γ-radiation (4.2x10 ⁶)	In presence of at- mospheric oxygen	2x10 ⁸	3.2	-	a,b,c,h,i, k,l	[38]
Ku-2	H ⁺	4.72	"	In vacuum	2x10 ⁸	3.2	-	"	"
Ku-2	H ⁺	4.72	"	In presence of oxygen	4x10 ⁸	6.1	-	"	"
Ku-2	H ⁺	4.72	"	In vacuum	6x10 ⁸	21.0	-	"	"
Ku-2	Fe ³⁺	4.72	"	"	6x10 ⁸	10.8	-	"	"
Ku-2	Cu ²⁺	4.72	"	"	6x10 ⁸	8.7	-	"	"
Ku-2	Ce ⁴⁺	4.72	"	"	6x10 ⁸	11.4	-	"	"
Ku-2	H ⁺	4.72	"	"	1x10 ⁹	18.3	-	"	"
Ku-2	Fe ³⁺	4.72	"	"	1x10 ⁹	8.1	-	"	"
Ku-2	Cu ²⁺	4.72	"	"	1x10 ⁹	9.7	-	"	"
Ku-2	H ⁺	4.72	"	In presence of oxygen	1x10 ⁹	16.3	-	"	"
Ku-2	Na ⁺	4.72	Accelerated electrons	In presence of oxygen	2.1x10 ⁹	0.4	-	a,b,c,h,i, k,l	[88]
Ku-2	H ⁺	4.72	⁶⁰ Co γ-radiation	In vacuum	2.1x10 ⁹	21.0	-	a,b,c,h,i, k,l	[38]

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-2	Fe ³⁺	4.72	"	"	2.1x10 ⁹	6.4	-	"	"
Ku-2	Cu ²⁺	4.72	"	"	2.1x10 ⁹	8.5	-	"	"
Ku-2	Ce ⁴⁺	4.72	"	"	2.1x10 ⁹	17.2	-	"	"
Ku-2	H ⁺	4.72	"	"	1x10 ⁸	2.4	-	"	"
Ku-2	H ⁺	5.0	⁶⁰ Co γ-radiation (1.44x10 ⁶)	Immersed in water	2x10 ⁸	11.0	-	a,c,d,e,i, k,l	[40]
Ku-2	H ⁺	5.0	"	"	3x10 ⁸	21.7	-	"	"
Ku-2	H ⁺	5.0	"	"	5x10 ⁸	32.4	-	"	"
Ku-2	H ⁺	5.0	"	"	1x10 ⁹	44.2	-	"	"
Ku-2x8	Li ⁺	4.71	⁶⁰ Co γ-radiation	Air-dry	10 ⁸	8.9	-	b,f,h,k,l	[42]
Ku-2x8	Li ⁺	4.39	"	Swollen in water	10 ⁸	4.8	-	"	"
Ku-2x8	Na ⁺	4.39	"	Air-dry	10 ⁸	7.1	-	"	"
Ku-2x8	K ⁺	4.09	"	Swollen in water	10 ⁸	6.1	-	"	"
Ku-2x16	Na ⁺	4.26	"	Air-dry	10 ⁸	9.6	-	"	"
Ku-2x16	K ⁺	3.99	"	Air-dry	10 ⁸	10.5	-	"	"
Ku-2x4	-	10.0	γ-radiations (8.64x10 ⁶)	In water	2.0x10 ⁸	30.6	-	a,h,i,k,l	[43]
Ku-2x4	-	10.0	"	"	4.3x10 ⁸	46.0	-	"	"
Ku-2x4	-	10.0	"	"	5.9x10 ⁸	53.2	-	"	"
Ku-2x4	-	10.0	"	"	1.11x10 ⁹	64.7	-	"	"
Ku-2x4	-	10.0	"	"	1.48x10 ⁹	77.9	-	"	"
Ku-2x4	-	10.0	"	"	2.91x10 ⁹	84.9	-	"	"
Ku-2x4	-	10.0	"	"	4.02x10 ⁹	88.5	-	"	"
Ku-2x8	-	8.0	γ-radiation (8.46x10 ⁶)	In water	2.0x10 ⁸	22.4	-	a,h,i,k,l	[43]
Ku-2x8	-	8.0	"	"	4.3x10 ⁸	33.6	-	"	"
Ku-2x8	-	8.0	"	"	5.9x10 ⁸	42.6	-	"	"
Ku-2x8	-	8.0	"	"	1.11x10 ⁹	55.9	-	"	"
Ku-2x8	-	8.0	"	"	1.48x10 ⁹	62.2	-	"	"
Ku-2x8	-	8.0	"	"	2.91x10 ⁹	76.2	-	"	"
Ku-2x8	-	8.0	"	"	4.02x10 ⁹	83.1	-	"	"
Ku-2x12	-	7.5	γ-radiation (8.46x10 ⁶)	In water	2.1x10 ⁸	20.9	-	a,h,i,k,l	[43]
Ku-2x12	-	7.5	"	"	4.5x10 ⁸	35.7	-	"	"
Ku-2x12	-	7.5	"	"	6.3x10 ⁸	42.1	-	"	"
Ku-2x12	-	7.5	"	"	1.05x10 ⁹	53.6	-	"	"
Ku-2x12	-	7.5	"	"	1.48x10 ⁹	62.3	-	"	"
Ku-2x12	-	7.5	"	"	2.91x10 ⁹	77.6	-	"	"
Ku-2x12	-	7.5	"	"	4.02x10 ⁹	80.8	-	"	"
Ku-2x16	-	7.0	γ-radiation (8.46x10 ⁶)	In water	2.0x10 ⁸	18.9	-	a,h,i,k,l	[43]
Ku-2x16	-	7.0	"	"	4.3x10 ⁸	30.8	-	"	"
Ku-2x16	-	7.0	"	"	6.3x10 ⁸	33.9	-	"	"
Ku-2x16	-	7.0	"	"	1.11x10 ⁹	50.4	-	"	"
Ku-2x16	-	7.0	"	"	1.48x10 ⁹	56.0	-	"	"
Ku-2x16	-	7.0	"	"	2.91x10 ⁹	71.8	-	"	"
Ku-2x16	-	7.0	"	"	4.02x10 ⁹	76.6	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-2x24	-	6.1	γ -radiation (8.46x10 ⁶)	In water	2.0x10 ⁸	17.7	-	a, h, i, k, l	[43]
Ku-2x24	-	6.1	"	"	4.3x10 ⁸	29.4	-	"	"
Ku-2x24	-	6.1	"	"	5.9x10 ⁸	36.0	-	"	"
Ku-2x24	-	6.1	"	"	1.11x10 ⁹	51.3	-	"	"
Ku-2x24	-	6.1	"	"	1.48x10 ⁹	55.4	-	"	"
Ku-2x24	-	6.1	"	"	2.91x10 ⁹	71.0	-	"	"
Ku-2x24	-	6.1	"	"	4.02x10 ⁹	76.2	-	"	"
Ku-3A	H ⁺	4.93	⁶⁰ Co γ -radiation (1.44x10 ⁶)	Immersed in water	2x10 ⁸	13.0	3.08	a, c, d, e, i, k, l	[40]
Ku-3A	H ⁺	4.93	"	"	3x10 ⁸	19.5	"	"	"
Ku-3A	H ⁺	4.93	"	"	5x10 ⁸	30.0	"	"	"
Ku-1	H ⁺	6.15	⁶⁰ Co radiation	Vacuum	3x10 ⁸	-	1.8	k	[1] Table 70
Ku-1	H ⁺	5.6	Electron Accelerator	Vacuum	3x10 ⁸	-	0.1	k	[1] Table 70
Ku-1	H ⁺	5.6	"	"	3x10 ⁸	-	0.4	k	"
Ku-1	H ⁺	5.6	Reactor	Air-dry	10 ¹¹	-	0.004	-	"
Ku-1	H ⁺	5.6	"	"	10 ¹¹	-	0.01	-	"
Ku-1	H ⁺	5.6	"	"	10 ¹¹	-	0.004	k	"
Ku-1	H ⁺	5.6	"	"	10 ¹¹	-	0.01	k	"
Ku-1	H ⁺	4.5	Electron accelerator (4.9x10 ⁸)	In distilled water	1.8x10 ⁹	-	0.2	k	[1] Table 77
Ku-1	Na ⁺ , Fe ³⁺ , Cr ³⁺	4.5	"	"	1.8x10 ⁹	-	0.16	k	"
Ku-1	Cu ²⁺	4.5	"	"	1.8x10 ⁹	-	0.1	k	"
Ku-1	H ⁺	3.9	"	"	3.4x10 ⁹	-	0.9	k	[1] Table 77
Ku-1	Na ⁺	3.9	"	"	1.6x10 ⁹	-	0.8	k	"
Ku-1	Na ⁺	3.9	"	In 0.5M CH ₃ COOH	1.6x10 ⁹	-	0.9	k	"
Ku-1	Na ⁺	-	Electron accelerator (4.9x10 ⁸)	In distilled water	1.7x10 ⁹	-	1.3	k	[1] Table 78
Ku-1	H ⁺	-	"	0.5 N HNO ₃	1.7x10 ⁹	-	1.2	k	"
Ku-1	H ⁺	-	"	In distilled water	3.4x10 ⁹	-	0.2	-	"
Ku-32	H ⁺	3.63	γ -radiation (⁶⁰ Co) (1.8x10 ⁶)	Moist, Swollen	2x10 ⁸	4.2	-	a, b, k	[6]
Ku-33	H ⁺	4.01	"	"	"	9.2	-	"	"
Ku-32	H ⁺	2.82	⁶⁰ Co γ -radiation (1.44x10 ⁶)	Immersed in water	2x10 ⁸	4.2	0.58	a, c, d, e, f, k, l	[40]
Ku-32	H ⁺	2.82	"	"	5x10 ⁸	5.6	"	"	"
Ku-33	H ⁺	3.03	⁶⁰ Co γ -radiation (1.44x10 ⁶)	Immersed in water	2x10 ⁸	9.2	1.35	a, c, d, e, i, k, l	[40]
Ku-33	H ⁺	3.03	"	"	3x10 ⁸	9.2	"	"	"
Ku-33	H ⁺	3.03	"	"	5x10 ⁸	13.0	"	"	"
Ku-33	-	2.3	Accelerated electrons	At pH 4.0	9.6x10 ⁸	-30	(SO ₄ ²⁻) 0.007- 0.09	a, b, i, k, l	[39] G(SO ₄ ²⁻) calculated
Ku-33	-	2.3	"	At pH 4.0	1.9x10 ⁹	-27	-	"	"
Ku-33	-	4.65	"	At pH 8.5	9.6x10 ⁸	-11.0	-	"	"
Ku-33	-	4.65	"	At pH 8.5	1.9x10 ⁹	-19.5	-	"	"
Ku-33	-	7.45	"	At pH 11.0	9.6x10 ⁸	None	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-34	-	2.3	Accelerated electrons	At pH 4.0	1.1×10^9	None	(SO_4^{2-}) 0.05	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated
Ku-34	-	2.3	"	At pH 4.0	2.1×10^9	5.0	-	"	"
Ku-34	-	3.74	"	At pH 8.5	1.1×10^9	-20	-	"	"
Ku-34	-	3.74	"	At pH 8.5	2.1×10^9	-16	-	"	"
Ku-34	-	3.74	"	At pH 11.0	1.1×10^9	-35	-	"	"
Ku-35	H^+	3.33	^{60}Co γ -radiation (1.44×10^6)	Immersed in water	2×10^8	9.3	1.50	a,c,d,e,i, k,l	[40]
Ku-35	H^+	3.33	"	"	3×10^8	7.5	"	"	"
Ku-35	H^+	3.33	"	"	5×10^8	16.5	"	"	"
Ku-35	-	2.3	Accelerated electrons	At pH 4.0	8.0×10^8	-36	(SO_4^{2-}) 0.24 to 0.26	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated
Ku-35	-	2.3	"	At pH 4.0	1.4×10^9	-36	-	"	"
Ku-35	-	3.44	"	At pH 8.5	8.0×10^8	-57	-	"	"
Ku-35	-	3.44	"	At pH 8.5	1.4×10^9	-90	-	"	"
Ku-36	H^+	2.48	^{60}Co γ -radiation (1.44×10^6)	Immersed in water	2×10^8	0.8	0.10	a,c,d,e,i, k,l	[40]
Ku-36	H^+	2.48	"	"	5.36×10^8	6.0	"	"	"
Ku-36	H^+	2.48	"	"	1×10^9	10.2	"	"	"
Ku-36	-	2.34	Accelerated electrons	At pH 4.0	1.1×10^9	2.3	(SO_4^{2-}) 0.06	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated
Ku-36	-	2.34	"	At pH 4.0	1.9×10^9	8.3	-	"	"
Ku-36	-	2.34	"	At pH 8.5	1.1×10^9	9.0	-	"	"
Ku-36	-	2.34	"	At pH 8.5	1.9×10^9	8.6	-	"	"
Ku-37	H^+	3.20	^{60}Co γ -radiations (1.44×10^6)	Immersed in water	2×10^8	10.0	1.55	a,c,d,e,i, k,l	[40]
Ku-37	H^+	3.20	"	"	3.10^8	11.5	"	"	"
Ku-37	-	3.0	Accelerated electrons	At pH 4.0	8.0×10^8	-4.0	(SO_4^{2-}) 0.18 to 0.2	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated
Ku-37	-	3.0	"	At pH 4.0	1.4×10^9	-4.0	-	"	"
Ku-37	-	4.45	"	At pH 8.5	8.0×10^8	-14	-	"	"
Ku-37	-	4.45	"	At pH 8.5	1.4×10^9	-27	-	"	"
Ku-37	-	6.2	"	At pH 11.0	8.0×10^8	-18.4	-	"	"
Ku-38	H^+	3.41	^{60}Co γ -radiation (1.44×10^6)	Immersed in water	2×10^8	None	0.39	a,c,d,e,i, k,l	[40]
Ku-38	H^+	3.41	"	"	5.36×10^8	9.3	"	"	"
Ku-38	H^+	3.41	"	"	1×10^9	10.6	"	"	"
Ku-38	-	3.1	Accelerated electron	At pH 4.0	9.6×10^8	3.5 to 0.12	(SO_4^{2-}) 0.10 to 0.12	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated
Ku-38	-	3.1	"	At pH 4.0	2.1×10^9	3.5	-	"	"
Ku-38	-	5.2	"	At pH 8.5	9.6×10^8	-25.0	-	"	"
Ku-38	-	5.2	"	At pH 8.5	2.1×10^9	-22.5	-	"	"
Ku-38	-	7.0	"	At pH 11.0	9.6×10^9	-20	-	"	"
Ku-40	H^+	3.25	^{60}Co γ -radiation (1.44×10^6)	Immersed in water	2×10^8	1.8	0.29	a,c,d,e,i, k,l	[40]
Ku-40	H^+	3.25	"	"	3×10^8	4.8	"	"	"
Ku-40	H^+	3.25	"	"	5×10^8	5.7	"	"	"
Ku-40	-	3.2	Accelerated electron	At pH 4.0	9.6×10^8	-25.0	(SO_4^{2-}) 0.14 to 0.16	a,b,i,k,l	[39] $G(\text{SO}_4^{2-})$ calculated

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-40	-	3.2	"	At pH 4.0	1.9×10^9	~22.5	-	"	"
Ku-40	-	4.1	"	At pH 8.5	9.6×10^8	~20	-	"	"
Ku-4x30	H ⁺	3.3	B,γ-radiations (Ad- sorbed ^{144}Ce , ^{147}Pm and/or ^{22}Na)	Processing, displace- ment chromatography	4.5×10^8	3.0	-	b,k	[7]
Ku-4x30	H ⁺	3.8	"	"	5.0×10^8 1.5×10^9	12.7 25.6	-	"	"
Ku-4x30	H ⁺	2.8	"	"	5.0×10^8	3.0	-	"	"
Ku-4x30	H ⁺	3.0	"	"	2.0×10^9	21.0	-	"	"
Ku-4x12	H ⁺	3.9	Accelerated electron	In water	4.8×10^8	15	-	a,b,k,l	[41]
Ku-4x12	H ⁺	3.8	"	"	9.6×10^8	17	-	"	"
Ku-4x20	H ⁺	3.4	Accelerated electron	In water	4.8×10^8	27	-	a,b,k,l	[41]
Ku-4x20	H ⁺	3.5	"	"	1.9×10^9	30	-	"	"
Ku-4x30	H ⁺	4.3	Accelerated electron	In Water	4.8×10^8	12.7	-	a,b,k,l	[41]
Ku-4x30	H ⁺	3.8	"	"	1.44×10^9	25.6	-	"	"
Ku-4x40	H ⁺	4.2	Accelerated electron	In water	3.2×10^8	8	-	a,b,k,l	[41]
Ku-4x40	H ⁺	3.9	"	"	4.8×10^8	14	-	"	"
Ku-4x40	H ⁺	3.9	"	"	9.6×10^8	16	-	"	"
Ku-4x40	H ⁺	3.3	"	"	1.9×10^9	35	-	"	"
Ku-4x50	H ⁺	3.9	Accelerated electron	In water	4.8×10^8	8	-	a,b,k,l	[41]
Ku-4x50	H ⁺	3.6	"	"	9.6×10^8	23	-	"	"
Ku-4x50	H ⁺	3.5	"	"	9.6×10^8	33	-	"	"
Ku-4x50	H ⁺	3.3	"	"	1.9×10^9	42	-	"	"
Ku-4x50	H ⁺	3.0	"	"	2.9×10^9	42	-	"	"
Ku-4x60	H ⁺	4.2	Accelerated electron	In Water	4.8×10^8	7.0	-	a,b,k,l	[41]
Ku-4x60	H ⁺	3.9	"	"	9.6×10^8	6.0	-	"	"
Ku-4x60	H ⁺	3.4	"	"	1.9×10^9	33.0	-	"	"
Ku-6	H ⁺ , Zn ²⁺	1.9	B,γ-radiations (Ad- sorbed radionuclides of ^{144}Ce , ^{154}Eu and ^{155}Eu)	Processing, displace- ment chromatography	6.7×10^8 2.0×10^9	0 0	- -	b,k "	"
Ku-160	H ⁺ , Zn ²⁺	2.0	"	"	5.8×10^8 1.7×10^9	0 6.5	- -	b,k "	[8]
Ku-158	-	3.0	Accelerated electrons	At pH 4.0	9.6×10^8	8.0	0.12 to 0.20	a,b,i,k,l	[39] G(SO ₄ ²⁻) calculated
Ku-158	-	3.0	"	At pH 4.0	1.6×10^9	13.0	-	"	"
Ku-158	-	3.0	"	At pH 4.0	2.6×10^9	13.5	-	"	"
Ku-158	-	3.9	Accelerated electrons	At pH 8.5	9.6×10^8	~16.5	-	"	"
Ku-158	-	3.9	"	At pH 8.5	1.6×10^9	~8.0	-	"	"
Ku-158	-	3.9	"	At pH 8.5	2.6×10^9	~33.0	-	"	"
Ku-158	-	4.95	"	At pH 11.0	9.6×10^8	~44.0	-	"	"
Ku-160	-	2.6	Accelerated electron	At pH 4.0	1.1×10^9	5.0	(SO ₄ ²⁻) 0.10 to 0.12	a,b,i,k,l	[39] G(SO ₄ ²⁻) reported
Ku-160	-	2.6	"	At pH 4.0	1.6×10^9	6.5	-	"	"
Ku-160	-	2.6	"	At pH 4.0	2.6×10^9	13.6	-	"	"
Ku-160	-	3.5	"	At pH 8.5	1.1×10^9	~32.0	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Ku-160	-	3.5	"	At pH 8.5	1.6×10^9	-28.0	-	"	"
Ku-160	-	3.5	"	At pH 8.5	2.6×10^9	-33.0	-	"	"
Ku-160	-	5.35	"	At pH 11.0	1.1×10^9	-29	-	"	"
Ku-160	-	5.35	"	At pH 11.0	1.6×10^9	-29	-	"	"
Ku-160	-	5.35	"	At pH 11.0	2.6×10^9	-29	-	"	"
SBS	H ⁺	4.0	Electron Accelerator	Vacuum	3×10^8	-	0.2	k	[1] Table 70
SBS	H ⁺	4.0	"	"	3×10^8	-	0.5	-	"
SBS	H ⁺	4.0	"	Air-dry	2×10^9	-	0.3	k	"
SBS	H ⁺	3.6	Reactor	Air-dry	10^{11}	-	0.004	k	"
SBS	H ⁺	3.6	"	"	10^{11}	-	0.004	k	"
SBS-2	H ⁺	2.7	Electron Accelerator (4.9×10^8)	In distilled water	3.5×10^9	-	0.17	k	[1] Table 77
SBS-2	H ⁺	2.4	"	"	3.5×10^9	-	0.06	k	"
SBS-2	H ⁺	-	Electron Accelerator (5.04×10^8)	In 0.5N CH ₃ COOH	2.2×10^9	-	0.6	k	[1] Table 78
SBS-2	H ⁺	-	"	0.5N CH ₃ COOH, COOH	2.2×10^9	-	0.7	k	"
SBS-2	H ⁺	-	"	In distilled water	3.4×10^9	-	0.8	-	"
Dowex-30	H ⁺	4.0	⁶⁰ Co, ¹⁴⁴ Ce-Pr radi- ations (2.52 to 6.01×10^5)	Air-dry	9×10^8	-	0.1	-	[1] Table 70
Duolite C-3	H ⁺	2.06	⁶⁰ Co radiation (1.87×10^5)	Air-dry	3.2×10^7	-	0.3	-	[1] Table 70
Duolite C-10	H ⁺	6.8	γ-emitter	Dry	1.5×10^8	-	4.0	k	[1] Table 70
Duolite C-10	H ⁺	6.80	γ-radiation (Mixed fission products from spent reactor fuels) (3×10^5)	Dry	1.5×10^8	9.0	-	a,b,c,h,i, k,m	[22]
Duolite CS101	H ⁺	7.85	γ-radiation (2×10^5)	Dry, resin	0.02 to 3.5×10^7	-1.0 to 2.2	-	i,k	[12]
F ₂ S	H ⁺	1.82	X-ray unit (1.69×10^5)	Air-dry	1.9×10^5	-	520	k	[1] Table 70
F ₂ S	H ⁺	1.82	"	Distilled water	1.9×10^5	-	150	k	[1] Table 77
F ₄ S	H ⁺	1.90	⁶⁰ Co radiations (1.69×10^5)	Air-dry	1.9×10^5	-	780	k	[1] Table 70
F ₄ S	H ⁺	1.90	"	Distilled water	1.9×10^5	-	300	k	[1] Table 77
FF ₂ S	H ⁺	3.15	X-ray unit (1.69×10^5)	Air-dry	1.9×10^5	-	1300	k	[1] Table 70
FF ₂ S	H ⁺	2.05	"	"	1.9×10^5	-	360	k	"
FF ₂ S	H ⁺	1.90	"	"	1.9×10^5	-	520	k	"
FF ₂ S	H ⁺	3.15	" (1.2×10^4)	"	1.9×10^5	-	2000	k	"
FF ₂ S	H ⁺	1.90	" (1.2×10^4)	"	1.9×10^5	-	830	k	"
FF ₂ S	H ⁺	1.90	" (1.69×10^5)	"	7.5×10^5	-	340	k	"
FF ₂ S	H ⁺ , Na ⁺	1.90	" (1.2×10^4)	"	1.9×10^5	-	520	k	"
FF ₂ S	H ⁺	1.93	⁶⁰ Co radiations (1.69×10^5)	Air-dry	1.9×10^5	-	1200	k	[1] Table 70
FF ₂ S	H ⁺ , Na ⁺	1.93	"	"	1.9×10^5	-	200	k	"
FF ₂ S	H ⁺	2.05	X-ray unit (1.69×10^5)	Distilled water	1.9×10^5	-	250	k	[1] Table 77

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
FF ₂ S	H ⁺ , Na ⁺	1.90	" (1.2x10 ⁴)	"	1.9x10 ⁵	-	250	k	"
FF ₂ S	H ⁺	1.93	⁶⁰ Co radiations (1.69x10 ⁵)	"	1.9x10 ⁵	-	650	k	[1] Table 77
FF ₂ S	H ⁺ , Na ⁺	1.93	"	"	1.9x10 ⁵	-	150	k	[1] Table 77
FF ₂ S	H ⁺ , Na ⁺	1.93	"	"	1.9x10 ⁵	-	200	k	[1] Table 77
CATEX F-Extra	H ⁺	4.5	⁶⁰ Co radiations (4.68 to 16.2x10 ⁴)	In water	2x10 ⁸	-	0.6	-	[1] Table 77
CATEX FN	H ⁺	3.4	"	"	2x10 ⁸	-	0.8	-	"
CATEX F-Extra	H ⁺	-	⁶⁰ Co radiations (0.47 to 1.62x10 ⁵)	In water	2x10 ⁸	-	1.5	-	[1] Table 78
CATEX FN	H ⁺	-	"	"	2x10 ⁸	-	1.1	-	"
CATEX S	H ⁺	-	"	"	2x10 ⁸	-	2.5	-	"
RF	H ⁺	5.5	Reactor	Air-dry	10 ¹¹	-	0.006	k	[1] Table 70
RF	H ⁺	5.5	"	"	10 ¹¹	-	0.01	k	"
RF	H ⁺	7.2	⁶⁰ Co radiations	Air-dry	10 ⁸	-	3.0	-	"
RF	H ⁺	7.2	"	"	10 ⁸	-	2.0	k	"
RF	H ⁺	2.1	Electron Accelerator (4.9x10 ⁸)	In Distilled water	4.5x10 ⁹	-	0.27	-	[1] Table 77
RF	H ⁺	-	"	"	2.8x10 ⁹	-	0.03	k	[1] Table 78
(RF-2 type) Organophosphorus resin	Na ⁺	4.7	⁶⁰ Co γ-radiations (2.16x10 ⁶)	In distilled water	9x10 ⁷	33.3	-	b,c,h,i,k, l,m	[44] Diallyl phosphate
"	UO ₂ ²⁺	4.0	"	"	"	22.5 to 35.0	-	"	"
"	Na ⁺	0	"	"	"	[changed from 0 to 4.0 meq/ gm.]	-	"	[44] Triallyl phosphate
"	UO ₂ ²⁺	1.95	"	"	"	74.4 to 94.3	-	"	"
(RF-2 type) Organophosphorus resin	Na ⁺	0	⁶⁰ γ-radiations (2.16x10 ⁶)	In distilled water	9x10 ⁷	[changed from 0 to 3.25 meq/gm]	-	b,c,h,i,k l,m	[44] Diallyl methyl phos- phonate
"	UO ₂ ²⁺	2.10	"	"	"	71.4 to 90.5	-	"	"
"	Na ⁺	0	"	"	"	[changed from 0 to 3.40 meq/gm]	-	"	[44] Diallyl butyl phos- phonate
"	UO ₂ ²⁺	3.30	"	"	"	78.8 to 90.9	-	"	"
"	Na ⁺	0	"	"	"	[changed from 0 to 3.30 meq./gm]	-	"	[44] Diallyl isopentyl phonate
"	UO ₂ ²⁺	2.95	"	"	"	76.3 to 89.8	-	"	"
"	Na ⁺	0	"	"	"	[changed from 0 to 3.32 meq./gm]	-	"	[44] Diallyl allyl phos- phonate
"	UO ₂ ²⁺	2.44	"	"	"	59.0 to 64.8	-	"	"
KB-4Px2	H ⁺	10.22	⁶⁰ Co radiations, (2.6 to 6.6)x10 ⁵	In water	6.2x10 ⁷	-	10	-	[1] Table 77
KB-4Px2	H ⁺	10.22	"	"	1.4x10 ⁸	-	28	k	[1] Table 77
KB-4Px2	Na ⁺	10.22	"	"	1.4x10 ⁸	-	60	k	"
KB-4Px2	H ⁺	10.22	"	"	1.4x10 ⁸	-	47	k	"
KB-4Px2	Na ⁺	10.22	"	"	1.4x10 ⁸	-	100	k	"
KB-4x10	H ⁺ , Na ⁺ , K ⁺ , Ba ²⁺ , UO ₂ ²⁺ , Cu ²⁺		γ-radiation, (⁶⁰ Co)	Moist	0.4 to 2.0x10 ⁸	2 to 18	-	a,b,c,k	[9]
KB-4x7.0	-		"	"	"	3 to 24	-	"	"
KB-4x2.5	-		"	"	"	5 to 40	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
KMT	H ⁺	9.98	⁶⁰ Co radiations (2.6 to 6.6x10 ⁵)	In water	6.2x10 ⁷	-	10	k	[1] Table 77
KMT	H ⁺	9.98	"	"	5.8x10 ⁷	-	29	k	"
KMT	H ⁺	9.98	"	"	5.8x10 ⁷	-	26	k	"
KFU	H ⁺	5.69	"	"	6.2x10 ⁷	-	3.4	k	[1] Table 77
KFU	H ⁺	5.69	"	"	1.4x10 ⁸	-	0.4	k	"
KF-1	H ⁺	-	Electron Accelerator (5.0x10 ⁸)	In distilled water	4.5x10 ⁹	-	0.3	-	[1] Table 78
KF-1	H ⁺	-	"	In 0.7N HNO ₃	1.8x10 ⁹	-	0.5	k	"
KF-1	H ⁺	-	"	In 3.0N HNO ₃	2.2x10 ⁹	-	0.7	k	"
KF-1	H ⁺	-	"	In 0.5N CH ₃ .COOH.COOH	2.2x10 ⁹	-	0.5	k	"
R ₅ C	H ⁺	3.68	X-ray unit (1.7x10 ⁵)	Air-dry	1.9x10 ⁵	-	3000	k	[1] Table 70
R ₅ C	H ⁺	3.68	"	In distilled water	1.9x10 ⁵	-	1100	k	[1] Table 77
Biorad AG50Wx8	H ⁺	-	⁶⁰ Co and reactor γ-radiations (7.5x10 ⁵)	In distilled water	8.5x10 ⁸	41	-	a,b,k,l	[11]
Biorad AG50Wx8	H ⁺	-	(1.0x10 ⁷)	"	8.5x10 ⁸	31	-	"	"
Biorad AG50Wx8	H ⁺	-	(1.85x10 ⁷)	"	8.5x10 ⁸	24	-	"	"
Biorad AG50Wx8	H ⁺	-	²⁴² Cm adsorbed γ-radiation (2.5x10 ⁶)	In 0.01N HNO ₃	7.6x10 ⁸	43	-	"	"
Biorad AG50Wx8	H ⁺	-	(1.85x10 ⁷)	"	7.6x10 ⁸	30	-	"	"
Zerolit-255x1	H ⁺	7.72	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin	1x10 ⁸	50	-	b,e,h,i,k, l,m	[18]
Zerolit-225x1	H ⁺	7.72	"	(30±0.5% water)	3x10 ⁸	51	-	"	"
" x1	H ⁺	7.72	"	"	5.12x10 ⁸	51	-	"	"
" x1	H ⁺	7.72	"	"	8x10 ⁸	56	-	"	"
Zerolit-225x2	H ⁺	5.32	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin (30±0.5% water)	1x10 ⁸	21	-	b,e,h,i,k, l,m	[18]
" x2	H ⁺	5.32	"	"	3x10 ⁸	21	-	"	"
" x2	H ⁺	5.32	"	"	5.12x10 ⁸	24	-	"	"
" x2	H ⁺	5.32	"	"	8x10 ⁸	31	-	"	"
" x2	H ⁺	5.32	"	"	1.2x10 ⁹	41	-	"	"
Zerolit-225x4-5	H ⁺	4.43	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin (30±0.5% water)	2x10 ⁸	7	-	b,e,h,i,k, l,m	[18]
" x4-5	H ⁺	4.43	"	"	3x10 ⁸	11	-	"	"
" x4-5	H ⁺	4.43	"	"	8x10 ⁸	21	-	"	"
" x4-5	H ⁺	4.43	"	"	1.2x10 ⁹	31	-	"	"
" x4-5	H ⁺	4.43	"	"	1.7x10 ⁹	45	-	"	"
Zerolit-225x8	H ⁺	4.89	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin (30±0.5% water)	2x10 ⁸	4	-	b,e,h,i,k, l,m	[18]
" x8	H ⁺	4.89	"	"	5.12x10 ⁸	6	-	"	"
" x8	H ⁺	4.89	"	"	8x10 ⁸	17	-	"	"
" x8	H ⁺	4.89	"	"	1.2x10 ⁹	24	-	"	"
" x8	H ⁺	4.89	"	"	1.7x10 ⁹	35	-	"	"
Zerolit-225x12	H ⁺	4.12	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin (30±0.5% water)	2x10 ⁸	2	-	b,e,h,i,k, l,m	[18]
" x12	H ⁺	4.12	"	"	8x10 ⁸	20	-	"	"
" x12	H ⁺	4.12	"	"	1.2x10 ⁹	32	-	"	"
" x12	H ⁺	4.12	"	"	1.7x10 ⁹	40	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
ZeroLit-225x20	H ⁺	3.89	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Moist resin (30±0.5% water)	2x10 ⁸	3	-	b,e,h,i,k, l,m	[18]
" x20	H ⁺	3.89	"	"	5.12x10 ⁸	7	-	"	"
" x20	H ⁺	3.89	"	"	8x10 ⁸	17	-	"	"
" x20	H ⁺	3.89	"	"	1.2x10 ⁹	28	-	"	"
" x20	H ⁺	3.89	"	"	1.7x10 ⁹	32	-	"	"
Zeocarb-225x8	Na ⁺	4.8	γ-radiation (1.63x10 ⁵)	Moist, varying ratios of resin to water	1.12x10 ⁸	2.33	-	b,c,i,j	[3]
Zeocarb-215	H ⁺	2.6	⁶⁰ Co γ-radiations (2.5x10 ⁵)	Dry	(0.5 to 2.0)x10 ⁸	-	(H ₂) 0.051	c,f,h,k	[47] G(SO ₂) is the initial G value for the lowest dose
"	"	"	"	"	"	-	(CO ₂) 0.019	"	"
"	"	"	"	"	"	-	(SO ₂) 0.001	"	"
Zeocarb-215	H ⁺	2.6	"	9.2 moles of water/eq. resin	"	-	(H ₂) 0.12	"	"
"	"	"	"	"	"	-	(CO ₂) 0.046	"	"
"	"	"	"	"	"	-	(CO) 0.005	"	"
"	"	"	"	"	"	-	(SO ₂) 0.005	"	"
Zeocarb-215	H ⁺	2.6	"	80 moles of water/eq. resin	"	-	(H ₂) 1.7	"	"
"	"	"	"	"	"	-	(CO ₂) 0.43	"	"
"	"	"	"	"	"	-	(SO ₂) 0.002	"	"
Phosphonic-acid Resin (DVB/iso- octane = 10/50)	Na ⁺	4.7	⁶⁰ Co γ-radiation	In water	1.9x10 ⁸	-25	-	a,c,f,i,l, m,n	[45]
" (10/50)	UO ₂ ²⁺	2.2	"	"	"	64	-	"	"
" (10/50)	UO ₂ ²⁺	2.2	"	2N HNO ₃	"	92	-	"	"
" (30/50)	Na ⁺	4.3-4.7	"	In water	"	21	-	"	"
" (30/50)	UO ₂ ²⁺	2.1	"	"	"	12	-	"	"
" (30/50)	Na ⁺	4.3-4.7	"	2N HNO ₃	"	-4.5	-	"	"
" (30/50)	UO ₂ ²⁺	2.1	"	"	"	17	-	"	"
" (40/50)	Na ⁺	3.3-4.7	"	In water	"	12	-	"	"
" (40/50)	UO ₂ ²⁺	2.0	"	"	"	0	-	"	"
" (40/50)	Na ⁺	3.3-4.7	"	2N HNO ₃	"	0	-	"	"
" (40/50)	UO ₂ ²⁺	2.0	"	"	"	0	-	"	"
Phosphonic-acid Resin (DVB/iso- octane = 10/70)	UO ₂ ²⁺	5.0	⁶⁰ Co γ-radiation	In water	8.7x10 ⁷	5	-	a,c,f,i,l, m,n	[45]
" (10/70)	Na ⁺	8.6	"	2N HNO ₃	9.1x10 ⁷	4.6	-	"	"
" (10/100)	Na ⁺	6.7	"	In water	7.6x10 ⁷	-1.5	-	"	"
" (10/100)	UO ₂ ²⁺	4.1	"	"	"	10	-	"	"
" (10/100)	Na ⁺	6.7	"	2N HNO ₃	8.2x10 ⁷	-3.0	-	"	"
" (30/100)	Na ⁺	5.3	"	In water	7.6x10 ⁷	2.0	-	"	"
" (30/100)	UO ₂ ²⁺	2.5	"	"	"	5.0	-	"	"
" (30/100)	Na ⁺	5.3	"	2N HNO ₃	7.8x10 ⁷	-1.5	-	"	"
" (30/100)	Na ⁺	5.3	"	In air	8.1x10 ⁷	-4	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY % (Z)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
" (12/60)	Na ⁺	8.5	"	In water	8.1x10 ⁷	7	-	"	"
" (12/60)	UO ₂ ²⁺	5.5	"	"	8.1x10 ⁷	7	-	"	"
" (16/60)	Na ⁺	7.8	"	"	7.9x10 ⁷	4	-	"	"
" (16/60)	UO ₂ ²⁺	5.5	"	"	"	7	-	"	"
" (16/60)	Na ⁺	7.8	"	2N HNO ₃	7.7x10 ⁷	3	-	"	"
" (16/60)	UO ₂ ²⁺	5.5	"	"	"	9	-	"	"
Phosphonic-acid Resin (DVB/iso- octane = (16/60)	Na ⁺	7.8	⁶⁰ Co γ-radiation	In air	8x10 ⁷	4	-	a,c,f,i,l, m,n	[45]
" (16/60)	UO ₂ ²⁺	5.5	"	"	"	10	-	"	"
" (16/80)	Na ⁺	7.8	"	In water	8.1x10 ⁷	6	-	"	"
" (16/80)	UO ₂ ²⁺	5.5	"	"	"	6	-	"	"
" (16/80)	Na ⁺	7.8	"	2N HNO ₃	7.5x10 ⁷	6	-	"	"
" (16/80)	UO ₂ ²⁺	5.5	"	"	"	10	-	"	"
" (16/80)	Na ⁺	7.8	"	In air	7.4x10 ⁷	4	-	"	"
" (16/80)	UO ₂ ²⁺	5.5	"	"	"	10	-	"	"
Sulfonated Poly- styrene DVB Resin (8% Commercial DVB)	H ⁺	5.29	⁶⁰ Co γ-radiation (2.9x10 ⁵)	Wet	9.1x10 ⁷	6.6	-	a,b,c,k	[46]
"	H ⁺	5.29	"	"	1.82x10 ⁸	10.8	-	"	"
"	H ⁺	5.29	"	"	1.90x10 ⁸	11.2	-	"	"
"	H ⁺	5.29	"	Dry	8.8x10 ⁷	4.7	-	"	"
"	H ⁺	5.29	"	"	8.9x10 ⁷	4.3	-	"	"
"	H ⁺	5.29	"	"	1.73x10 ⁸	5.5	-	"	"
"	H ⁺	5.29	"	"	1.75x10 ⁸	5.7	-	"	"
(8% 2:l:m:p-DVB)	H ⁺	5.29	"	Wet	9.1x10 ⁷	5.8	-	"	"
"	H ⁺	5.29	"	"	9.2x10 ⁷	4.2	-	"	"
"	H ⁺	5.29	"	"	1.82x10 ⁸	9.3	-	"	"
"	H ⁺	5.29	"	"	1.90x10 ⁸	10.2	-	"	"
"	H ⁺	5.29	"	Dry	8.9x10 ⁷	3.2	-	"	"
"	H ⁺	5.29	"	"	9.0x10 ⁷	2.5	-	"	"
"	H ⁺	5.29	"	"	1.73x10 ⁸	5.1	-	"	"
"	H ⁺	5.29	"	"	1.75x10 ⁸	4.5	-	"	"
(8% p-DVB)	H ⁺	5.33	"	Wet	9.1x10 ⁷	7.1	-	"	"
"	H ⁺	5.33	"	"	1.14x10 ⁸	8.6	-	"	"
"	H ⁺	5.33	"	"	1.82x10 ⁸	10.7	-	"	"
"	H ⁺	5.33	"	Dry	8.8x10 ⁷	3.4	-	"	"
"	H ⁺	5.33	"	"	9.0x10 ⁷	3.4	-	"	"
"	H ⁺	5.33	"	"	1.73x10 ⁸	5.2	-	"	"
"	H ⁺	5.33	"	"	1.75x10 ⁸	4.5	-	"	"
(8% m-DVB)	H ⁺	5.30	"	Wet	9.1x10 ⁷	5.8	-	"	"
"	H ⁺	5.30	"	"	1.14x10 ⁸	7.2	-	"	"
Sulfonated Poly- styrene DVB Resin (8% m-DVB)	H ⁺	5.30	⁶⁰ Co γ-radiation (2.9x10 ⁵)	Wet	1.80x10 ⁸	10.4	-	a,b,c,k	[46]
"	H ⁺	5.30	"	Dry	8.4x10 ⁷	3.1	-	"	"
"	H ⁺	5.30	"	"	1.73x10 ⁸	5.3	-	"	"
"	H ⁺	5.30	"	"	1.75x10 ⁸	5.2	-	"	"

TABLE III (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	C VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Sulfonated Poly- styrene DVB Resin (4% Commercial DVB)	H ⁺	5.32	⁶⁰ Co γ-radiation (2.9x10 ⁵)	Wet	9.1x10 ⁷	7.7	-	a,b,c,k	[46]
"	H ⁺	5.32	"	"	1.82x10 ⁸	12.8	-	"	"
"	H ⁺	5.32	"	Dry	8.5x10 ⁷	2.3	-	"	"
"	H ⁺	5.32	"	"	1.66x10 ⁸	5.1	-	"	"
"	H ⁺	5.32	"	"	1.70x10 ⁸	5.1	-	"	"
(4% 2:1/m:p DVB)	H ⁺	5.34	"	Wet	9.1x10 ⁷	5.6	-	"	"
"	H ⁺	5.34	"	"	1.76x10 ⁸	12.0	-	"	"
"	H ⁺	5.34	"	"	1.80x10 ⁸	12.3	-	"	"
"	H ⁺	5.34	"	Dry	8.5x10 ⁷	2.1	-	"	"
"	H ⁺	5.34	"	"	1.67x10 ⁸	4.8	-	"	"
"	H ⁺	5.34	"	"	1.70x10 ⁸	4.8	-	"	"
(4% p-DVB)	H ⁺	5.34	"	Wet	9.1x10 ⁷	7.1	-	"	"
"	H ⁺	5.34	"	"	1.76x10 ⁸	12.0	-	"	"
"	H ⁺	5.34	"	Dry	8.5x10 ⁷	2.1	-	"	"
"	H ⁺	5.34	"	"	1.66x10 ⁸	4.5	-	"	"
"	H ⁺	5.34	"	"	1.70x10 ⁸	4.9	-	"	"
(4% m-DVB)	H ⁺	5.32	"	Wet	9.1x10 ⁷	6.5	-	"	"
"	H ⁺	5.32	"	"	1.80x10 ⁸	12.0	-	"	"
"	H ⁺	5.32	"	Dry	8.4x10 ⁷	2.6	-	"	"
"	H ⁺	5.32	"	"	1.66x10 ⁸	4.7	-	"	"

(a) weight change, (b) swelling/shrinkage or volume change, (c) water content, (d) solubility, (e) oxidizability, (f) gas evolution, (g) thermal stability, (h) products of decomposition, (i) formation of ionic species such as SO₄²⁻, H⁺, Cl⁻, etc., (j) use of scavenger, (k) exchange capacity measurements other than TEC, (l) attempt to propose mechanism(s), (m) study of water soluble products, (n) microscopic examination of resin beads.

TABLE IV
SUMMARY OF EXPERIMENTAL DATA ON THE EFFECT
OF IONIZING RADIATION ON SYNTHETIC ANION EXCHANGERS

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Dowex 1	OH ⁻	3.0	⁶⁰ Co and ¹⁴⁴ Ce-Pr radiations (2.5 to 6.0x10 ⁵)	Air-dry	1.0x10 ⁹	-	3	-	[1] Table 70
Dowex 1x8	Cl ⁻	3.8	γ-emitter	Air-dry	7.6x10 ⁷	-	13	k	"
Dowex 1x8	OH ⁻	3.8	"	Moist	2.7x10 ⁹	-	11	k	[1] Table 77
Dowex 1x8	OH ⁻	3.8	"	"	2.7x10 ⁹	-	27	k	"
Dowex 1x8	Cl ⁻	3.8	"	Swollen in water	8.7x10 ⁷	-	13	k	"
Dowex 1x4	NO ₃ ⁻	4.8	"	Moist	1.1x10 ⁸	-	10	k	"
Dowex 1x4	NO ₃ ⁻	3.8	⁶⁰ Co radiations	In 7M HNO ₃	1.9x10 ⁸	-	10	-	"
Dowex 1x8	OH ⁻	-	γ-emitter	Moist	2.7x10 ⁸	-	3.8	k	[1] Table 78
Dowex 1x8	Cl ⁻	-	"	Swollen in water	8x10 ⁸	-	2.9	k	"
Dowex 1x4	NO ₃ ⁻	-	"	Moist	1.1x10 ⁸	-	3.7	k	"
Dowex 1x8	OH ⁻	3.80	γ-radiation from spent reactor fuels (3x10 ⁵)	Moist (52.4% water)	1.06x10 ⁸	35	-	a,b,c,h,i, k,m	[22]
Dowex 1x8	OH ⁻	3.80	"	Moist (46.9% water)	1.69x10 ⁸	43.3	-	"	"
Dowex 1x8	OH ⁻	3.80	"	Moist (31.7% water)	2.67x10 ⁸	58.4	-	"	"
Dowex 1x8	Cl ⁻	2.31	"	Air-dried (41.3% water)	0.76x10 ⁸	22.3	-	a,b,c,h,i, k,m	[22]
Dowex 1x8	Cl ⁻	2.31	"	Immersed in water (43.7% water)	0.87x10 ⁸	27.6	-	"	"
Dowex 1x4	NO ₃ ⁻	2.79	"	Moist (49.4% water)	1.10x10 ⁸	13.7	-	a,b,c,h,i, k,m	[22]
Dowex 1x4	NO ₃ ⁻	2.28	γ-radiation (⁶⁰ Co) (1.2x10 ⁶)	Air-dried (47.4% water)	0.81x10 ⁸	17.1	-	c,h,k,n	[24]
Dowex 1x4	NO ₃ ⁻	2.28	"	" (49.3% ")	1.11x10 ⁸	13.6	-	"	"
"	NO ₃ ⁻	2.28	"	" (47.1% ")	1.41x10 ⁸	23.2	-	"	"
"	NO ₃ ⁻	2.28	"	" (42.3% ")	1.52x10 ⁸	16.2	-	"	"
"	"	"	"	" (48.2% ")	1.71x10 ⁸	19.7	-	"	"
"	"	"	"	" (49.6% ")	2.01x10 ⁸	22.3	-	"	"
"	"	"	"	" (48.6% ")	2.49x10 ⁸	23.2	-	"	"
"	"	"	"	" (46.6% ")	3.68x10 ⁸	27.6	-	"	"
"	"	"	"	" (46.5% ")	4.35x10 ⁸	4.8	-	"	"
"	"	"	"	" (42.6% ")	6.00x10 ⁸	36.4	-	"	"
"	"	"	"	" (41.2% ")	6.90x10 ⁸	38.2	-	"	"
Dowex 1x4	Cl ⁻	2.28	γ-radiation ⁶⁰ Co (1.2x10 ⁶)	Air-dried (46.9% water)	0.91x10 ⁸	39.4	-	c,h,k,n	[24]
"	"	"	"	" (46.6% ")	1.20x10 ⁸	60.1	-	"	"
"	"	"	"	" (42.3% ")	1.71x10 ⁸	41.7	-	"	"
"	"	"	"	" (38.7% ")	2.16x10 ⁸	53.9	-	"	"
"	"	"	"	" (45.7% ")	2.70x10 ⁸	57.5	-	"	"
"	"	"	"	" (37.1% ")	3.00x10 ⁸	56.1	-	"	"
Dowex 1x4	NO ₃ ⁻	2.28	γ-radiation ⁶⁰ Co (1.2x10 ⁶)	In 7N HNO ₃ (52.0% water)	0.81x10 ⁸	19.7	-	c,h,k,n	[24]
"	"	"	"	" (56.5% ")	1.11x10 ⁸	28.5	-	"	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
"	"	"	"	" (59.0% ")	1.41×10^8	39.9	-	"	"
"	"	"	"	" (60.7% ")	1.52×10^8	36.0	-	"	"
"	"	"	"	" (61.5% ")	1.71×10^8	53.5	-	"	"
"	"	"	"	" (65.9% ")	2.01×10^8	52.2	-	"	"
"	"	"	"	" (71.2% ")	2.49×10^8	64.9	-	"	"
"	"	"	"	" (79.6% ")	3.68×10^8	78.9	-	"	"
"	"	"	"	" (91.4% ")	4.35×10^8	36.8	-	"	"
Dowex 1	OH ⁻	5.35	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 1 \times 10^9$	43.8	-	a,d,g,i,k	[37]
Dowex 1x1	OH ⁻	5.23	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 5 \times 10^8$	41	-	a,d,g,i,k	[37]
Dowex 1x2	OH ⁻	6.25	"	"	"	56	-	"	"
Dowex 1x4	OH ⁻	5.94	"	"	"	66	-	"	"
Dowex 1x8	OH ⁻	4.21	"	"	"	56	-	"	"
Dowex 1x10	OH ⁻	4.19	"	"	"	48	-	"	"
Dowex 1	Cl ⁻	-	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 5 \times 10^8$	60	-	a,d,g,i,k	[37]
Dowex 1	OH ⁻	-	"	"	"	49	-	"	"
Dowex 2	Cl ⁻	2.1	^{60}Co radiations ($\sim 1.9 \times 10^5$)	Air-dry	3.2×10^7	-	14	-	[1] Table 70
Dowex 2	OH ⁻	2.1	"	"	"	-	20	-	"
Dowex 2	Cl ⁻	2.10	γ -radiation (^{60}Co) (2×10^5)	Dry resin	0.02×10^7	6.7	-	i,k	[12]
Dowex 2	Cl ⁻	2.10	"	"	0.3×10^7	4.8	-	-	"
Dowex 2	Cl ⁻	2.10	"	"	0.4×10^7	5.2	-	-	"
Dowex 2	Cl ⁻	2.10	"	"	3.54×10^7	23.3	-	-	"
Dowex 2	OH ⁻	2.10	γ -radiation (2×10^5)	Dry resin	0.02 to 3.54×10^7	10.5 to 33.3	-	i,k	[12]
Dowex 3	OH ⁻	5.5	X-ray unit (1.1×10^8)	Air-dry	2.2×10^9	-	3	-	[1] Table 70
Dowex 3	Cl ⁻	2.45	γ -radiation (2×10^5)	Dry resin	0.02 to 3.54×10^7	-0.8 to 16.1	-	i,k	[12]
Dowex 3	OH ⁻	5.58	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 1 \times 10^9$	19	-	a,d,g,i,k	[37]
Dowex 11	NO ₃ ⁻	2.12	γ -radiation (^{60}Co) (0.65×10^6)	Air-dried (51.7% water)	1.56×10^8	22.6	-	c,f,g,k	[26][27]
"	"	"	"	" (49.0% ")	3.12×10^8	42.9	-	"	"
"	"	"	"	" (45.2% ")	4.68×10^8	57.1	-	"	"
"	"	"	"	" (51.8% ")	5.62×10^8	64.2	-	"	"
Dowex 11	NO ₃ ⁻	2.12	γ -radiation (^{60}Co) (0.65×10^6)	In 7N HNO ₃ (68.1% water)	1.56×10^8	54.2	-	c,f,g,k	[26][27]
"	"	"	"	" (82.0% ")	3.12×10^8	83.0	-	"	"
"	"	"	"	" (89.5% ")	4.68×10^8	93.4	-	"	"
Dowex 21K	NO ₃ ⁻	4.5	^{60}Co γ -radiation	In 7N HNO ₃	2.8×10^8	-	18	-	[1] Table 77
Amberlite IRA-400	OH ⁻	3.2	X-ray unit (1.1×10^8)	Air-dry	2.2×10^9	-	3.6	-	[1] Table 70
"	OH ⁻	3.2	^{60}Co and $^{144}\text{Ce-Pr}$ radiations (2.5 to 6.0×10^5)	Air-dry	9×10^8	-	1.6 to 3.2	-	[1] Table 70
"	OH ⁻	3.2	"	Moist	9×10^8	-	"	-	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Amberlite IRA-400	OD ⁻	3.3	β, γ -radiation from activation and fis- sion products (1.4×10^7)	Moist (on-line cleanup system of D ₂ O moderator)	up to 2.0×10^8	~5 to 25		k,m	[13][15]
Amberlite IRA-400	-	3.72	^{182}Ta - γ -radiations (4.0 - 4.2×10^5)	Dried (Ar 60°C for 48 hrs)	1.62×10^6	1.6	-	c,h,i,k	[34][35][36]
"	-	3.72	"	"	1.61×10^7	0.8	-	"	"
"	-	3.72	"	Wet (filtered)	2.13×10^6	5.4	-	"	"
"	-	3.72	"	"	1.62×10^7	0.8	-	"	"
"	-	3.72	^{60}Co - γ -radiations (4.2×10^5)	"	1.75×10^8	20.2	-	"	"
Amberlite IRA-400	OH ⁻	5.30	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 1 \times 10^9$	42.1	-	a,d,g,i,k	[37]
Amberlite IRA-401	OH ⁻	3.5	^{60}Co and ^{144}Ce -Pr radiations (2.5 to 6.0×10^5)	Air-dry	9×10^8	-	1.8 to 3.6	-	[1] Table 70
"	OH ⁻	2.15	Reactor (2.6×10^6)	Air-dry	1.1×10^9	-	1.3	-	"
"	OH ⁻	3.5	^{60}Co and ^{144}Ce -Pr radiations (2.5 to 6.0×10^5)	Moist	9×10^8	-	1.8 to 3.6	-	[1] Table 77
"	NO ₃ ⁻	3.5	^{60}Co γ -radiation	In 7M HNO ₃	4.2×10^8	-	5.5	-	[1] Table 77
Amberlite IRA-401	-	3.81	^{182}Ta γ -radiations	Dry	1.62×10^6	-0.8	-	c,h,i,k	[34][35][36]
"	-	3.81	"	"	1.61×10^7	-1.6	-	"	"
"	-	3.81	"	Wet (filtered)	1.66×10^8	-3.4	-	"	"
"	-	3.81	"	"	2.13×10^6	6.6	-	"	"
"	-	3.81	^{60}Co γ -radiations	"	1.75×10^8	26.8	-	"	"
Amberlite IRA-410	OH ⁻	3.5	X-ray unit (1.1×10^8)	Air-dry	2.2×10^9	-	4.0	-	[1] Table 70
"	OH ⁻	3.4	^{60}Co and ^{144}Ce -Pr radiations (2.5 to 6.0×10^5)	Air-dry	9×10^8	-	1.7 to 3.4	-	"
"	OH ⁻	3.4	"	Moist	9×10^8	-	1.7 to 3.4	-	[1] Table 77
Amberlite IRA-410	-	3.88	^{182}Ta γ -radiation (4 to 4.2×10^5)	Dry	1.62×10^6	-4.1	-	c,h,i,k	[34][35][36]
"	-	3.88	"	"	1.61×10^7	0	-	"	"
"	-	3.88	^{60}Co γ -radiation (4.2×10^5)	"	1.66×10^8	20.1	-	"	"
"	-	3.88	^{182}Ta γ -radiation (4 to 4.2×10^5)	Wet (filtered)	2.13×10^6	0.3	-	"	"
"	-	3.88	"	"	1.73×10^7	-2.3	-	"	"
Amberlite IRA-410	OH ⁻	4.89	X-ray machine ($\sim 10^6$)	Air-dry	$\sim 1 \times 10^9$	39.6	-	a,d,g,i,k	[37]
Amberlite IRA-411	OH ⁻	3.0	^{60}Co and ^{144}Ce -Pr radiations (2.5 to 6.0×10^5)	Air-dry	9×10^8	-	1.5 to 3.0	-	[1] Table 70
"	OH ⁻	3.0	"	Moist	9×10^8	-	1.5 to 3.0	-	[1] Table 77
Amberlite IRA-411	-	3.70	^{182}Ta γ -radiations (4 to 4.2×10^5)	Dry	1.62×10^6	5.4	-	c,h,i,k	[34][35][36]
"	-	3.70	"	"	1.61×10^7	7.6	-	"	"
"	-	3.70	"	Wet (filtered)	2.13×10^6	5.7	-	"	"
"	-	3.70	"	"	1.73×10^7	9.5	-	"	"
"	-	3.70	^{60}Co γ -radiations (4.2×10^5)	"	1.71×10^8	29.5	-	"	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Amberlite XE-58	OH ⁻	8.0	X-ray unit (1.1x10 ⁸)	Air-dry	2.2x10 ⁹	-	5.3	-	[1] Table 70
Amberlite XE-58	OH ⁻	6.01	X-ray machine (~10 ⁶)	Powdered Air-dry sample	~1x10 ⁹	20	-	a,d,g,i,k	[37]
Amberlite IR-4B	OH ⁻	9.2	X-ray unit (1.1x10 ⁸)	Air-dry	2.2x10 ⁹	-	3.3	-	[1] Table 70
Amberlite IR-4B	-	10.85	¹⁸² Ta γ-radiations (4 to 4.2x10 ⁵)	Dry	1.62x10 ⁶	-0.5	-	c,h,i,k	[34][35][36]
"	-	10.85	"	"	1.61x10 ⁷	0.9	-	"	"
"	-	10.85	⁶⁰ Co γ-radiations (4.2x10 ⁵)	"	1.72x10 ⁸	6.0	-	"	"
"	-	10.85	¹⁸² Ta γ-radiations (4.0 to 4.2x10 ⁵)	Wet (filtered)	1.68x10 ⁶	9.2	-	"	"
"	-	10.85	"	"	1.73x10 ⁷	16.1	-	"	"
"	-	10.85	⁶⁰ Co γ-radiations (4.2x10 ⁵)	"	1.73x10 ⁸	18.0	-	"	"
Amberlite IR-4B	OH ⁻	8.32	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	13	-	a,d,g,i,k	[37]
Amberlite IR-45	OH ⁻	5.5	X-ray unit (1.1x10 ⁸)	Air-dry	2.2x10 ⁹	-	8.0	-	[1] Table 70
Amberlite IR-45	-	5.10	¹⁸² Ta γ-radiations (4 to 4.2x10 ⁵)	Dry	1.61x10 ⁶	2.4	-	c,h,i,k	[34][35][36]
"	-	5.10	"	"	1.53x10 ⁷	2.9	-	"	"
"	-	5.10	⁶⁰ Co γ-radiations	"	1.72x10 ⁸	25.1	-	"	"
"	-	5.10	¹⁸² Ta γ-radiations (4 to 4.2x10 ⁵)	Wet (filtered)	1.68x10 ⁶	1.0	-	"	"
"	-	5.10	"	"	1.72x10 ⁷	8.6	-	"	"
"	-	5.10	⁶⁰ Co γ-radiations (4.2x10 ⁵)	"	1.73x10 ⁸	12.7	-	"	"
Amberlite IR-45	OH ⁻	6.35	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	53	-	a,d,g,i,k	[37]
Amberlite XE-114	-	9.50	¹⁸² Ta γ-radiations (4 to 4.2x10 ⁵)	Dry	1.61x10 ⁶	-1.3	-	c,h,i,k	[34][35][36]
"	-	9.50	"	"	1.53x10 ⁷	4.7	-	"	"
"	-	9.50	⁶⁰ Co γ-radiations (4.2x10 ⁵)	"	1.72x10 ⁸	14.2	-	"	"
"	-	9.50	¹⁸² Ta γ-radiations (4.0-4.2x10 ⁵)	Wet (filtered)	1.68x10 ⁶	0.4	-	"	"
"	-	9.50	"	"	1.72x10 ⁷	18.3	-	"	"
"	-	9.50	⁶⁰ Co γ-radiations (4.2x10 ⁵)	"	1.73x10 ⁸	28.9	-	"	"
Imac S-4	OH ⁻	1.5	Reactor (2.6x10 ⁶)	Air-dry	1.1x10 ⁹	-	1.1	-	[1] Table 70
Imac S5-40	OH ⁻	3.62	γ-radiation (⁶⁰ Co) (1x10 ⁶)	Resin immersed in water	1.x10 ⁷	9.9	35 (radio- tatively labile)	h,k,l,m	[20] (Decomposi- tion follows the first order kinet- ic equation)
"	"	"	"	"	2x10 ⁷	13.3	-	"	"
"	"	"	"	"	3x10 ⁷	14.1	-	"	"
"	"	"	"	"	4x10 ⁷	11.1	-	"	"
"	"	"	"	"	8x10 ⁷	16.3	-	"	"
"	"	"	"	"	1x10 ⁸	17.1	7 (radio- tatively more stable)	"	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
"	"	"	"	"	2.15×10^8	35.1	-	"	"
"	"	"	"	"	3.05×10^8	47.5	-	"	"
"	"	"	"	"	4.15×10^8	51.1	-	"	"
"	"	"	"	"	6.0×10^8	64.6	-	"	"
"	"	"	"	"	8.0×10^8	79.0	-	"	"
"	"	"	"	"	1.0×10^9	88.7	-	"	"
"	"	"	"	"	1.5×10^9	90.1	-	"	"
"	"	"	"	"	2.0×10^9	97.2	-	"	"
Zerolit FF-IP X7-9	Cl ⁻	2.9	γ -radiation ^{60}Co (0.43 and 1.0×10^6)	Air-dried (12% water)	1×10^8	8.6	3.5	c,h,i,k,l, m	[16][17][19]
" X7-9	Cl ⁻	2.9	"	"	1.7×10^8	25.9	3.5	"	"
" X7-9	Cl ⁻	2.9	"	"	2.0×10^8	31.0	3.5	"	"
" X7-9	Cl ⁻	2.9	"	"	2.4×10^8	44.8	3.5	"	"
" X7-9	Cl ⁻	2.9	"	"	3.8×10^8	67.2	3.5	"	"
" X7-9	Cl ⁻	2.9	"	"	1.0×10^9	82.8	-	"	"
Zerolit FF-IPx2-3	Cl ⁻	4.12	γ -radiation ^{60}Co (0.43 and 1.0×10^6)	Air-dried (17% moisture)	1×10^8	12.6	4.1	c,h,i,k,l, m	[16][17][19]
"	Cl ⁻	"	"	"	2×10^8	26.0	4.1	"	"
"	Cl ⁻	"	"	"	3×10^8	53.9	4.1	"	"
"	Cl ⁻	"	"	"	4.4×10^8	72.1	4.1	"	"
"	Cl ⁻	"	"	"	1×10^9	87.9	-	"	"
Zerolit FF-IPx7-9	Cl ⁻	2.9	γ -radiation ^{60}Co (0.43 and 1.0×10^6)	Wet resin	4.05×10^8	68	5.4	c,h,i,k,l, m	[16][17][19]
"	Cl ⁻	2.9	"	"	1.0×10^9	85.5	-	"	"
"	Cl ⁻	2.9	"	"	1.5×10^9	-	-	"	"
Zerolit FF-IPx2-3	Cl ⁻	4.12	γ -radiation ^{60}Co (0.43 and 1.0×10^6)	Wet resin	4.05×10^8	81	8.9	c,h,i,k,l, m	[16][17][19]
"	Cl ⁻	4.12	"	"	1.0×10^9	94	-	"	"
"	Cl ⁻	4.12	"	"	1.5×10^9	-	-	"	"
"	Cl ⁻	4.12	"	"	2.0×10^9	-	-	"	"
"	Cl ⁻	4.12	"	"	2.5×10^9	-	-	"	"
Zerolit FF-IPx7-9	Cl ⁻	2.9	γ -radiation ^{60}Co (0.4 and 1.0×10^6)	Dry resin	4.05×10^8	50	3.1	c,h,i,k,l, m	[16][17][19]
"	Cl ⁻	2.9	"	"	1.0×10^9	66	-	"	"
"	Cl ⁻	2.9	"	"	1.5×10^9	85	-	"	"
Zerolit FF-IPx2-3	Cl ⁻	4.12	γ -radiation ^{60}Co (0.4 and 1.0×10^6)	Dry resin	4.05×10^8	45	3.4	c,h,i,k,l, m	[16][17][19]
"	Cl ⁻	4.12	"	"	1.0×10^9	55	-	"	"
"	Cl ⁻	4.12	"	"	1.5×10^9	82	-	"	"
"	Cl ⁻	4.12	"	"	2.0×10^9	88	-	"	"
"	Cl ⁻	4.12	"	"	2.5×10^9	87	-	"	"
Dienon SA-100	Cl ⁻	2.06	^{60}Co γ -radiations (1.9×10^5)	Air-dry	3.2×10^7	-	8.5	-	[1] Table 70
"	OH ⁻	2.06	"	"	3.2×10^7	-	15	-	[1] Table 70
Diaion SA#100	Cl ⁻	2.06	γ -radiation (2×10^5)	Dry resin	0.02 to 3.54×10^7	1.9 to 14.1	-	i,k	[12]

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
Diaion SA#100	OH ⁻	2.06	γ-radiation (2x10 ⁵)	Dry resin	"	10.5 to 25.8	-	i,k	[12]
Nalcite SAR	OH ⁻	3.9	X-ray unit (1.1x10 ⁸)	Air-dry	2.2x10 ⁹	-	4.0	-	[1] Table 70
Nalcite SAR	OH ⁻	3.78	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	37.0	-	a,d,g,i,k	[37]
Nalcite WBR	OH ⁻	3.5	X-ray unit (1.1x10 ⁸)	Air-dry	2.2x10 ⁹	-	2	-	[1] Table 70
Nalcite WBR	OH ⁻	6.01	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	20	-	a,d,g,i,k	[37]
Permutit SK	OH ⁻	-	γ-emitter	Moist	2.7x10 ⁸	-	4.6	k	[1] Table 78
Permutit SK	Cl ⁻	-	"	"	10 ⁸	-	2.5	k	"
Permutit SK	OH ⁻	4.47	γ-radiation from spent reactor fuels	Moist (63.3% water)	1.69x10 ⁸	4.9	-	a,b,c,h,i, k,m	[22]
Permutit SK	OH ⁻	4.47		Moist (61.4% water)	2.67x10 ⁸	7.8	-	"	"
Permutit SK	Cl ⁻	4.47	"	Dry (62.8% water)	1.06x10 ⁸	4.3	-	a,b,c,h,i, k,m	[22]
Permutit SK	Cl ⁻	4.47	"	Moist (59.3% water)	1.08x10 ⁸	7.6	-	"	"
Permutit S-2	OH ⁻	3.4	X-ray unit (1.1x10 ⁶)	Air-dry	2.2x10 ⁹	-	3.5	-	[1] Table 70
Permutit S-2	OH ⁻	4.4	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	38.3	-	a,d,g,i,k	[37]
Deacidite FFx7-9	OH ⁻	4.02	γ-radiation ⁶⁰ Co (6.1x10 ⁵)	Aqueous slurries	5.5x10 ⁷	12.2	G-value for var- ious product formation reported	b,h,k,l	[28] Also in- cluded in Ref. [1]
Deacidite FFx7-9	OH ⁻	4.02	(1.8x10 ⁵)	"	6.5x10 ⁷	15.7			
Deacidite FFx7-9	SO ₄ ²⁻ , Cl ⁻		γ-radiation (⁶⁰ Co) (8.01x10 ⁵)	Dry	4.81x10 ⁶	-	4.0-4.4 (Me ₃ N)	h,j,k,l,m	[29]
"	"		"	Slurried with 2 units of water	4.81x10 ⁶	-	3.2 (Me ₃ N)		
Permutit Deacidite	OH ⁻	7.64	X-ray machine (~10 ⁶)	Air-dry	~1x10 ⁹	3	-	a,d,g,i,k	[37]
AV-16	OH ⁻	7.5	⁶⁰ Co γ-radiations	Vacuum dry	3x10 ⁸	-	9	h,k	[1] Table 70
"	OH ⁻	7.5	"	Air-dry	5x10 ⁷	-	4.5	k	[1] Table 70
"	OH ⁻	7.5	"	Air-dry	5x10 ⁷	-	2.0	k	"
"	OH ⁻	8.08	Electron accelerator	Vacuum-dry	3x10 ⁸	-	0.1	k	"
"	OH ⁻	8.08	"	Vacuum-dry	3x10 ⁸	-	11	k	"
"	OH ⁻	8.08	"	Air-dry	2x10 ⁹	-	1.2	k	"
"	OH ⁻	8.08	"	Air-dry	2x10 ⁹	-	0.5	k	"
AV-17	OH ⁻	3.45	Electron accelerator (4.9x10 ⁸)	In distilled water	2.9x10 ⁸	-	1.8	-	[1] Table 77
"	Cl ⁻	3.45	"	"	2.9x10 ⁸	-	2.3	k	"
"	NO ₃ ⁻	3.45	"	"	2.9x10 ⁸	-	1.7	k	"
"	CrO ₄ ²⁻	3.45	"	"	2.9x10 ⁸	-	2.4	k	"
"	CrO ₄ ²⁻	3.45	"	"	2.9x10 ⁸	-	3.6	k	"
"	PO ₄ ³⁻	3.45	"	"	2.9x10 ⁸	-	2.6	k	"
"	OH ⁻	3.5	"	"	1.1x10 ⁹	-	4.2	-	"
"	OH ⁻	3.6	Reactor (1.1x10 ⁷)	"	2.5x10 ⁸	-	32	k	"
"	OH ⁻	3.6	"	"	2.5x10 ⁸	-	24	k	"
"	NO ₃ ⁻ , OH ⁻	4.3	Electron accelerator (3.6 to 5.0x10 ⁸)	"	10 ⁹	-	2.6	-	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
AV-18	OH ⁻	3.0	Electron accelerator (3.6 to 5.0x10 ⁸)	In distilled water	2x10 ⁹	-	0.2	-	[1] Table 77
AV-27	OH ⁻ , NO ₃ ⁻	3.6	"	"	"	-	1.1	-	"
AVKh-8P (x8)	NO ₃ ⁻	2.3	γ-radiation (⁶⁰ Co)	Vacuum dry	2x10 ⁸	0	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	4.4	-	"	"
"	"	"	"	"	6x10 ⁸	4.4	-	"	"
"	"	"	"	"	10x10 ⁸	0	-	"	"
AVKh-8P (x8)	NO ₃ ⁻	2.3	γ-radiation (⁶⁰ Co)	Air-dry	2x10 ⁸	4.4	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	8.7	-	"	"
"	"	"	"	"	6x10 ⁸	8.7	-	"	"
"	"	"	"	"	10x10 ⁸	8.7	-	"	"
AVKh-8P (x8)	NO ₃ ⁻	2.3	γ-radiation (⁶⁰ Co)	In distilled water	2x10 ⁸	4.4	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	8.7	-	"	"
"	"	"	"	"	6x10 ⁸	8.7	-	"	"
"	"	"	"	"	10x10 ⁸	13.0	-	"	"
AVKh-8P (x8)	NO ₃ ⁻	2.3	γ-radiation (⁶⁰ Co)	In 7N HNO ₃	2x10 ⁸	13.0	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	30.2	-	"	"
"	"	"	"	"	6x10 ⁸	39.0	-	"	"
"	"	"	"	"	10x10 ⁸	52.0	-	"	"
AVI-8P (x8)	NO ₃ ⁻	2.8	γ-radiation	Vacuum-dry	2x10 ⁸	3.5	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	7.1	-	"	"
"	"	"	"	"	6x10 ⁸	7.1	-	"	"
"	"	"	"	"	1x10 ⁹	14.3	-	"	"
AVI-8P (x8)	NO ₃ ⁻	2.8	γ-radiation (⁶⁰ Co)	Air-dry	2x10 ⁸	0	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	3.5	-	"	"
"	"	"	"	"	6x10 ⁸	0	-	"	"
"	"	"	"	"	1x10 ⁹	14.3	-	"	"
AVI-8P (x8)	NO ₃ ⁻	2.8	γ-radiation (⁶⁰ Co)	In distilled water	2x10 ⁸	3.5	-	a,b,e,k,l	[31][32]
"	"	"	"	"	6x10 ⁸	7.1	-	"	"
"	"	"	"	"	1x10 ⁹	14.3	-	"	"
AVI-8P (x8)	NO ₃ ⁻	2.8	γ-radiation (⁶⁰ Co)	In 7N HNO ₃	2x10 ⁸	14.3	-	a,b,e,k,l	[31][32]
"	"	"	"	"	4x10 ⁸	25.0	-	"	"
"	"	"	"	"	6x10 ⁸	28.5	-	"	"
"	"	"	"	"	1x10 ⁹	53.6	-	"	"
AM	OH ⁻	3.2	Electron accelerator (3.6 to 5.0x10 ⁸)	In distilled water	1.1x10 ⁹	-	0.4	-	[1] Table 77
AM	OH ⁻	3.7	Reactor (1.1x10 ⁷)	"	3.5x10 ⁸	-	30	k	"
AM	OH ⁻	3.7	"	"	3.5x10 ⁸	-	17	k	"
AMP	OH ⁻	2.9	Electron accelerator (2.9 to 57.6x10 ⁵)	In distilled water	1.5x10 ⁹	-	0.07	-	[1] Table 77
AN-2F	Cl ⁻	4.02	⁶⁰ Co γ-radiations (6.6x10 ⁵)	In water	1.2x10 ⁸	-	4.0	k	[1] Table 77
AN-31	OH ⁻	8.98	γ-radiation (⁶⁰ Co) (1.86x10 ⁶)	Moist, swollen	2x10 ⁸	-	-	a,b,k	[6]
AN-25x6	OH ⁻	8.0	Accelerated electrons	In distilled water	1.44x10 ⁹	0	-	b,e,h,k	[30]
AN-25x6	OH ⁻	8.0	"	In 7N HNO ₃	1.92x10 ⁹	2.5	-	"	"

TABLE IV (Cont'd)

RESIN (Trade Name)	IONIC FORM	EXCHANGE CAPACITY (meq/g)	RADIATION SOURCE (Rad/Hr.)	IRRADIATION CONDITION(S)	INTEGRAL DOSE (RAD)	LOSS OF EXCHANGE CAPACITY (%)	G VALUE	OTHER PARAMETERS MEASURED	REFERENCE NUMBER AND NOTES
AN-25Ax6	OH ⁻	3.56	Accelerated electrons	In distilled water	1.44x10 ⁹	0	-	b,e,h,k	[30]
AN-25Ax6	OH ⁻	3.56	"	"	2.40x10 ⁹	5.6	-	-	"
EDE-10P	Cl ⁻	5.04	⁶⁰ Co γ-radiation (6.6x10 ⁵)	In water	1.2x10 ⁸	-	5.5	-	[1] Table 77
EDE-10	OH ⁻	9.75	⁶⁰ Co γ-radiations	Air-dry	5x10 ⁷	-	21	k	[1] Table 70
"	OH ⁻	7.23	Electron accelerator	Vacuum-dry	3x10 ⁸	-	0.1	k	[1] Table 70
"	OH ⁻	7.23	"	Air-dry	2x10 ⁹	-	0.7	k	"
"	OH ⁻	9.75	⁶⁰ Co γ-radiations	Vacuum-dry	3x10 ⁸	-	14	k	"
"	OH ⁻	9.75	"	Air-dry	5x10 ⁷	-	26	k	"
"	OH ⁻	7.23	Electron Accelerator	Vacuum-dry	3x10 ⁸	-	12	k	"
VP-1	OH ⁻	7.6	Electron Accelerator	In distilled water	3.4x10 ⁹	-	0.1	-	[1] Table 77
Anion Exchanger (not identified by Trade Name)	OH ⁻	-	γ-radiation (spent reactor fuel) (2.6x10 ⁶)	Covered with water	Up to 2x10 ⁸	~2 to 30	-	b,d,i,k,m	[14] Mixed bed and par- titioned anion ex- changer used

(a) weight change, (b) swelling/shrinkage or volume change, (c) water content, (d) solubility, (e) oxidizability, (f) gas evolution, (g) thermal stability, (h) products of decomposition, (i) formation of ionic species such as SO₄²⁻, H⁺, Cl⁻, etc., (j) use of scavenger, (k) exchange capacity measurements other than TEC, (l) attempt to propose mechanism(s), (m) study of water soluble products, (n) microscopic examination of resin beads.

IV. GENERALIZATIONS ON THE EFFECTS OF RADIATION ON ION EXCHANGE RESINS

In many instances, the effects of intense radiation exposures of synthetic organic ion exchangers resemble similar effects observed on organic high polymers. However, the ion exchange resins are distinctly different in their macromolecular structure due to the presence of functional groups and the desired features of porosity and elasticity in the structure of resinous exchangers. In addition, the process applications of ion exchangers always involve other materials incorporated in the resin beads and the ion exchanger beds. This ever-present influence of foreign materials in the environment of ion exchangers and the distinct macromolecular structural features makes the overall radiation chemical changes in synthetic organic ion exchange resins extremely complex.

On exposure to ionizing radiations, macromolecular structures undergo molecular changes such as bond breakages, bond formation, oxidation, and gas product formation. Of these, the reactions of particular significance are:

- (i) the scission of chemical bonds of the main chain of the polymeric structure accompanied by a change in the molecular weight (degradation)

- (ii) the changes in chemical bonds maintaining the tridimensional structure of the matrix (cross-linkage).

These reactions result in the formation of terminal or residual macroradicals, which in turn can enter into a variety of chemical transformations. Even though the radiation chemical yields in high polymers are relatively low, it is well known that the effects of radiation on the physical and chemical properties of organic polymers can be significant. In synthetic organic ion exchangers, these effects are enhanced by the relative ease of cleavage of the functional groups and secondary effects due to the products of radiation in the ion exchanger's

vicinity as well as by the chemical effects such as oxidation, hydrolysis and double decomposition.

The changes in the molecular structure of organic polymers leads to changes in their density, molecular weight, elasticity, porosity, solubility, thermal stability and other mechanical as well as electrical properties. Similar changes in ion exchangers are compounded by both direct radiation effects on the ion exchangers macromolecules and the secondary effects mentioned above.

Little is known about the mechanisms of the various radiation chemical effects on ion exchange resins. This is primarily due to the complexity of these matrices and the limited efforts spent so far in the detailed study of these radiation chemical changes. Although most of the presently known efforts at explaining the mechanisms of these reactions are extensions of knowledge gained in the study of radiation effects on high polymers and aqueous systems, there have been several experimental studies directed at elucidating the modifications in the properties of ion exchangers which are of importance in process applications. The present knowledge on these changes in the properties of synthetic organic resins can be summarized in the form of a set of qualitative and semiquantitative generalizations ("rules of thumb"). These generalizations listed below are derived from various experimental studies surveyed during this study. Additional discussions of these rules and known exceptions are considered in the following section of this report.

In listing these generalizations, it should be pointed out that while there are agreements in several areas among experimental findings of several workers, there exist both differences of opinions and demonstrated exceptions to these rules. The qualitative and semi-quantitative generalizations are:

1. Radiation chemical changes in ion exchange resins are a direct function of the total dose absorbed by the resin.

2. Most anion exchange resins show considerable degradation when the total absorbed dose increases above 10^7 to 10^8 rads, while most cation exchangers show significant attrition only above 10^8 rads.

3. In most ion exchange resins, an absorbed dose of 10^9 rads or higher results in sufficient damage to make the material unserviceable.

4. There are two well recognized forms of radiation effects on ion exchange systems - one is the direct action of radiation on the ion exchanger matrix while the other is the indirect action of radiolytic products of the materials in the environment of the resin.

5. The primary effects of radiation on ion exchange resins are degradation and cross-linking of the macromolecular structure along with the scission of ion exchange functional groups.

6. The radiation chemical yields (G value) for radicals, ions, gaseous and other decomposition products are not constants. They vary within the same resin depending on factors such as temperature, constituents of the matrix of the resin and the nature of the medium surrounding the resin.

7. Like high polymers, the free radicals formed during radiolytic decomposition of ion exchangers may be stable for extended periods at ordinary temperatures.

8. The free radical concentration in ion exchange resins being irradiated increase steadily and tend to reach a limiting concentration. This limiting concentration of free radicals is reached at integral doses of 10^8 to 10^9 rads in most resins.

9. The exchange capacity of ion exchange resins, in general, decreases with increasing radiation dose.

10. In cation exchangers, there is initially an increase in functional groups capable of exchange as a result of irradiation in the presence of air or moisture. These are phenolic and carboxyl groups produced as a result of oxidation.

11. The initial increase in exchange sites tends to increase the total exchange capacity (TEC) of the resin. However, the accompanying scission of existing exchange groups often results in a net decrease in TEC values.

12. The overall radiation chemical change in ion exchangers is drastically different for a given resin irradiated in the presence of water or aqueous solutions, when compared with similar irradiations in the dry state. Some of the important properties (especially TEC values) of ion exchangers important to process applications change by a factor of 2 to 5 during irradiation in aqueous media.

13. Radiation resistance of ion exchangers increases with increase in their cross-linkage.

14. Radiation chemical changes producing cross-linkages are more dominant in ion exchange resins of lower cross-linkage.

15. Although anion exchange resins in general are more susceptible to radiation damage compared to cation exchangers, there are special formulations of anion exchangers (pyridine-derived) which are significantly superior in their radiation resistance than most cation exchangers.

16. While the physical, chemical and mechanical properties of polymerization type resins are generally superior to those of polycondensation type resins, the polycondensation type resins are superior in their radiation resistance.

17. Among polycondensation type resins, the exchangers with structural aromatic groups are more radiation resistant when compared with purely aliphatic resins. This protective effect of aromatic groups is found in all organic systems and it is generally true in synthetic resins.

18. In general, the salt forms of ion exchange resins are more resistant to radiation than the H^+ or OH^- forms.

19. Organic resins show variations in the protective effect (radiation protection) depending on the salt forms of the resins. The protective effects are significantly higher when ions of variable valences are involved.

20. The radiation stability of polymeric styrene-divinylbenzene resins, when irradiated in water in the H^+ or OH^- forms show the following order of stability:

Pyridine anion exchangers > nuclear sulfonic and carboxyl cation exchangers > weakly basic anion exchangers of the primary, secondary and tertiary type > strongly basic anion exchangers of quarternary ammonium base type.

21. Strong (acid/base) monofunctional ion exchange resins, in general, are more resistant to radiation damage than weak (acid/base) resins and polyfunctional resins.

22. The radiation protection of ion exchange systems can be improved through the presence of scavengers such as methanol, ethanol, cysteamine, cysteine, etc., although their potential process applications have not been reported.

23. Under identical conditions, when radiation sources of low LET values (γ -rays, x-rays, fast electrons and β -particles) are used, there are no apparent differences between the radiation effects on resins, whether the source is external or internal.

24. There are some recognizable differences between the radiation chemical effects on ion exchange resins of high and low LET radiation. This is particularly true between internal irradiation with heavy particles (recoil protons and α -particles) of high LET values and with internal or external irradiations with particles of low LET values.

25. Among synthetic organic cation exchangers, the resins with carboxylic functional groups are least resistant to radiation and those with phosphate functional groups are most resistant.

26. During irradiation in aqueous media, the swelling tendency of ion exchange resins shows an initial increase (up to $\sim 10^6$ rads) followed by a decrease due to the moisture absorption capacity steadily decreasing.

27. The swelling capacity of a resin is a function of the medium in which the resin is irradiated.

28. The polycondensation type resins show an extended duration for the increase in swelling ability compared to polymerization type resins. Both types continue to show decreased swelling as the dose reaches 10^7 rads or higher.

29. Radiation effects on organic ion exchangers result in column changes of the resin matrix. The resins change from their original shades to amber, brown, dark red and black with increased doses.

30. As a consequence of radiation damage, the particles of resins (beads) become gouged, pitted, cracked and at times solubilized when the integral dose exceeds $10^8 - 10^9$ rads.

31. The effluents from ion exchange columns being exposed to ionizing radiation show measurable changes (decrease) in pH. At an integral dose of 10^8 rads, the effluent from anion exchangers also begin to show a darkening effect

due to solubilization. For cation exchangers, this attrition starts at higher doses.

32. Prolonged exposure of ion exchange resins to radiation in flowing (dynamic) systems causes more drastic changes in their physical and chemical properties than ion exchange resins irradiated in static systems.

33. Irradiated resins are less resistant to degradation by thermal effects.

34. Gaseous products resulting from the action of ionizing radiation on ion exchange resins primarily consist of hydrogen. Other gaseous products of resin decomposition include CO_2 , CO , N_2O , NO and SO_2 .

35. The radiation chemical yield of H_2 , CO_2 and CO in general show a linear dependency on dose.

36. Gaseous products in ion exchange columns exposed to radiation are liable to produce gas blocks and channelling, the results of which can be more catastrophic than the radiation degradation of the resin matrix.

37. Synthetic organic ion exchangers which are not true compounds are significantly less resistant to radiation damage when compared with inorganic ion exchangers, which are well defined chemical species. However, there exist other serious limitations to the use of inorganic ion exchangers in radiochemical processing.

These generalizations are valuable in qualitatively evaluating the radiation chemical effects on synthetic organic ion exchangers. However, it should be recognized that the processes involved are too complex to be presented as simple rules, which are universally applicable. Some discussions of important phenomenological changes, proposed mechanisms and recognized limitations to the above mentioned general rules are considered in the following section.

V. RADIATION EFFECTS ON ION EXCHANGE RESINS

Ionizing radiation doses of ten to one hundred megarads significantly alters the properties of synthetic organic ion exchangers. Anion exchangers, in general, exhibit less resistance to radiation damage when compared with cation exchangers. The radiation chemical effects on ion exchange resins are dependent on several factors related to the resin itself. These include the chemical composition, the ionic form in which they are exposed to radiation, the moisture content and the degree of crosslinkage of the macromolecular structure. In addition, many factors related to the radiation sources and the environment of the resins during irradiation control the overall radiation chemical change that of the ion exchange resins experience.

V.1 Polymerization Type Cation Exchange Resins

Since many of the commercially important cation exchangers are polymerized nuclear sulfonic type, many of the reported experimental studies have used this type of resin. It has been satisfactorily demonstrated that the radiation chemical stability of polymerization type cation exchange resins is a function of the degree of cross-linkage of their macromolecular structure. Several experimental studies have confirmed that the radiation stability of these resins increases with increased cross-linkage. Early work by Wedemeyer (37) and Cathers (95) on styrene-divinylbenzene polymerization type Nalcite-HCR resins, as well as more recent studies by Semushin, et al. (9) on methacrylic acid-divinylbenzene copolymer KB-4 and Kiseleva et al. (41) on acenaphthalene-divinylbenzene KU4, are typical of the various studies reported, illustrating the relationship between radiation stability and cross-linkage. There have been several other investigations during the past two decades that have generally concluded that an increase in cross-linkage had beneficial effects on the radia-

tion stability of synthetic organic cation exchangers (4, 10, 18, 22, 23, 43, 46, 48, 49, 93).

One of the ways of characterizing the stability of ion exchangers is by measuring the change in total exchange capacity (TEC) as a function of irradiation. Many commercially important polymerization type cation exchangers have been examined using these procedures. Resins with crosslinkage varying from 4 to 24% examined during various experimental studies have confirmed the stabilizing influence of cross-linkage both in the starting material and the cross-linkage produced during the course of irradiation. While resins with low cross-linkage show a higher radiation damage initially, the subsequent changes in the TEC are more or less identical. This may be due to the initial processes involving cross-linkage and rupture of $-SO_3H$ groups resulting in resins of somewhat similar radiation chemical properties during the initial stages of irradiation.

Unlike the generally held view, Tulupov et al. (43) reports that an increase in cross-linkage (DVB content) of the nuclear sulfonic resin, KU-2, from 8% to 24% has no significant effect on the radiation stability as measured by the TEC. Detailed results of this study are tabulated in Table III.

There are very few experimental studies on radiation chemical effects on ion exchange resins that can be justifiably compared to generate quantitative data typical of a class of synthetic resins. Figure 1 is a comparison of three independent experimental studies (23, 43, 49) using nuclear sulfonic styrene-DVB polymeric resins. The details of the experimental conditions and a comparison of the change in TEC at a dose of about 5×10^8 rads are summarized in Table V. The significant differences in the rate of change of TEC with dose in these three studies cannot be adequately explained by the minor changes in the experi-

Figure 1. A comparison of the change in total exchange capacity (TEC) of 4% cross-linked styrene-DVB sulfonic acid resin [23,43,49].

Table V

COMPARISON OF THE RESULTS OF THREE EXPERIMENTAL STUDIES
ON 4% CROSS-LINKED STYRENE-DVB RESIN

<u>Resin</u>	<u>Radiation Source*</u>	<u>Water Content (%)</u>	<u>Initial TEC</u>	<u>% Change in TEC^{††}</u>	<u>Ref.</u>
Dowex 50 x 4	X-rays (1.44×10^7)	28	4.95	42	(44)
Dowex 50W x 4	γ -rays (1.25×10^6)	66	5.35	66	(23)
KU-2 x 4	γ -rays (8.46×10^6)	70	10.0	50	(43)

*The number in the paranthesis indicates the radiation dose rate in rads/hr.

^{††}TEC is the total exchange capacity of the resin.

mental parameters of these three investigations. This type of difference in the reported results of different experimental studies on similar types of resin are not uncommon.

A factor that may be responsible for the differences in the results of various experimental studies is the difference in the constituents of the resin. Such differences can be due to various impurities that are commonly present in the starting materials used in the polymerization of the resin itself. Wiley et al. (46) reports an interesting study on the radiation stability of sulfonated styrene-divinylbenzene resins with various isomers of divinylbenzene and mixtures of the isomers of this cross-linking agent. Wiley, et al. have found that there are measurable differences in the degree of radiation chemical decomposition of commercial resins compared to various laboratory preparations of the same composition, the latter being more radiation resistant. Further, it is reported that the variations in the use of pure para- or meta- substitution products of DVB in resin preparations did not result in any significant differences in the radiation stability of the product. In a systematic investigation of the constituents of commercial DVB, using vapor-phase chromatographic separations, Wiley and Associates (91) found that the commercial DVB contained eight or ten different compounds and their ratio varied in DVB from different commercial sources. The authors point out that it may be the ethylvinylbenzene impurity in DVB used in some of the preparations which enhances its radiation stability (46). It is also suggested (92) that the structural factors which presumably create differences in the rates of sulfonation for p and m-substituted DVB should be operative in the desulfonation during irradiation and the reactions induced under the influence of radiation.

An important parameter that is often used as a measure of radiation chemical effects is the G value. The degree of cross-linkage of the resin and its relationship to G value has been reported during several investigations. The results of one such study (49) are illustrated in Figure 2. The data presented are in terms of energy required (in e.v.) per $-\text{SO}_3\text{H}$ group released during the irradiation of the nuclear sulfonic resins of various cross-linkage. In 4 and 8 percent cross-linked Dowex 50 resins, there is an initial sharp increase in the energy required (or a sharp decrease in the G value) for the removal of $-\text{SO}_3\text{H}$ groups, whereas in resins with higher cross-linkage such a deflection in the slope of the curve is not apparent. The change in G value with dose is explained by the changes in the resin matrix. Prior to irradiation, the $-\text{SO}_3\text{H}$ groups are uniformly distributed in the resin matrix. During early stages of irradiation, the externally located functional groups would be readily accessible for direct interaction of radiation or radiation produced species. However, as the irradiation progresses, loss of the internally located $-\text{SO}_3\text{H}$ groups, which are less susceptible to direct or indirect action of radiation becomes important and therefore more and more energy has to be expended per dissociation of the remaining $-\text{SO}_3\text{H}$ groups.

Another property of ion exchange resins that changes with cross-linkage is the swelling ability of the matrix. Swelling of the resin is caused by the expansion of the structure as a result of water (or other liquid) molecules penetrating the matrix. This effect is a maximum for low cross-linkage resin because of the flexibility of the macromolecular structure. Water is also associated with the hydrophylic exchange groups, which also contribute to swelling.

It is generally believed that the swelling ability of cation exchange resins decreases as a result of radiation exposure. As the irradiation of resin

Figure 2. Changes in radiation chemical yield (expressed as eV/SO₃H group released) as a function of cross-linkage and dose [49].

is continued, the cross-linkage increases and the functional groups are ruptured resulting in a decrease in the water content of the resin matrix. A typical study (51) of the change in swelling of the resin as a function of total dose and dose rate is illustrated in Figure 3. The sulfonic cation exchange resin KU-2 shows significant changes in its swelling capacity up to a total dose of 4×10^9 rads and a complete breakdown beyond 10^{10} rads.

Utley (49) has shown that for various cross-linkage of Dowex-50 resin with a moisture level of $\sim 25\%$, there is a consistent decrease in water absorption capacity, when exposed to x-rays. However, Smith, et al. (22) have pointed out that the moisture content of Dowex 50 x 12 increases steadily up to $\sim 2.8 \times 10^8$ rads, which they believe is due to a decrease in the cross-linkage of this resin during irradiation. Similar increases in moisture holding capacity of Dowex-50 have been reported by Bauman (14) and by Kazanjian et al. (23, 25). One further observation by Kazanjian et al. (25) is that the moisture content of Dowex-50 W begin to decrease when the radiation dose increases above $\sim 4 \times 10^8$ rads. Similar observations have been reported by Dornow et al. (11, 96) for the cation exchanger AG 50W X 8 and by Kiseleva et al. (52) for KU-2 sulfonic acid resin. During irradiation in water, it is observed that the swelling capacity of KU-2 resin increased with dose of $\sim 8 \times 10^7$ rads, but with higher doses the swelling decreased. In acidic solutions, however, the decrease in swelling capacity at higher doses was not as significant as irradiations in pure water (52).

Cation exchangers of the styrene-DVB type undergoes weight losses during irradiation. This change in weight is attributed to the attrition of the macrostructure due to rupture of functional groups and evolution of gaseous products. The weight change of resin is both dose and dose-rate dependent (51). Figure 4 is an illustration of the percent loss or weight of the sulfonated

Figure 3. Change in swelling capacity of styrene - DVB copolymer with dose and dose-rates [51].

Figure 4. Weight loss of styrene-DVB sulfonic resin as a function of dose at two different dose rates [51].

styrene-DVB copolymer as a function of dose (51). The data illustrating the loss of weight at higher dose rate shows increased attrition rate and higher rate of weight loss. In a more recent study, Pesek and Spurny (97) examining a variety of strongly acidic cation exchange resins, have shown that both the change in exchange capacity and weight losses depend significantly on the degree of cross-linkage and porosity of the resin.

As pointed out earlier, radiation chemical effects are influenced by the moisture content of the resin. An illustration of the loss of exchange capacity (based on $-\text{SO}_3\text{H}$ groups) as function of water content of the resin is presented in Figure 5. This data from Kiseleva, et al. (38) shows that the radiation chemical effects are significantly influenced by the moisture content of the resin until the sorbent-water ratio reaches a value of about 1:1. Beyond this point, the water content does not seem to have any significant influence on the rates of reactions. The dependence of total dose on the loss of exchange capacity are also illustrated in Figure 5.

A study of the interaction of sulfonic acid ion exchange resins with tritiated water during α -irradiation has shed some light on the degree of interaction between the radicals produced in the resin structure and those resulting from the radiolysis of water molecules. Mohorcic et al. (33) found that during irradiation of ion exchange resins in tritiated water, a significant amount of hydrogen (^3H) from water gets irreversibly bound in the resin matrix. The data from this study (33) included in Table III and illustrated in Figure 6 shows the variations in the bound tritium in the resin phase as a function of dose at various moisture content. In the reported results, the authors chose to ignore isotope effects and conclude that the reactions of tritium radical with

Figure 5. Loss of exchange capacity (based on SO_3H groups) as a function of water content [38].

Figure 6. Irreversible bonding of tritium from water in the cation exchanger matrix during irradiation [33].

carbon atoms from which the $\text{-SO}_3\text{H}$ group has ruptured could be the most important mechanism by which the tritium gets incorporated into the resin matrix.

Several experimental studies, under a variety of conditions, have demonstrated that the presence of air, oxygen and moisture accelerates radiation decomposition of cation exchangers. A parallel effect identified in the polymerization type cation exchange resins is the formation of new functional groups that act as new exchange sites for cations. Through careful experimentation involving the study of dissociation constants of the acid radicals involved, these new functional groups formed during the irradiation of cation exchange resins have been identified as phenolic hydroxyl groups and carboxylic groups. The results of one of these studies (51) is illustrated in Figure 7. The formation of -OH and -COOH groups in the resin matrix increases the exchange capacity of the resin. However, the net change in TEC is a decrease because of the relatively increased loss of $\text{-SO}_3\text{H}$ functional groups which provides some of the sites for the formation of -OH and -COOH groups. Figure 7 shows the net change in exchange capacity as well as the changes in the exchange capacities due to $\text{-SO}_3\text{H}$, -OH and -COOH functional groups. Kiseleva, et al. (51) have studied the formation of new functional groups at three different dose rates and only a few of these results are included in Figure 7. Total exchange capacity for the irradiation at a dose rate of 1.27 rads/hr was calculated by summing up the reported values of the exchange capacities for the three functional groups. These authors, while studying the effect of different types of aqueous media on the formation of new functional groups, have demonstrated that the rate of formation of new -OH and -COOH groups are most pronounced in water, when compared with aqueous solutions of nitric, lactic and acetic acids (52).

Figure 7. Variation in the TEC and exchange capacities with respect to individual functional groups during the irradiation of a sulfonic polymerization type resin [51].

V.2 Other Types of Cation Exchange Resins

Cation exchange resins of the polycondensation type are more resistant to radiation than the polymerization type resins, although their chemical, mechanical and thermal properties are significantly poorer. Experimental studies using Dowex-30, Amberlite IR-105, Duolite C-3, Zeolex, KU-1, KU-5, KU-32, KU-33, Catex FN, F₂S, RF-8 etc. have repeatedly confirmed this generalization (1, 6, 12, 34, 39, 40, 54, 58, 94, 95). However, there is a reported study by C'ostachel and Furnica (96), which does not support this generalization.

The change in properties such as the decrease in TEC, change in the swelling ability, appearance of new functional groups, weight loss and gas evolution are common to both types of cation exchange resins. The difference between the two types being in the rate of change of these properties with dose, which take place at a slower pace in the polycondensation type cation exchange resins.

Among the strong acid type cation exchange resins containing C-S bonds, the chemically unstable phenol-sulfonic acid-formaldehyde resin is more stable to ionizing radiation in a variety of aqueous solutions than the chemically stable styrene-DVB-sulfonic resin (58).

Investigations of radiation stability of cation exchangers in relation to their functional groups have showed that the weakly acidic carboxylic acid resins containing C-C bonds are more resistant to radiation than the strongly acidic resins containing C-S, C-P or C-O bonds (6, 12, 58). A polycondensation resin based on salicylic acid and furfural has high resistance to radiation compared to several condensation products of sulfonic acid derivatives (6). Its exchange capacity, swelling and other characteristics are unchanged at radiation doses of 2×10^8 rads. Shigematsu and Oshio (12) confirms this generalization

of the radiation stability of weakly basic cation exchangers. Among eight different types of cation exchangers exposed to a total dose of 4×10^7 rads, a carboxylic acid resin, Duolite CS101 showed an increase of 2% in TEC. All the other cation exchangers in this study (12) showed varying losses of TEC ranging from 0.5 to 10.5% during the period.

V.3 Radiation Protective Effect of Some Cation Exchangers

The radiation protective effect of ion exchange resins primarily result from the nature of their macromolecular structure. The protective effect of macromolecules such as naphthalene, anthracene, phenanthrene and hydroquinone in polycondensation type resins have been systematically studied (40, 54). The findings are in agreement with the established findings concerning the protective effect of aromatic compounds. However, there are no significant differences in radiation stabilities among the resins containing the above mentioned aromatic configurations (40).

Another form of radiation protection effect is known to exist in salt forms of cation exchangers. In general, the salt forms of cation exchange resins are more radiation resistant than their H^+ -forms. Further examination of this phenomenon has repeatedly demonstrated that in aqueous solutions, certain ionic species attached to the resin provides a significant radiation protection effect (9, 10, 38, 42, 56, 60, 61). This protection effect is exceptionally predominant in cation exchangers with ionic species of variable valence (10, 38). One unique exception reported (1) is that the radiation stability of the salt forms of polycondensation type cation exchange resin (even with reducible ionic species) is not significantly different from its H^+ -form.

Ichikawa et al. (10) reported on the effects of adsorbed species on radiation damage to Dowex-50 W and Kiseleva, et al. (38) have done similar studies

using KU-2 cation exchange resin. When Dowex-50 W resins of various ionic forms were exposed to similar doses of γ -radiation, the loss of exchange capacity varies from ~ 1 to 7% depending on the ionic form of the resin (10). Some of the results from this investigation and (38) are summarized in Table VI which illustrates the distinct protective effect by variable valence ionic species on sulfonic polymerization type resins. In addition, Ichikawa et al. (10) also report on the irradiation of Dowex-50 W in Na^+ and K^+ , NH_4^+ , Ca^{2+} , Mg^{2+} and Mn^{2+} forms. None of these seem to have any significant effect on the radiolytic decomposition of the resin under similar conditions of irradiation. Similar findings were reported by Skorokhod, et al. (42) showing that there is no appreciable difference in the radiation damage to KU-2 resin when irradiated in the H^+ form or in Li^+ , Na^+ and K^+ forms.

Similar protective effects of Cu^{2+} ions in resin matrix have been observed for amphoteric resins (56) and for methacrylic acid-DVB copolymers (9).

V.4 Anion Exchange Resins

Radiation effects on anion exchange materials are less extensively studied compared to the study of similar effects on cation exchangers. Resins of the polymerization type incorporating quarternary ammonium groups --

$\text{C}_6\text{H}_4\text{CH}_2\text{N}^+(\text{CH}_3)_3\text{OH}$ -- continue to be the most important anion exchanger used in the process industry. Several of this type of resin have been the subject of radiation chemical effect studies over the past two decades (1, 12, 13, 16, 17, 19, 20, 22, 24, 26, 28, 29, 30, 31, 32, 37, 50, 53, 62, 63, 97). However, only a few of these experimental studies offer any quantitative data of significance that are applicable to all polymerization type anion exchangers.

Radiation chemical changes in anion exchange resins are characterized by darkening of the color of resin, evolution of odorous free amines, gas evolu-

Table VI

EFFECT OF IONIC FORMS OF CATION EXCHANGE RESINS
ON RADIATION STABILITY

<u>Resin*</u>	<u>Ionic Form</u>	<u>Integral Dose (Rads)</u>	<u>% Loss of TEC^{††}</u>	<u>Ref.</u>
Dowex 50W	H ⁺	6.1x10 ⁷	6.8	(10)
Dowex 50W	Cu ²⁺	"	0.7	"
Dowex 50W	UO ₂ ⁺	"	0.7	"
Dowex 50W	Fe ³⁺	"	0.6	"
Dowex 50W	H ⁺	1.9x10 ⁸	18.3	(10)
Dowex 50W	Fe ³⁺	"	1.5	"
KU-2	H ⁺	2.1x10 ⁹	21.0	(38)
KU-2	Ce ⁴⁺	"	17.2	"
KU-2	Cu ²⁺	"	8.5	"
KU-2	Fe ³⁺	"	6.4	"

*Dowex 50W resin was irradiated in wet conditions and KU-2 resin in the absence of air.

††TEC is the total exchange capacity of the resin.

tion, loss of exchange capacity, decrease in swelling capacity and degradation of the resin matrix. As a rule, the resistance of anion exchange resins to radiation does not vary very much with the basicity of the resin. This is in contrast to the high radiation stability of strong acid cation exchange resins compared to weakly acidic resins. Among various anion exchange resins, those containing aromatic systems with conjugated bonds in the functional groups are more resistant to radiation than all other types of synthetic organic ion exchangers. Examples of the radiation stabilities of this type of resin are further discussed in Section V.5 of this chapter.

Most of the polymerization type anion exchange resins are based on styrenedivinylbenzene copolymers. Even though this structure is known to be highly resistant to radiation damage, the anion exchangers containing quarternary, teritary, secondary or primary amino groups begin to show marked attrition at doses of $\sim 10^7$ rads. Cation exchange resins of similar structural origin generally suffer little damage at 10^7 rads of exposure. Again, in general, the attrition of anion exchangers are more extensive in the presence of water or aqueous electrolytes as compared to irradiations of resins in the air-dry state.

The available experimental data on the radiation effects on anion exchangers indicate that a complex mechanism of radiation induced chemical changes takes place in strongly basic monofunctional anion exchangers. It is suggested (1, 20, 28) that there may exist two types of exchange groups that differ in relative stability toward radiation chemical changes. These groups are believed to be the ones attached to the aromatic ring in ortho- and para-positions; the ortho groups being less stable than the para-substituents (20). There is adequate experimental evidence to suggest that strongly basic

quarternary ammonium type resins undergo radiation decomposition primarily via deamination processes. This leads to the breakage of the C-N bond connecting $N(CH_3)_3$ groups with the benzyl radicals (16, 17, 28). Other competing reactions, in addition to C-N bond rupture, have been suggested by Hall and Streat (28), Basinski et al. (16) and by Narebska, et al. (17), while studying the radiation decomposition of Deacidite-FF (28) and Zerolitt FF-IP (16, 17). Egorov and Novikov (1) also point out that anion exchange resins of the quarternary ammonium type lose their exchange capacity primarily due to the decomposition of functional ion exchange groups. They also suggest that this decomposition is dependent on the nature of the functional groups and their ionic form. Like cation exchangers, the salt forms of anion exchangers are reported to be more radiation resistant compared to hydroxide forms. While there are some reported exceptions to this (12, 16, 22), generally the nitrate, chloride, chlorate and sulfate forms of anion exchangers are reported to be more radiation resistant (1, 12, 16, 22, 28, 29, 30).

Several of the experimental studies have attempted to examine the loss of exchange capacity of anion exchange resins as a function of absorbed dose. The results of one study by Kazanjian and Horrel (24) are summarized in the illustrations in Figure 8. It is evident here that both ionic form and the environment of the resin during irradiation influences the radiation chemical changes as measured by the loss of total exchange capacity. The resin irradiated in the nitrate form is much more stable than the chloride forms. The ability of nitrate ions to scavenge hydrated electrons and the strong oxidizing characteristics of chloride radicals are attributed as the reasons for this behavior (24).

Anion exchangers with quarternary ammonium base groups, when irradiated, steadily loses the strong base exchange capacity. However, some of the groups

Figure 8. Change in total exchange capacity of a quarternary ammonium type anion exchanger with radiation dose.

degrade to weakly basic amino groups, which in turn improves the total exchange capacity of the resin (16, 28). It is also reported that the irradiation of anion exchangers induces oxidation with the formation of carboxyphenolic and hydroxy groups similar to radiation chemical effects in strongly acidic cation exchangers. This process introduces weakly acidic cation exchange sites in the matrix.

It was pointed out earlier (Section V.1) that several experimental studies on cation exchangers showed that increased cross-linkage of the resin sometimes exhibited greater resistance to radiation damage. This type of relationship between degree of cross-linkage and radiation stability has been apparent in anion exchangers AV-17 and Zerolitt FF-IP (1,16). However, an earlier study by Wedemeyer (37) using Dowex-1 resins of various crosslinkages showed maximum degradation (minimum stability) with 4% cross-linked Dowex-1. Increased radiation stability was apparent in Dowex-1 for both higher and lower cross-linkages.

Identification and quantitative analysis of the decomposition products of anion exchange resins during irradiation was undertaken by several investigators (17, 24, 28, 29, 30, 31, 32, 50). Quantitative yields of tertiary, secondary and primary aliphatic amines and ammonia have been studied. Kiseleva, et al. (50) have reported the results of their analyses of both tertiary and secondary amines from AV-17 anion exchanger under two irradiation conditions. Figure 9 illustrates some of the results on t-amine losses from the resin matrix as a function of dose. The amounts of secondary amines identified (not shown in Figure 9) were extremely small compared to the quantities of t-amines. Also included in Figure 9 is the percent weight loss (dotted line) of the resin as a function of absorbed dose. It is obvious that the decrease in weight of these specimens cannot be accounted for by the loss of amino groups alone. Hall and

Figure 9. Percent weight loss and the loss of tertiary amine from AV-17 anion exchange resin as a function of absorbed dose.

Streat (28) in a detailed study of all the basic products (trimethylamine, dimethylamine, methylamine and ammonia) from the anion exchange resin Deacidite-FF reports that all the loss of exchange capacity of this anion exchanger during irradiation can be accounted for by these products alone. Litowska and Narebska (20) using Imac S5-40 anion exchanger have examined the water soluble aliphatic amines and conclude that most of the loss of exchange capacity can be accounted for by deamination rather than other forms of degradation.

It is generally well established that irradiation of anion exchangers with quarternary ammonium groups results in the formation of soluble amines and ammonia, with trimethylamine as the major decomposition product. However, the yield of these products vary in a rather complex manner depending on the moisture content of the resin. Kiseleva, et al. (50) have reported on both the weight loss of the resin and the loss of amines as a function of water content of AV-17 anion exchange resin. The results of this study, illustrated in Figure 10, was conducted at a radiation dose of $\sim 10^9$ rads. The trimethylamine loss from the resin matrix increases steadily up to a point where the water to resin ratio reaches a value of about 0.2:1. Beyond this point, further increase in the water content drastically reduces the yield of trimethylamine. The variation in the weight loss of the resin almost parallels this relationship of trimethylamine production with water content of the resin. These variations cannot be solely explained by the interaction of the resin with the radiolysis products of water, since in this case the dilution law characterizing an indirect action of the radiolysis product of the medium does not hold.

Polycondensation type anion exchange resins are mostly polyfunctional resins of medium and low basicity, with a few exceptions (1). Polycondensation type anion exchangers containing purely aliphatic structural constituents and

Figure 10. Loss of tertiary amine and percent loss of weight of AV-17 anion exchanger as a function of water content of the resin (at $\sim 10^9$ rads).

those with aromatic groups are common. Those with aromatic groups are less sensitive to radiation damage owing to the protective effect of these groups. Radiation chemistry of polycondensation type resins have been less rigorously explored and many features of their radiolysis remain unexplained.

V.5 High Radiation Resistance of Some Anion Exchange Resins

A number of studies have demonstrated that anion exchangers containing aromatic systems with conjugated bonds have high radiation stability. Smith and Groh in 1961 reported (22) on the unusually high radiation stability of Permutit SK, a chemically less stable polyfunctional resin derived from copolymerization of styrene, divinylbenzene and pyridine. Since that time several anion exchangers containing pyridine, quinoline and derivatives of pyridine or quinoline have been shown to possess high degrees of resistance to radiation decomposition (1, 30, 31, 32, 53).

Resins prepared from 2,5 methylvinyl-pyridine and its substitution products were shown to exhibit no loss of exchange capacity for a total absorbed dose of $\sim 1.4 \times 10^9$ rads, when irradiated in water (30). Similar types of radiation resistance were exhibited by resins prepared from quinoline and isoquinoline with chloromethylated styrene-divinylbenzene copolymers under a variety of irradiation conditions. When irradiated in vacuum-dry and air-dry conditions, the exchange capacity of these resins changed by less than 10% at a total absorbed dose of $\sim 10^9$ rads. However, irradiation of these resins in water and 7N HNO_3 resulted in total exchange capacity losses of 15% and 55% respectively at the same dose. Anion exchange resins with pyridine groups show a change in exchange capacity of only about 2.5% when irradiated in 7N HNO_3 at $\sim 10^9$ rads. These resins with pyridine exchange groups are more stable to

ionizing radiations than all the other types of synthetic organic ion exchangers that have been examined for radiation induced chemical changes (1, 30, 53).

V.6. Gas Evolution During the Radiolysis of Ion Exchange Resins

Irradiation of ion exchange resins, just like organic high polymers, result in evolution of gaseous products. This phenomenon is of great importance in the process applications of ion exchange resins, since the gases evolved can seriously interfere with the use of ion exchangers. There are only a few reported experimental studies which have attempted to study the nature of gas evolution during the irradiation of ion exchange resins (1, 23, 24, 26, 27, 33, 42, 45, 47). Of these, the works of Moharcic et. al. (33, 47) and Kazanjian et. al. (23, 24) have been successful in making some quantitative estimates of the gaseous product formation during the radiolysis of ion exchange resins.

The main gaseous products formed during the irradiation of ion exchange resins are hydrogen and carbon dioxide. Other gases such as carbon monoxide, oxygen, methane, nitrogen, and oxides of nitrogen have been identified. The radiation chemical yields of some of these major products are summarized in Table VII. Most of the results reported are for cation exchangers, but some attempts have been successful in identifying and measuring the gaseous products of radiolysis of anion exchange resins (24, 26). During the irradiation of cation ion exchange resins H_2 , CO_2 , CO , SO_2 , O_2 and CH_4 have been identified (1, 23, 33, 47), while H_2 , CO_2 , CO , N_2 , N_2O and NO have been reported among the gaseous products of radiolysis of anion exchange resins (24, 26, 27).

In cation exchange resins, the evolution of hydrogen is a linear function of absorbed dose (47). Hydrogen evolution is also shown to increase with the water content (swelling) of the resin. The results reported by Moharcic and Kramer (47) on Dowex 50W resin are used in the illustration in Figure 11. The

Figure 11. Evolution of hydrogen during the irradiation of Dowex 50W.

G-values for hydrogen (see Table VII) evolution from the lithium salt form of this cation exchange resin shows considerable high stability, whereas the H^+ form under water shows the least stability toward hydrogen formation.

Sulfur dioxide is formed by the direct action of ionizing radiation on dry forms of sulfonic acid resins. In the presence of water, the SO_2 undergoes secondary reactions and for this reason SO_2 is not identified during the irradiation of moist and wet resins. The evolution of SO_2 during the irradiation of two ionic forms of Dowex 50W in dry and swollen forms reported by Moharcic et. al. (47) are illustrated in Figure 12. These authors also point out that when a polycondensation type sulfonic resin (Zeo-Karb 215) was irradiated in the dry form, under similar irradiation conditions, only traces of SO_2 were identified. The G-values for SO_2 formation reported in Table VII are all calculated for the lowest absorbed dose.

Carbon dioxide and carbon monoxide are products of irradiated resins. Like hydrogen, the evolution of CO_2 and CO are quite linear with absorbed dose. Again, the results of Moharcic and Kramer (47) on CO_2 and CO evolution from Dowex 50 are used in the illustrations in Figures 13 and 14. In general, the radiation chemical yield of carbon monoxide is significantly less than that of carbon dioxide.

Comparative studies done on two commercial cation exchangers, Dowex 50W and Zeo-Karb 215, have demonstrated that polycondensation type cation exchangers are more resistant to gaseous product formation during radiolysis, when compared with styrene-divinylbenzene copolymer resins (47).

Experimental studies identifying and measuring gaseous products of the radiolysis of anion exchangers are very few, although it is recognized that the irradiations of anion exchangers are accompanied by copious evolution of gases (1,

Table VII

G-values for Gaseous Product Formation During the
Radiation Decomposition of Ion Exchange Resins

Resin	Ionic Form	Irradiation Condition	$G(H_2)$	$G(SO_2)^*$	$G(CO_2)$	$G(CO)$	Ref. No.
Dowex 50W x 4	H^+ , Na^+	Air-dry and 0.1N Hel	0.1	-	-	-	[23]
Dowex 50W x 10	H^+	Dry	0.026	0.087	0.035	0.009	[47]
KU-2 x 8	H^+	Dry	1.1	-	0.06	-	[1]
Zeo-Karb 215	H^+	Dry	0.051	0.001	0.019	-	[47]
Dowex 50W x 10	H^+	12-47% water	0.04 to 0.12	~ 0.14	~ 0.023	~ 0.022	[33]
Dowex 50W x 10	Li^+	Dry	0.001	0.26	0.007	0.002	[47]
KU-2 x 8	Na^+	Dry	1.0	-	0.03	-	[1]
Dowex 50W x 10	Li^+	Swollen	0.095	0.006	0.019	0.009	[47]
KB-4P-2	H^+	Swollen	1.22	-	0.60	0.39	[1]
Dowex 50W x 10	H^+	Swollen	0.095	0.006	0.019	0.027	[47]
KB-4P-2	Na^+	Swollen	3.10	-	0.09	-	[1]
Zeo-Karb 215	H^+	Swollen	0.12	0.005	0.046	0.005	[47]
Zeo-Karb 215	H^+	Immersed in water	1.7	0.002	0.43	-	[47]

Table VII (Cont'd)

Resin	Ionic Form	Irradiation Condition	$G(H_2)$	$G(SO_2)^*$	$G(CO_2)$	$G(CO)$	Ref. No.
Dowex 50W x 10	H^+	Immersed in water	1.7	-	0.41	-	[47]
Dowex 50W x 10	Li^+	Immersed in water	1.3	-	0.41	-	[47]
Dowex 1 x 4	NO_3^-	Air-dry	0.09	-	-	0.02	[24]
Dowex 11	NO_3^-	Air-dry	0.10	-	0.06	0.01	[26]
Dowex 1 x 4	NO_3^-	In 7N HNO_3	0.02	-	0.6	-	[24]

*G-values for the lowest absorbed dose.

Figure 12. Sulfur dioxide generation during the radiolysis of Dowex 50W.

Figure 13. Carbon dioxide evolution during the irradiation of various forms of Dowex 50W.

Figure 14. Evolution of carbon monoxide during the irradiation of two ionic forms of Dowex 50W.

24, 26). Some of the results of Kazanjian et. al. (24, 26) on the evolution of gases during radiolysis of ion exchange resins could be very valuable in predicting potential gas blocks and channeling in ion exchange columns used in intense radiation fields.

V.7 Mechanistic Considerations in the Radiolysis of Ion Exchange Resins

The purpose of this section is to discuss the mechanism of resin radiation damage in the most general terms plausible. The discussion will not cite specific experimental results since the state of knowledge on general mechanisms does not warrant such detail. Rather an overview approach will be taken which will include a general approach for discerning mechanistic details and identify the required specific parameters. The reader is referred to references (1, 21, 38, 46, 57, 58 and 66) for the experimental details upon which the following discussion is based.

Under the conditions used in waste reprocessing the action of ionizing radiation on resin materials can, at least formally, be classified into two competing processes: direct radiation action on the resin matrix and indirect attack on the exchangers by solvent or solute radiolysis products. Both processes will be a function of reprocessing conditions such as mobile phase composition, contact time, temperature, pressure, packing, density etc. There is a definite absence of general common factors by which one can characterize the susceptibility of a given resin to radiation damage. Radiation studies of both dried resin and heterogeneous mixtures of resins and solutions were considered in formulating this section.

Radiolysis studies of dried resins are useful in terms of discerning direct radiation damage mechanisms.

Alteration in resin properties such as exchange capacity, acidity, basicity, swelling, solubility, selectivity and exchange kinetics may be a result of functional group cleavage or alteration and/or matrix cross-linking or degradation. The structure and cross-linking properties of resin matrices are important because an increase in the degree of cross-linking stabilizes functional and matrix groups. This stabilizing behavior is interpreted in terms of the cage effect whereby the radiation produced free radical chain and function group fragments can not escape their cleavage site nor can external species enter this local cage before recombination occurs. Thus the net resin damage per unit radiation dose is less. These cage reactions are represented by reactions (4) and (5) below.

The electronic structure of resin matrix components is important due to energy transfer effects. This behavior manifests itself in the form of different susceptibilities to degradation or cleavage for a given matrix or matrix/function group combination. Resin matrices containing unsaturated linkages, in particular aromatic groups, transfer energy readily to the resin exchange functional groups thereby decreasing resin degradation but increasing functional group loss (i.e., decreasing exchange capacity). Reaction (15) below depicts this energy transfer process. For a given resin susceptible to energy transfer effects, the order of decreasing functional group stability has tended to be: phenolic and sulfonic > secondary and tertiary amine > carboxylic and quaternary ammonium. Due to conflicting results on phosphate and pyridine groups, the relative stability of these groups cannot be presently assigned in the above series. It must be emphasized that general trends such as the above are by no means without exception. For example, the exchange functional group radiation stability of styrene-divinylbenzene resins decreases in the order:

pyridine > sulfonic and carboxylic > primary, secondary and tertiary amine > quaternary ammonium. Apparently, there is a general tendency for increased susceptibility to cleavage as the degree of substitution on the functional group increases.

The radiolysis of a resin-solution mixture will be a function of the kind of ionizing radiation (α , β , γ or x-ray), the dose rate and the total dose. The radiation from nuclides during ion exchange stages in a spent fuel reprocessing stream will interact in proportion to the mass energy absorption coefficient ratios (for γ - and x-rays) or mean mass stopping power ratios (for α or beta particles) of the compounds, molecules or functional groups comprising the stream. For materials of similar composition these absorbed dose ratios can be approximated by the electron density ratios for the stream components. The production reactions of reactive species by radiation for an ion exchange column are:

where R - X represents any ion exchanger with functional group X, R denotes any resin matrix component, AB represents any solvent or solute component, the dot by a symbol denotes a free radical species, the asterisk denotes an excited species and the wavy reaction arrows conotate interaction between a species and one of the forms of radiation.

The initial populations of the radiation generated reactive species (i.e., the products in the above reactions) will be a function of the absorbed dose ratio for a given species, the absorbed dose rate $I(t)$ and the radiation chemical yield $G(t)$ where t denotes a possible time dependent function. The fraction of the initially generated species population available for net reaction with the ion exchange resin will depend upon the reaction rates for loss of reactive species

and upon reactions of the initial species with solvent, solute or resin to form new reactive species P (e.g., $H + H_2O \longrightarrow H_2 + OH$). The delta sign Δ in the above equations denotes energy release in the form of heat or light. Note that each of the above reactions represents one reaction class such that there could, and probably will be, several reactions in each class.

Not all of the above reactions will be competitive. Some rates will be much faster than the average such that they will constitute the rate determining steps in producing reactive species for resin attack. For example, the direct interaction of the ionizing radiation can be eliminated for minor stream components based on electron densities. If the reaction rate constants for the loss of species reactions are known the mechanism can be further simplified. It is

at this point that the lack of basic knowledge prevents clarification of the resin radiation damage mechanism. Experimental work is needed to identify the yields and kinetics of these reactive species.

The reactions that the reactive species can undergo with the resin are:

Here again the mechanism cannot presently be simplified since the relevant rate constants are not known. Note that specific study of each resin under varying reaction conditions would not be required. If the various classes of the above reactions were sufficiently characterized such that the rate determining steps could be identified and representative rate parameters for these steps were known, a kinetic model could be built for predicting the radiation damage behavior of resins under varied process conditions.

The utility and attainability of using individual chemical reactions to build a mechanistic model which describes and predicts the course of complex chemical systems is exemplified by results obtained by atmospheric chemical

studies. The number of possible chemical reactions which can occur in the atmosphere is large in comparison to those for a nuclear waste reprocessing stream. Yet through careful experimentation the more important atmospheric reactions have been identified and formulated into mechanistic models. These studies reveal that using the individually determined rate parameters one can predict data that agrees with the results observed in the atmosphere. Thus the very complex and uncontrolled (by man) chemistry of the atmosphere can be described and predicted from an understanding of the basic chemistry. For nuclear reprocessing streams, where the reaction conditions are carefully controlled, similar predictive modeling can be realized. Before such useful modeling can be achieved, more experimental work on the basic reactions important to reprocessing must be done.

In the absence of such information one has to look for empirical relationships based on known resin studies. This approach is at best tenuous since one can not be sure that empirical relationships based on one set of data for a resin also holds for this same resin under different conditions (much less for a new resin). This, to a large part, is exemplified by the extensive inconsistency of the literature data. Of the numerous equations cited in the literature most can be formulated into one of two types of relationships. Both relationships attempt to describe a given resin properties, for example, the behavior of resin capacity C , as a function of total radiation dose D . One is based on an exponential relation between C and D :

$$C = C_0 e^{-kD} \quad \text{(Equation 1)}$$

where C_0 is the initial resin capacity and k is a coefficient for a given resin

under particular radiation conditions with units of reciprocal dose. For low dose conditions k is related to the initial radiation chemical yield for the loss of resin capacity G_o :

$$k = \frac{G_o \times 10^{-9}}{C_o}$$

where the factor of 10^{-9} is required for unit conversions.

The second type of empirical relationship describes the decrease in capacity as a linear function of dose:

$$C = C_o - \beta D \quad (\text{Equation 2})$$

where β is a coefficient which depends on the nature of the resin and the condition of irradiation with units of capacity per dose. For low dose conditions β is related to G_o :

$$\beta = G_o \times 10^{-9}$$

and is thus equivalent to $k C_o$. In fact, the linear equation 2 is just the first two terms in the series expansion of the exponential equation 1, and as such is just an approximation of the latter.

The values of G_o given in Tables III and IV have been classified with respect to the nature of the resin damage:

i) for $G_o = 0.1 - 0.01$ the radiation energy absorbed by the matrix and functional groups is dissipated as heat resulting in little damage to the resin.

ii) for $G_0 = 1 - 5$ the radiation energy absorbed directly by the functional groups results in their decomposition

iii) for $G_0 = 5 - 15$ the radiation energy absorbed by the matrix is transferred to the functional groups which thus undergo indirect radiation decomposition in addition to the direct radiation decomposition above. Data which follows the exponential type relationship has been cited as evidence that the main radiation process is destruction of functional groups due to their direct absorption of the radiation energy. The linear relationship has been interpreted as evidence that the main radiation process leading to functional group loss is energy transfer from the matrix to the functional groups. Such classifications of G_0 and general mechanistic statements ignore indirect processes due to radiation produced solvent or solute species and should be viewed in that light. Furthermore, the above relationships in general only hold for low degrees of radiation damage.

Resin degradation processes may take place even after irradiation is terminated due to long lived reactive species formed by various chemical reactions. For example, radiation induced oxidation can give peroxides which will subsequently decompose and react with a resin. Any mechanism of practical use must take post irradiation effects into account. This can be done if the basic types of reactions that occur are identified and kinetically characterized. Once identified it would not be unexpected that the kinetics of a large fraction of the post reactions could be extracted from existing literature.

It must be stressed that the empirical relationships and equations are hypothetical. Low accuracy of parameters and poor reproducibility of experimental results are a typical feature of the radiation chemistry of ion exchange

resins. This is a result of both the complexity of the systems and of the lack of standardized preparation, conditioning, testing and irradiation procedures. Reliable mechanistic characterization of the radiolysis of ion exchange resins must wait more uniform and more basic experimentation.

VI. CONCLUSIONS

For more than three decades there have been extensive applications of ion exchange materials in the nuclear process industry. Process related problems of serious nature caused by radiation chemical changes in the ion exchange medium have been occasionally mentioned in the open literature as well as in safety evaluation studies of radioactive material processing (106, 108). The present literature survey identified a number of reports on experimental studies to evaluate the process related properties of organic ion exchangers. Still, there are numerous problems associated with the radiation chemical changes of ion exchange materials that are not properly understood. Thus, in spite of the apparent abundance of experimental studies, there is no reliable information to allow one to predict the radiation chemical effects on process applications of ion exchange materials in the nuclear industry.

The radiation stabilities of a variety of ion exchange resins have been studied by exposing dry, moist or wet resins to a variety of ionizing radiation sources, both internal and external to the resin. The early works of Wedemeyer (37), Higgins (94), Fisher (34), Payne (48) and Utley (50) during the 1950's have been repeatedly mentioned in numerous publications on the effects of intense radiation on ion exchange materials. In spite of the recognized limitations of these early investigations using a few of the important ion exchangers of that period, these studies remain primarily the basis for radiation damage evaluation of ion exchange materials used in the U.S.

The need to fully understand the effects of radiation in process applications of ion exchange materials is apparent from the increasing number of reports in the open literature on process related incidents (99 to 108). From

the present survey of current knowledge on the radiation effects on ion exchange materials, it can be concluded that:

- (i) The fundamental processes involved in radiation damages to ion exchange materials are not understood
- (ii) structural and chemical constituent modifications can significantly change the radiation resistance of ion exchange materials
- (iii) there is a serious gap in systematic investigations to develop highly radiation resistant inorganic ion exchangers of high exchange capacity
- (iv) there is a need to extend the radiation effect studies to include investigations of secondary reactions of the radiolysis products of all the materials in a process system
- (v) radiation-resistant and process-efficient organic and inorganic ion exchangers tailored to the special needs of radiochemical processing in the nuclear industry need to be developed.

Recent work on radiation chemical effects on ion exchangers from the U.S. (14, 23, 24, 25) are few and these are simply attempts to examine a process related problem of immediate concern to these investigators. Almost all the recent work (see Reference list, Section VII of this report) published in the open literature on radiation stability of ion exchangers are from the Soviet Union and East European countries and involve the examination of ion exchangers that are of interest to their process industry. Because of the proprietary nature of commercial resin manufacture and the nature of the trade nomenclature of ion exchange materials, it is difficult to examine the possible applications of Soviet experimental studies to ion exchange materials that are used in the U.S. However, with an accurate knowledge of the generic chemical nature of the ion

exchange resin to be used in a process application, the data assembled here can be profitably used to gain knowledge about the effects of radiation on process materials.

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APPENDIX I

This material was extracted from reference number one:

E. V. Egorov and P. D. Novikov, "Action of Ionizing Radiation on Ion-Exchange Materials," Atomizdat, Moscow (1965), Israel Program for Scientific Translations, Jerusalem (1967),

Appendix I, pages 230-239 with the permission of the publisher. This Appendix contains useful information of the chemical composition and structure of the major types of ion exchange resins.

APPENDIX-I
BRIEF DESCRIPTION OF MAJOR TYPES OF ION-EXCHANGE MATERIALS⁽¹⁾

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
1	Strongly acid, monofunctional sulfonated cation exchangers based on styrene-DVB copolymers: KU-2; SDV-3; Dowex-50 and 50W; Amberlite IR-120 and IR-112; Wofatit KPS (KPS-200); Catex S; Imac C-12; Zeolex SA; Dienon SK-1 and SK-100; Nalcite HCR; Permutit Q	-SO ₃ H		Styrene, DVB	4.5-5	Cation exchangers differ from one another in their DVB content, copolymerization techniques employed, conditions of sulfonation, etc.
2	Strongly acid, monofunctional sulfonated cation exchangers based on styrene-butadiene copolymers: SBS-1 and SBS-2	-SO ₃ H		Styrene, butadiene	2.3-4	SBS-1 and SBS-2 differ from each other in their content of styrene and butadiene. Tridimensional structure produced by formation of sulfone bridges
3	Strongly acid, polyfunctional sulfonated cation exchangers based on phenol-formaldehyde resins: KU-1; KU-1g; Wofatit F; F ₂ S; F ₄ S; FF ₂ S	-SO ₃ H -OH		Phenol, formaldehyde	4.5-6	KU-1g (granulated) has better hydrodynamic characteristic than KU-1. Sulfone groups may also be located in the ortho-position

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
4	Strongly acid, polyfunctional sulfonated cation exchangers based on phenol-formaldehyde resins: Dowex-30; Catex F-extra; Amberlite IR-105; Zeo Rex; Duolite C-3; Wofatit P	$-\text{CH}_2\text{SO}_3\text{H}$ $-\text{OH}$		Phenol, formaldehyde	4-6	Sulfomethylene groups may also be located in o-position
5	Strongly acid, polyfunctional sulfonated cation exchangers based on phenol-formaldehyde resins: Catex FN and Duolite C-10	$-\text{SO}_3\text{H}$		Phenol, formaldehyde, naphthalene	3.4-3.5	When more than one sulfone group is introduced into the condensed ring, the capacity of the resin may attain 7 meq/g
6	Strongly acid, polyfunctional sulfonated cations based on polyphenylenequinones: P3, P4 and PS3	$-\text{SO}_3\text{H}$		Benzoquinone, benzidine-disulfonic-2,2' or stilbene-disulfonic-2,2'-acids	3-5	Structure of P3 and P4 resins corresponds to the first, that of PS3 to the second formula
7	Strongly acid, monofunctional phosphated cation exchangers based on styrene-DVB copolymers: KF-1 and SF	$-\text{PO}_3\text{H}_2$		Styrene, DVB	7.5-10	-
8	Strongly acid, polyfunctional phosphated cation exchangers based on phenol-formaldehyde resins: RF	$-\text{OPO}_3\text{H}_2$ $-\text{OH}$		Phenol, resorcinol, formaldehyde or monohydroxyphenyl phosphate and formaldehyde	8-10	First formula corresponds to RF-1, second formula to RF-2. The RF-2 resin is monofunctional

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC meq/g	Notes
9	Weakly acid, monofunctional carboxylic cation exchangers based on styrene-DVB copolymers: KB-6 and KS	-COOH		Styrene, DVB	4-4.5	-
10	Weakly acid, monofunctional carboxylic cation exchangers based on copolymers of methacrylic acid and DVB: KB-4; KB-4P-2; Amberlite IRC-50; Permutit H-70 and Zeolox WA	-COOH		Methyl methacrylate or methacrylic acid, DVB	8.5-10	KB-4 and KB-4P-2 resins differ from each other in their DVB content
11	Weakly acid, monofunctional carboxylic cation exchangers based on acrylic acid-DVB copolymers: Duolite CS-101 and Wofatit CP	-COOH		Acrylic acid (ester), DVB	9-12	-
12	Weakly acid, monofunctional carboxylic cation exchangers based on copolymers of methacrylic acid and hexahydro-1,3,5-triacrylylsym-triazine: KMT	-COOH		Methyl methacrylate or methacrylic acid, acrylamide	10	KMT resin is permeable to large ions; ion-exchange equilibrium is rapidly established
13	Weakly acid, monofunctional carboxylic cation exchangers based on copolymers of methacrylic acid and ethylene glycol dimethacrylate: SG-1	-COOH		Methyl methacrylate or methacrylic acid, ethylene glycol dimethacrylate	8-10	-

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
14	Weakly acid, polyfunctional carboxylic cation exchangers based on phenol-formaldehyde resins: KFU	-COOH -OH		Phenoxy-acetic acid, formaldehyde, phenol	6-7	-
15	Weakly acid, polyfunctional carboxylic cation exchangers based on resorcinol-formaldehyde resins: Wofatit C and R ₅ C	-COOH -OH		Resorcylic acid, formaldehyde	3.5-7	-
16	Weakly acid, polyfunctional carboxylic cation exchangers based on resorcinol-formaldehyde resins: Wofatit CN	-COOH -OH		Resorcylic acid, phenol, formaldehyde	2-3	TEC of Wofatit CN is lower than that corresponding to structural formula
17	Strongly basic, monofunctional anion exchangers based on styrene-DVB copolymers: AV-17; AM; ASD-2; Dowex-1 and 21K; De-Acidite FF; Amberlite IRA-400 and IRA-401; Wofatit-SBW; Zeolux SBI and Dienon SA-200	-N ⁺ (CH ₃) ₃		Styrene, DVB	2.5-3.8	Anion exchangers differ from each other in their DVB content, amination techniques, etc.
18	Strongly basic, monofunctional anion exchangers based on styrene-DVB copolymers: ASD-4	-N ⁺ (CH ₂ CH ₂ OH) ₃		Styrene, DVB	2-2.5	-

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
19	Strongly basic, monofunctional anion exchangers based on copolymers of styrene and DVB: AV-27; Dowex-2; Permutit S-2; Nalcite SAR; Amberlite IRA-410 and IRA-411; Dienon SA-100; Zeolex SBII and Wofatit SBS-400	$-\overset{+}{N}(\text{CH}_3)_2\text{C}_2\text{H}_4\text{OH}$		Styrene, DVB	2.5-4	Anion exchangers differ from each other in their DVB content, amination techniques, etc. In Wofatit SBS-400 the nitrogen atom is bound to three different groups
20	Strongly basic, monofunctional anion exchangers of quaternary pyridinium base type, based on styrene-DVB copolymers: AMP; AV-18; ASD-3; Permutit SK	$-\overset{+}{N} \text{ (pyridine ring)}$		Styrene, DVB, pyridine	3-4	-
21	Strongly basic, monofunctional anion exchangers based on copolymers of 2-vinylnaphthalene and DVB: AV-19	$-\overset{+}{N}(\text{CH}_3)_3$		2-vinylnaphthalene, DVB	2.5-3	-
22	Strongly basic, monofunctional anion exchangers based on copolymers of acenaphthalene and DVB: AV-21	$-\overset{+}{N}(\text{CH}_3)_3$		Acenaphthalene, DVB	2.5-3	-
23	Strongly basic, monofunctional anion exchangers based on polyxylylene: Imac S-4	$-\overset{+}{N}(\text{CH}_3)_3$		p-Xylene	1.5-2	-

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
24	Strongly basic, monofunctional anion exchangers based on trianiso-sole sulfonium-formaldehyde resins: Stamex S; (Stamex S-44)	$\equiv S^+$		Anisole, formaldehyde	1.5-2	—
25	Polyfunctional anion exchangers of the condensation type with quaternary pyridinium base groups: AV-16	$\text{—N}^+\text{—}$ (pyridinium ring)		Pyridine, polyethylene polyamines, epichlorohydrin	8.5-10.5	AV-16 contains 25-20% pyridinium groups and 75-80% secondary and tertiary amino groups
26	Polyfunctional anion exchangers of the condensation type: EDE-10; EDE-10P; Wofatit L (L-150); Amberlite XE-114	$\equiv N^+$ $\equiv N$ $=NH$		Polyethylene polyamines, epichlorohydrin	8-9.5	EDE-10P may be considered as either medium or weakly basic anion exchangers. EDE-10 contains a smaller amount of polyethylene polyamines than EDE-10P
27	Weakly basic, monofunctional pyridine-containing, anion exchangers based on copolymers of 2-methyl-5-vinylpyridine and DVB: VP-1			2-methyl-5-vinylpyridine, DVB	6-7	VP-1 is analogous to AN-25
28	Weakly basic, monofunctional anion exchangers based on styrene-DVB copolymers: AN-24			Styrene, DVB	4-4.5	AN-24 may also be considered as medium-basic anion exchanger

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
29	Weakly basic, polyfunctional anion exchangers based on styrene-DVB copolymers: Nalcite WBR; Dowex-3; Amberlite IR-45; Zeolex WB	$\equiv N$ $=NH$ $-NH_2$		Styrene, DVB	3.5-5.5	In anion exchangers of this type, R_1 and R_2 can be $-CH_3$, $-CH_2$, $-C_2H_5$. The degree of cross-linking is increased by methylene bridges linking two nitrogen atoms
30	Weakly basic, polyfunctional condensation type anion exchangers: MMG-1	$\equiv N$ $=NH$	Data on chemical structure not available	Urea, melamine, guanidine, formaldehyde	3.5-4.5	MMG-1 is sometimes classified as a medium-basic anion exchanger
31	Weakly acid, polyfunctional anion exchangers of the condensation type, based on melamine: AN-1	$=NH$ $-NH_2$		Melamine, formaldehyde	4-5	Since not all the amino groups of the melamine participate in the condensation reaction, the exchanger contains a certain amount of primary amino groups. AN-1 may also be obtained by the condensation of trimethylolmelamine in acid medium

APPENDIX-I (Continued)

Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
32 Weakly basic, polyfunctional anion exchangers of the condensation type: AN-9	$\equiv N$ $=NH$		Ammonium sulfate, phenol, formaldehyde	4.5	Due to the presence of phenol groups, the exchanger is bipolar and displays weakly acid properties
33 Weakly basic, polyfunctional anion exchangers of the condensation type: AN-2F; Amberlite IR-4B; XE-58 and Wofarit MD	$\equiv N$ $=NH$		Polyethylene polyamines, phenol	7.5-9.5	Due to its content of phenol groups, AN-2F is bipolar and displays weakly acid properties
34 Cation exchange membranes: Nepton CR-51 and CR-61	$-CH_2SO_3H$ $-OH$		Sulfonated resins of phenol-formaldehyde type in the initial setting stage	0.8-3	Homogeneous membranes Nepton CR-51 and CR-61 prepared on a Saran base
35 Anion exchange membranes: Nepton AR-111; Permaplex A-10	$\equiv N^+$	-	-	1.3-1.6	Nepton AR-111 is a homogeneous, Permaplex A-10 or a heterogeneous membrane
36 Cation exchange membranes based on copolymers of styrene and acrylic acid	$-SO_3H$ $-COOH$		Sodium styrene-sulfonate, acrylic acid	3-10	Tridimensional network is produced by irradiating the copolymer with Co^{60} -emitted γ -quanta

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
37	Ion-exchange membranes based on graft copolymers	$-\text{SO}_3\text{H}$ $-\text{PO}_3\text{H}_2$ $-\text{COOH}$ $-\text{N}(\text{CH}_3)_3^+$	$\left[\begin{array}{c} \text{H}_2\text{C} \\ \\ \text{HC}-\text{COOH} \end{array} \right]_{n_1}$ $\left[\begin{array}{c} \text{H}_2\text{C} \\ \\ \text{HC}-\text{C}_6\text{H}_4-\text{SO}_3\text{H} \end{array} \right]_{n_2}$ $-\text{CH}_2-\text{CH}-\text{CH}_2-$	Polyolefin membranes, styrene, acrylic acid, vinyl acetate, acrylonitrile	4-5	Membranes prepared by radiation graft polymerization of the monomers onto various polyolefinic (mainly polyethylene) membranes
38	Coal-based polyfunctional sulfonated cation exchangers: sulfonated coals, Dusarit S	$-\text{SO}_3\text{H}$ $-\text{COOH}$ $-\text{OH}$	Sorbents are frequently synthesized from activated coals consisting of complex aggregates formed from crystalline carbon with a graphite lattice	Black coal, brown coal and charcoal	0.8-3.6	The various sulfonated coals differ from each other in the identity of the raw material and sulfonation techniques
39	Polyfunctional weakly acid cation exchangers based on oxidized coals: lump coal; BAU; KAU; SKT and SKLT	$-\text{COOH}$ $-\text{OH}$	—	Black coal and charcoal	4	Capacity of oxidized coals strongly depends on the pH of the solution
40	Polyfunctional, weakly basic anion exchangers based on coals: BAU; KAU, SKT and SKLT		—	The same	0.35-0.5	The exchanger is obtained by treating active (nonoxidized) coals with HF and HCl. In a number of cases the TEC of anion-exchanger coals may be as high as 2-3 meq/g
41	Inorganic cation exchangers of mineral origin: kaolinite	$-\text{OH}$	$\text{Al}_2[\text{Si}_4\text{O}_{10}](\text{OH})_2$	Kaolinite group minerals	0.02-0.05 (in neutral solutions)	Sorbent is unstable in alkaline solutions. It is sometimes used compounded with binder (cellulose)
42	Inorganic cation exchangers based on hydrated silicic acid: silica gel	$-\text{OH}$	$\begin{array}{c} \text{CH} \quad \text{OH} \\ \quad \\ -\text{Si}-\text{O}-\text{Si}-\text{O}- \\ \quad \end{array}$	Hydrogel of silicic acid	10^{-3} - 10^{-8} (in neutral solution)	Sorbent is unstable in alkaline solutions

APPENDIX-I (Continued)

	Type and brand of ion exchanger	Active groups	Structural formula	Base material	TEC, meq/g	Notes
43	Inorganic cation exchangers based on aluminosilicates: Permutit G	Na ⁺	Na ₂ O · Al ₂ O ₃ · 6SiO ₂	Sodium carbonate, feldspar, kaolinite	2.5	Prepared by fusing components at 1000°C
44	Inorganic cation exchangers based on metal oxides and hydroxides: manganese dioxide	—OH	$\begin{array}{c} \text{MnO}_2 \cdot n\text{H}_2\text{O} \text{ или} \\ \text{OH} \quad \text{OH} \\ \quad \\ -\text{Mn}-\text{O}-\text{Mn}-\text{O}- \\ \quad \end{array}$	Manganese hydroxide or salts of manganese	2—4	Obtained by thermal decomposition of manganese salts or manganese hydroxide
45	Inorganic cation exchangers based on zirconium: zirconium phosphate (zirconyl phosphate, zirconium polyphosphate)	$\begin{array}{l} -\text{OPO}_3\text{H}_2 \\ -\text{O} \diagup \text{PO}_2\text{H} \\ -\text{O} \diagdown \\ -\text{O} \diagup \text{ZrOH} \\ -\text{O} \diagdown \end{array}$	$\begin{array}{c} \text{O} \quad \quad \text{O} \\ \quad \quad \\ \text{HO}-\text{P}-\text{OH} \quad \text{HO}-\text{P}-\text{OH} \\ \quad \quad \\ -\text{Zr}-\text{O}-\text{Zr}- \\ \quad \quad \\ \text{HO}-\text{P}=\text{O} \quad \text{HO}-\text{P}=\text{O} \\ \quad \quad \\ -\text{Zr}-\text{O}-\text{Zr}- \\ \quad \quad \end{array}$	Zirconium nitrate zirconium oxychloride, orthophosphoric acid, monosubstituted sodium phosphate	1.5—7	Capacity of sorbent is a function of its relative contents of zirconium and phosphorus
46	Inorganic cation exchangers based on tin: tin phosphate (tin polyphosphate)	$\begin{array}{l} -\text{OPO}_3\text{H}_2 \\ -\text{O} \diagup \text{PO}_2\text{H} \\ -\text{O} \diagdown \\ -\text{O} \diagup \text{SnOH} \\ -\text{O} \diagdown \end{array}$	$\begin{array}{c} \text{O} \quad \quad \text{O} \\ \quad \quad \\ \text{HO}-\text{P}-\text{OH} \quad \text{O}=\text{P}-\text{OH} \\ \quad \quad \quad \quad \\ -\text{Sn}-\text{O}-\text{Sn}-\text{O}-\text{P}-\text{O}-\text{Sn}-\text{O}-\text{Sn}- \\ \quad \quad \quad \quad \\ \text{OH} \quad \text{OH} \quad \text{OH} \quad \text{OH} \quad \text{OH} \\ \text{O}=\text{P}-\text{OH} \quad \quad \text{HO}-\text{P}-\text{OH} \\ \quad \quad \\ \text{OH} \quad \quad \text{O} \end{array}$	Stannic salts, orthophosphoric acid or orthophosphates	1.3—1.4 (in neutral solutions)	Sorbent unstable in alkaline solutions
47	Strongly basic, monofunctional mineral-organic anion-exchangers based on styrene graft polymers	—N ⁺ (CH ₃) ₃	$\begin{array}{c} \text{H}_3\text{C} \\ \\ \text{HC} - \text{C}_6\text{H}_4 - \text{CH}_2\text{N}^+(\text{CH}_3)_3 \\ \quad \\ \text{O} \quad \text{OH} \\ \quad \\ -\text{Si}-\text{O}-\text{Si}-\text{O}- \\ \quad \end{array}$	Styrene, silica gel	0.6—1 (in neutral solutions)	Sorbent unstable in alkaline solutions. Owing to its —OH group content it is bipolar

APPENDIX II

This material was extracted from reference number two:

I.A.E.A. Technical Report Series No. 78, "Operation and Control of Ion-exchange Processes for Treatment of Radioactive Wastes," International Atomic Energy Agency, Vienna (1967),

Tables X through XIII on pages 108 to 127 with the permission of the publisher.

This appendix is a listing of the general physical properties of ion exchange resins useful to nuclear waste separations.

APPENDIX-II
GENERAL PROPERTIES OF ION EXCHANGE MATERIALS^[2]
(From Manufacturers' Brochures)

SYNTHETIC CATION EXCHANGERS

a. Polystyrene base, bead form addition polymers

Trade name	Manufacturer	Functional group	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
				(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Allasion CS	Prosim, France	-SO ₃ ⁻					0.3 - 0.8	110	1 - 14	
Amberlite IRN- 77	Rohm & Haas Co.,	-SO ₃ ⁻	H	4.7		55	0.3 - 1.2			Nuclear grade
" XE-100	USA	-SO ₃ ⁻	Na	4.5	1.5	56 - 60		120	0 - 14	~5% DVB
" IRN-163	distributed by	-SO ₃ ⁻	Li	4.6		55	0.3 - 1.2	150		Nuclear grade
" IRN-169	Mallinckrodt, USA	-SO ₃ ⁻	NH ₄	4.4		55	0.3 - 1.2	150		Nuclear grade
" IRN-218	and	-SO ₃ ⁻	Li	4.6		55	0.3 - 1.2	150		Nuclear grade
" IR-120	Tokyo Organic	-SO ₃ ⁻	Na	4.3 - 5	1.9	44 - 48	0.3 - 1.2	120	0 - 14	~ 8% DVB
" IR-122	Chemical Industry	-SO ₃ ⁻	Na	4.3 - 5	2.1	39 - 43	0.3 - 1.2	120	0 - 14	~ 10% DVB
" IR-124	Ltd., Japan	-SO ₃ ⁻	Na	4.3 - 5	2.2	37 - 41	0.3 - 1.2	120	0 - 14	~ 12% DVB
" 200		-SO ₃ ⁻	Na	4.3	1.75	46 - 51	0.3 - 1.2	120	0 - 14	'Macroreticular' resins
" 200C		-SO ₃ ⁻	Na	4.3	1.75	46 - 51		120	0 - 14	'Macroreticular' resins
Amberlyst 15 (Amberlyst resins are designed for non-aqueous applications)		-SO ₃ ⁻		4.9	1.2	60 - 66		120	0 - 14	'Macroreticular' resins
Diaion SK 1A	Mitsubishi Chemical	-SO ₃ ⁻	Na	-	1.9	43 - 50	0.3 - 1.2	120	0 - 14	~ 8% DVB
" SK 1B	Industries Ltd.,	-SO ₃ ⁻	Na	-	1.9	43 - 50	0.3 - 1.2	120	0 - 14	~ 8% DVB
" SK-102	Japan	-SO ₃ ⁻	Na	-	0.6	72 - 82	0.3 - 1.2	120	0 - 14	~ 2% DVB
" SK-103		-SO ₃ ⁻	Na	-	0.9	64 - 74	0.3 - 1.2	120	0 - 14	~ 3% DVB
" SK-104		-SO ₃ ⁻	Na	-	1.2	57 - 67	0.3 - 1.2	120	0 - 14	~ 4% DVB
" SK-106		-SO ₃ ⁻	Na	-	1.6	47 - 57	0.3 - 1.2	120	0 - 14	~ 6% DVB
" SK-110		-SO ₃ ⁻	Na	-	2.0	35 - 45	0.3 - 1.2	120	0 - 14	~ 10% DVB
" SK-112		-SO ₃ ⁻	Na	-	2.1	32 - 42	0.3 - 1.2	120	0 - 14	~ 12% DVB
" SK-116		-SO ₃ ⁻	Na	-	2.1	27 - 37	0.3 - 1.2	120	0 - 14	~ 16% DVB
Dowex 50-X8	Dow Chemical Co.,	-SO ₃ ⁻	H	5.0	1.7	53	0.3 - 0.8	150		~ 8% DVB
" 50W -X4	USA	-SO ₃ ⁻	H	5.0	1.7	53	0.3 - 0.8	150		~ 4% DVB; replace Dowex 50 resins
" 50W-X8	Nalco Chemical Co.,	-SO ₃ ⁻	Na	4.8	1.9	42 - 48	0.3 - 0.8	150		~ 8% DVB
" 50W-X10	USA	-SO ₃ ⁻	H	-	1.9	46 - 52	0.3 - 0.8	150		~ 10% DVB
" 50W-X12		-SO ₃ ⁻	H	-	2.1	42 - 48	0.3 - 0.8	150		~ 12% DVB
" 50W-X16		-SO ₃ ⁻	H	-	2.3	36 - 42	0.3 - 0.8	150		~ 16% DVB
" MPC-1		-SO ₃ ⁻	H	4.5 - 4.9	1.6 - 1.8		0.4 - 1.2	300		Macroporous

APPENDIX-II (Continued)

Duolite C-20	Diamond Alkali	-SO ₃ ⁻	Na	5.1	2.2	45-51	0.3-1.2	150		~ 8% DVB
" C-25		-SO ₃ ⁻	Na	5.1	1.7	55-62	0.3-1.2	120		Porous resin ~ 5% DVB
" ES-63		-PO ₃ ⁻	H	6.6	3.3	-	0.3-1.2	100	4-14	Intermediate acid
Imac C-12	IMACTI, Netherlands	-SO ₃ ⁻	Na	-	2.0	-	0.3-1.2	120	0-14	
" C-16P		-SO ₃ ⁻	Na	-	2.1	-	0.3-1.2	120	0-14	
Ionac C-240	Permutit Q, marketed by Ionac Co., USA									
Kastel C-300	Montecatini, Italy	-SO ₃ ⁻	Na	4.25	-	45	0.3-1.2	120	0-14	~ 8% DVB
" C-300 AGR		-SO ₃ ⁻	Na	4.5-4.7	-	45	0.3-1.2	120	0-14	~ 12% DVB
" C-300 P		-SO ₃ ⁻	Na	-	1.7	53	0.3-1.2	120	0-14	Highly porous
KF-1	NIIP, USSR	-PO ₃ ²⁻	-	5.0	-	-	-	-	-	Intermediate acid
KF-2	" "	-CH ₂ PO ₃ ²⁻ & -PO ₃ ²⁻	-	7.0	-	-	-	-	-	Intermediate acid
KU-2-8	" "	-SO ₃ ⁻	Na, H	4.7	-	60	0.3-1.5	120	-	~ 8% DVB; 2, 8, 12, 16% also available
KU-2-8-CHS	" "	-SO ₃ ⁻	H	4.7	-	45-65	0.4-1.5	-	-	Special purity
Lewatit S-100	Farbenfabriken	-SO ₃ ⁻	-	4.75	2.5	40-45	0.5-1.0	120	0-14	~ 8% DVB
" S-115	Bayer A.G.,	-SO ₃ ⁻	-	4.6	2.4	40-45	0.3-2.0	120	0-14	Higher resistance to oxidizing agents
" SP-100	Fed. Rep. of Germany	-SO ₃ ⁻	-	4.75	1.3	-	0.3-1.4	120	0-14	Macroporous
Mykion PS	MUKY, Hungary	-SO ₃ ⁻	-	4.0	1.57	-	-	-	-	
" PSM		-SO ₃ ⁻	-	4.0	1.0	-	-	-	-	
Nalcite HCR	Dowex 50-X8 marketed by Nalco Chemical Co., USA									
" HGR	" 50-X10	" "	" "	" "	" "	" "	" "	" "	" "	" "
" HDR	" 50-X12	" "	" "	" "	" "	" "	" "	" "	" "	" "
Permutit Q	Permutit Co.,	-SO ₃ ⁻	Na, H	4.6	1.9	45-55	0.3-1.2	120	0-13	~ 10% DVB
" QB	USA	-SO ₃ ⁻	Na, H	5.0-4.6	2.1-1.9	45-55	0.3-1.2	120	0-13	~ 12% DVB
" QC		-SO ₃ ⁻	Na	5.0	2.1	45-55	0.3-1.2	120	0-13	~ 15% DVB
" QR		-SO ₃ ⁻	Na	3.9	1.7	45-55	0.3-1.2	120	1-14	High stability to oxidizing conditions
" NQ (H, NH ₄ , Li)		-SO ₃ ⁻	H, NH ₄ , Li	4.6	1.8	45-55	0.3-1.2	120	0-13	Nuclear grade
" NQ ⁷ Li		-SO ₃ ⁻	⁷ Li	4.6	1.8	45-55	0.3-1.2	150	-	Nuclear grade

APPENDIX-II (Continued)

Trade name	Manufacturer	Functional group	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
				(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Permutit RS	Permutit A. G., Fed. Rep. of Germany	-SO ₃ ⁻	Na	5.2	2.2	-	0.3 - 1.2	150	-	Nuclear grade
Resex P	Jos. Crosfield, UK	-SO ₃ ⁻	Na	4.8	2.0	-	0.3 - 1.2	120	-	
S-katex	Výzkumný ústav synthetických pryskyřic a laků, Pardubice, CSSR	-SO ₃ ⁻	H	4.9	0.5	-	0.3 - 1.2	120	0 - 14	
SDV	Moskovsk Chem. Technol. Inst., USSR	-SO ₃ ⁻		4.2	-	-	0.3 - 1.4	-	-	Fine ground
Wolfatit KPS " R (H, L, K, M)	VEB Farbenfabrik Wolfen, German Democratic Rep.	-SO ₃ ⁻	Na	4.5	1.8	45 - 53	0.3 - 1.2	115	3 - 14	Nuclear grade
		-SO ₃ ⁻	H, Li, K and NH ₄	-	1.8	-	0.3 - 1.2	115	3 - 14	
Zerolit 225	Zerolit Ltd., UK	-SO ₃ ⁻	Na	4.8	2.1	45 - 50	0.3 - 1.2	120	0 - 14	Standard resin 8% DVB, also available with 1, 2, 4.5, 12 & 20% DVB

b. Vinyl addition polymers (acrylic, methacrylic)

Trade name	Type of acid	Manufacturer	Functional group	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
					(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Amberlite IRC-50 " IRC-84	Weak "	Rohm & Haas Co., USA	-CCO ⁻	H	10.0 - 10.2	3.5	43 - 53	0.3 - 1.2	120	5 - 14	Capacities - in alkaline media; spherical beads
			-COO ⁻	H	10.0	3.5	43 - 50	0.3 - 1.2	150	4 - 14	
CFB-P	Strong	Chem. Fabrik Budenheim, Fed. Rep. of Germany	-OSO ₃ ⁻	-	-	-	-	-	100	-	
Duolite CS-101	Weak	Diamond Alkali Co., USA	-COO ⁻	H	10.0	3.5	-	0.3 - 1.2	100	-	~ 10% DVB; beads

APPENDIX-II (Continued)

Ionac C-270	Permutit H-70 marketed by Ionac Co., USA										
Imac Z5	Weak	IMACTI, Netherlands	-COO ⁻	H	-	3.0	-	0.3 - 1.2	100	4 - 14	Beads
Kastel C-100	Weak	Montecatini, Italy	-COO ⁻	H	-	3.0	45 - 50	0.3 - 1.2	110	0 - 14	Beads; ~ 10% DVB
Karboxylovy	Weak	Spolek pro chemickou výrobu, CSSR	-COO ⁻	H	10.0	3.5	-	0.3 - 1.2	120	5 - 14	Beads
KB-1	Weak	NIIP, USSR	-COO ⁻	-	10.0	-	-	0.3 - 1.5	-	-	Beads
KB-2	"	" "	-COO ⁻	-	10 - 11	-	-	0.3 - 1.0	-	-	Beads
KB-3	"	" "	-COO ⁻	-	6 - 7	-	-	0.3 - 1.5	-	-	Beads; acrylonitrile-DVB
KB-4P-2	"	" "	-COO ⁻	Na	9.5	-	-	0.25 - 1.0	-	-	Beads
Kn	Weak	Moakovsk Chem. Technol. Inst., USSR	-COO ⁻	-	6.0	-	-	0.25 - 1.5	-	-	Fine ground
KF-3	Intermed.	NIIP, USSR	-PO ₃ ²⁻	-	3.5	-	-	-	-	-	
KF-4	Intermed.	" "	CH ₂ PO ₃ ²⁻	-	5.5	-	-	-	-	-	
KU-3	Strong	" "	-SO ₃ ⁻	-	5.5	-	-	-	-	-	Fine ground
Mykion KMK	Weak	MUKY, Hungary	-COO ⁻	-	8.6	1.2	-	-	-	-	
" CP	"	" "	-COO ⁻	-	8.0	2.8	-	-	-	-	
Permutit C	Weak	Permutit A.G., Fed. Rep. of Germany	-COO ⁻	H	10.0	4.0	-	-	100	6 - 14	Beads
" H-70	"	Permutit Co., USA	-COO ⁻	H	6.5	2.4	40 - 50	0.3 - 1.2	120	5 - 14	Beads
Wolfatit CP	Weak	VEB Farbenfabrik Wolfen, German Democratic Republic	-COO ⁻	Na	10.0	3.5	43 - 53	0.5 - 2.0	100	7	~ 5% DVB, beads
Zerolit 226	Weak	Zerolit Ltd., UK	-COO ⁻	H	10.0	3.5	-	0.3 - 1.2	100	-	Beads; 2.5 & 4.5% DVB available

c. Phenolic resins

APPENDIX-II (Continued)

Trade name	Type of acid	Manufacturer	Functional group	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
					(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Dorolit FK-22	Strong	MUKY, Hungary	-SO ₃ ⁻ , OH ⁻	-	2.7	0.6	-	-	-	-	Fine ground
Dowex CCR-1	Weak	Dow Chemical Co., USA	-COO ⁻ -OH	H	-	1.4	-	0.3 - 0.8	100	-	Marketed by Nalco Chem. Co., USA, granular
Duolite C-3	Strong	Diamond Alkali Co., USA	-SO ₃ ⁻	H	2.9	1.2	-	0.3 - 2.0	60	0 - 9	Beads; -CH ₂ SO ₃ ⁻ groups
" C-10	"	" "	-SO ₃ ⁻	H	2.9	0.6	-	0.3 - 2.0	40	0 - 9	Beads; -CH ₂ SO ₃ ⁻ groups
Lewatit KSN	Strong	Farbenfabriken Bayer A.G., Fed. Rep. of Germany	-SO ₃ ⁻	-	4.0	1.6	45 - 50	0.3 - 1.5	30	0 - 8	Granular
" CNS	Strong & weak	" "	-SO ₃ ⁻	-	5.0	2.5	36 - 43	0.3 - 1.6	40	0 - 10	Granular
" CNO	Weak	" "	-COO ⁻ -COO ⁻	H -	4.0	2.4	30 - 35	0.3 - 1.6	40	0 - 10	Granular
MSF-3	Weak	Moskovsk Chem. Tech. Inst., USSR	-SO ₃ ⁻ , -OH	-	4.3	-	-	0.3 - 2.0	-	-	Fine ground
Mykion FG	Strong	MUKY, Hungary	-CH ₂ SO ₃ ⁻ , -OH	-	2.8	0.9	-	-	-	-	
" P	"	" "	-OH	-	2.2	0.65	-	-	-	-	
NSF	Strong	Moskovsk Chem. Tech. Inst., USSR	-SO ₃ ⁻	-	3.0	-	-	0.3 - 1.5	-	-	Fine ground
Permutit H	Weak	Permutit Co., USA	-COO ⁻	-	5.0	1.9	-	-	65	-	Granular
"	"	Permutit A.G., Fed. Rep. of Germany	-COO ⁻	-	4.0	-	-	-	40	-	Granular
Resex W	Weak	Jos. Crosfield, UK	-COO ⁻	-	2.5 - 3.0	-	-	-	-	-	Granular
RF	Intermed.	Moskovsk Chem. Tech. Inst., USSR	-PO ₃ ²⁻	-	4.3	-	-	-	-	-	

APPENDIX-II (Continued)

SN	Strong	Institut vysokomol., USSR	-SO ₃ ⁻ , -OH	-	5.2	-	-	0.3 - 1.5	-	-	Fine ground
SNF	Strong	" "	-SO ₃ ⁻ , -OH	-	5.2	-	-	0.3 - 1.5	-	-	Fine ground
FN-katex	Strong	Chemický kombinát záluž, CSSR	-SO ₃ ⁻	H	-	0.54	-	0.3 - 1.5	-	1 - 9.5	Beads, fine ground
KB-5	Weak	NIIP, USSR	-CH ₂ COO ⁻ , OH	-	7.5	-	-	0.25 - 1.5	-	-	
KU-1	Strong	" "	-SO ₃ ⁻ , -OH	-	4.0	-	50	0.3 - 3.0	-	-	Dark brown grains
KU-1G	Strong	" "	-SO ₃ ⁻ , -OH	-	4.5	-	50	0.3 - 2.0	-	-	Beads, black or brown
KRFU	Weak	Institut vysokomol., USSR	-COO ⁻	-	4.0	-	-	0.25 - 1.5	-	-	Fine ground
KU-5	Strong	NIIP, USSR	-SO ₃ ⁻	-	5.0	-	-	0.3 - 2.0	-	-	Beads, fine ground
KU-6	Strong	" "	-SO ₃ ⁻	-	5.5	-	-	-	-	-	
KU-6F	& weak	" "	-COO ⁻	-	5.6	-	-	-	-	-	
KU-7	"	" "	-COO ⁻	-	5.5	-	-	-	-	-	
KU-8	"	" "	-SO ₃ ⁻ , -COO ⁻	-	6.0	-	-	-	-	-	
KU-9	Strong	" "	-SO ₃ ⁻ , -OH	-	6.0	-	-	-	-	-	Fine ground
KU-21	"	" "	-SO ₃ ⁻	-	5.5	-	-	-	-	-	Fine ground
Staionit F-extra	Strong	Chemický kombinát záluž, CSSR	-CH ₂ SO ₃ ⁻ , -OH	Na	-	0.2	-	0.5 - 2.5	-	1 - 9.5	Fine ground
Wolfatit F	Strong	VEB Farbenfabrik Wolfen, German Democratic Republic	-SO ₃ ⁻	Na	2.9	-	-	0.3 - 1.5	50	-	Granular
" P	"	" "	-SO ₃ ⁻	Na	1.9	-	-	0.3 - 1.5	50	-	Granular
" CN	Weak	" "	-COO ⁻	Na	2.0	-	-	0.3 - 1.5	30	-	Granular
" CV	"	" "	-COO ⁻	-	4.0	1.6	40 - 50	0.3 - 1.5	40	0 - 8	Granular
Zerolit 215	Strong	Zerolit Ltd., UK	-SO ₃ ⁻ , OH	Na	-	0.92	-	0.3 - 1.2	40	0 - 9	Granular
" 216	Weak	" "	-COO ⁻ , OH	H	2.5	1.1	-	0.3 - 1.2	30	0 - 9	Granular

d. Inorganic exchangers (synthetic zeolites)

APPENDIX-II (Continued)

Matrix	Chemical or trade name	Manufacturer	Functional group	Exchange capacity		Operational controls		Physical form	Remarks
				(meq/g) (dry)	(meq/ml) (wet)	Max. oper. temp. (°C)	pH range		
Aluminosilicates	Decalco	Permutit Co., USA	AlO ₂ Na	1.4	0.53	40	6.9 - 8.0	Granules	Na form; intermediate capacity
	Doucil	Jos. Crosfield, UK	-	1.2	-	-	-	Granules	
	Molecular sieve 3A	Davison Chemical Div., W. R. Grace Co., USA	-	-	-	590	-	Powder, pellets, granules	
	Molecular sieve 4A	"	-	-	-	590	-	Powder, pellets, granules	
	Molecular sieve 5A	"	-	-	-	590	-	Powder, pellets, granules	
	Molecular sieve 10A	"	-	-	-	590	-	Powder, pellets granules	
	Molecular sieve 4A	Linde Co., USA	-	5.3	-	400	-	Pellets	Synthetic zeolites; nominal pore diameter 4 Å
	Molecular sieve 5A	"	-	-	-	400	-	Pellets	Synthetic zeolites; nominal pore diameter 5 Å
	Molecular sieve 13X	"	-	4.8	-	400	-	Pellets	Synthetic zeolites; nominal pore diameter 10 Å
	AW300	"	-	1.7	-	-	-	-	Nominal pore diameter 4 Å
	AW400	"	-	2.0	-	-	-	-	-
	AW500	"	-	2.0	-	-	-	-	Nominal pore diameter 5 Å
	Zeolon	Norton, USA	-	1.9	-	538 (Na form)	-	Pellets or powder	Synthetic mordenite
Ammonium-molybdoarsenate									K _d (Cs) = 400 to 4000 (method of prep.)
Ammonium-12-molybdophosphate									K _d (Cs) = 6000
Ammonium-tungstophosphate									K _d (Cs) = 3300 to 3500 (method of prep.)

APPENDIX-II (Continued)

Matrix	Chemical or trade name	Manufacturer	Exchange capacity (meq/g) (dry)	Remarks
Arsenates	Ferric arsenate Zirconium arsenate		At pH 3.55 - 10.95: 1.18 - 5.73 (Sr) At pH 3.12 - 10.68: 2.87 - 6.15 (Sr)	
Cerium (IV) compounds	Ceric phosphate, H ⁺ form; ceric phosphate, NH ₄ form; ceric oxide. All not available commercially		At pH 0.10 - 11.7: 0.07 - 3.24	Na ⁺ ion-exchange capacity
Ferrocyanide-molybdate	Not available commercially FEM			
Hydrous oxides	Not available commercially CO(OH) ₃ Sn(OH) ₄ Al(OH) ₃ Ni(OH) ₂ Fe(OH) ₃ Lead sulphate (tribasic)		At pH 7 - 10: 0.25 - 0.78 At pH 4 - 11: 0.73 - 1.78 At pH 7 - 10: 0.10 - 1.24 At pH 6.5 - 10: 0.02 - 2.25 At pH 6 - 10: 0.11 - 2.19 (Sr) At pH 1 - 6.7: 8.5 - 0.8 (anion exch.) At pH 7.2 - 12.5: 0.1 - 7.5 (cation exch.)	Blue particles White particles White particles Green particles
Phosphates	ABEDEM Sn ABEDEM TIA ABEDEM TiB ABEDEM Zr	SERA1, Belgium - - - - - -	3.70 (H) 7.50 (H) 9.50 (H) 5.20 (H)	
Potassium hexacyanocobalt (II) ferrate (III)	Not available commercially		6.0 (Cs)	
Quinoline-molybdophosphate				K _d (Cs) = 1500 ml/q
Silicates	Al ₂ O ₃ • X SiO ₂ SnO ₂ • X SiO ₂ AnO • X SiO ₂ (X = varying number of silicates)			
Thorium-base	Thorium phosphate		At pH 3.0 - 11.0: 0.30 - 1.1	
Titanium-base	Titanium phosphate		At pH 2.5 - 11.5: 0.20 - 3.5	
Zirconium-base	Zirconium arsenate Zirconium oxide Zirconium phosphate (ZP) Zirconium phosphate with citrate (Z CP) Zirconium tungstate Bio-Rad ZP-1 " ZT-1 " ZM-1	Bio-Rad Labs, USA	At pH 2.5 - 1.30: 0.30 - 3.0 At pH 3.5 - 11.5: 0.10 - 5.5 At pH 2.5 - 12.0: 0.3 - 1.5 1.0	

APPENDIX-II (Continued)

NATURAL CATION EXCHANGERS

a. Organic

Matrix	Mineral or trade name	Manufacturer	Functional group	Exchange capacity		Operational controls		Physical form	Remarks
				(meq/g) (dry)	(meq/ml) (wet)	Max. oper. temp. (°C)	pH range		
Coals	Dusarit S	IMACTI, Netherlands	-SO ₃ ⁻ -COONa		0.7 (strong) 0.35 (weak)	80	0 - 14	Granules	Polyfunctional
	Imac C 19	" "	-SO ₃ ⁻ -COOH		0.3 (strong) 1.0 (weak)	80	4 - 14	Granules	Polyfunctional
	Soucol	Jos. Crosfield, UK	-SO ₃ ⁻	1.8	0.6	30		Granules	
	Zeokarb-H	Permutit Co., USA	-SO ₃ ⁻ -COOH	1.6	0.56	70	0 - 8.5	Granules	Intermediate acidity
Brown coal (lignite)	Local - Mol, Belgium Idaho, USA		-COOH	0.45 At pH 4.1: 0.02 - 1.08					
Peat	Local - Poland			0.05 - 0.4					

b. Inorganic

Greensand (stabilized)	Zerolit	Zerolit Ltd., UK							
Greensand (stabilized)	Zeodur	Permutit Co., USA	AlO ₂ Na	0.11	0.14	60	6.2 - 8.0	Granules	Na form

APPENDIX-II (Continued)

Clay minerals (natural)	Kaolinite	0.03 - 0.15		
	Halloysite 2H ₂ O	0.05 - 0.10		
	Halloysite 4H ₂ O	0.40 - 0.50		
	Montmorillonite	0.80 - 1.50		
	Illite	0.10 - 0.40		
	Vermiculite	1.00 - 1.50		
	Chlorite	0.10 - 0.40		
	Sepiolite-attapulgite	0.20 - 0.30		
	Palygorskite			
	Analcite	1.50		
Zeolite minerals (natural)	Clinoptilolite	1.5	2.8 - 3.2	Granules
		1.61 ± 0.01		Granules
		1.7		Granules
		At pH 4.1: 0.35		Granules
	Cancrinite	10.0		
	Erionite	2.2		
	Heulandite	3.30		
	Mordenite	1.40		
	Natrolite	5.3		
	Phillipsite	2.3		
	Sodalite	9.2		
	Ultramarine	8.3		
Pyroclastic rocks	Andesitic tuff	0.10 - 0.40		
	Rhyolitic tuff	0.0 - 0.30		
	Rhyodacitic tuff	0.80 - 1.30		
	Basaltic tuff	0.30 - 0.80		
	Tefritic & fonolitic tuff	0.20 - 0.80		
	Tuffites	0.0 - 0.50		

APPENDIX-II (Continued)

SYNTHETIC ANION EXCHANGERS

a. Strong base polystyrene addition polymers Type I [functional group - N(CH₃)₃]

Trade name	Manufacturer	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
			(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Amberlite IRA-400	Robm & Haas Co., USA	Cl	3.7	1.4	42-88	0.3-0.08	60 (OH)	0-14	Beads, ca. 8% DVB; avail. in larger particle size as 400 C
" IRA-401	Tokyo Organic Chemical	Cl	3.5	1.0	53-58	0.3-0.8	60 (OH)	0-14	Beads, porous
" IRA-401S	Industry Ltd.,	Cl	3.4	0.8	59-65	0.3-0.8	60 (OH)	0-14	Beads, porous
" IRA-402	Japan	Cl	4.4	1.25	50-57	0.3-1.2	80 (Cl)	0-14	Beads, porous
" IRA-900		Cl	4.4	1.0	60-64	0.3-1.2	60 (OH)	0-14	Beads, porous, mean pore size 250 'A'
" IRA-904		Cl	2.6	0.7	56-62	0.3-1.2	60 (OH)	0-14	Beads, porous, mean pore size 645 'A'
" IRN-78		OH	3.5	-	60	0.3-1.2	60 (OH)	-	Reactor grade
AV-15	NIDP, USSR	-	3.0	-	-	-	-	-	Beads
AV-17-6	" "	Cl	4.3	-	40-60	0.35-1.2	50	-	Beads; 8% DVB
AV-17-8	" "	Cl	3.8-4.5	-	40-60	0.35-1.2	50	-	Beads; 8% DVB
AV-17-8	" "	-	3.4	-	-	0.4-1.2	-	-	Beads, special porosity
Diaion SA 10A	Mitsubishi Chemical	Cl	-	1.2	43-47	0.3-1.2	60 (OH)	0-12	Beads; 8% DVB
" SA 101	Industries Ltd.,	Cl	-	0.85	50-65	0.3-1.2	60 (OH)	0-12	Beads, porous, low crosslinking
" SA 11A	Japan	Cl	-	0.85	55-65	0.3-1.2	60 (OH)	0-12	Beads, porous, 4% DVB
" SA 100		Cl	-	1.0-1.3	50-60	0.07-0.15	-	0-12	Beads, analytical uses
Dowex 1	Dow Chemical	Cl	3.5	1.33	43	0.3-0.8	50	0-14	Beads, ca. 8% DVB; 1, 2, & 4% DVB also available
" 21K	" "	Cl	4.5	1.25	57	0.3-0.8	50	0-14	Beads; improved mech. stability
" 11	" "	Cl	4.0	1.24	57	0.3-0.8	50	0-14	Beads; uranium recovery
Duolite A-101D	Diamond Alkali	Cl	4.2	1.4	50-55	0.3-1.2	60 (OH)	0-14	Beads
" ES-111	Co., USA	Cl	4.7	1.0	45-50	0.3-1.2	40 (OH)	0-14	Limited quantities; beads
Imac S 5-40	IMACTI, Netherlands	Cl	-	1.0	55	0.4-0.85	50 (OH)	0-14	Beads
" S 5-50		Cl	-	1.2		0.4-0.85	50 (OH)	0-14	Beads
Ionac A-540	(Permutit S-1, marketed by Ionac Co., USA)								

APPENDIX-II (Continued)

Kastel A-500	Montecatini, Italy	Cl	3.0	-	-	0.3-1.0	60 (OH)	0-14	Beads
" A-500P		Cl	3.3	-	-	0.3-1.0	60 (OH)	0-14	Beads, porous
Lewatit M-500	Farbenfabriken	Cl	4.0	1.6	-	0.3-1.2	70	0-14	Beads
" MP-500	Bayer A.G.,	Cl	4.0	1.2	-	0.3-1.6	70	0-14	Beads, porous
" M-600	Fed. Rep. of Germany	-	3.7	1.6	-	0.3-1.2	40	0-14	Beads, porous
" MP-600		-	3.7	1.1	-	0.3-1.5	40	0-14	Beads, porous
Nalcite SBR	(Dowex 1, marketed by Nalco Chemical Co., USA)								
" SBR-P									Porous
Permutit ESB	Permutit A.G.,	Cl	3.2	1.2	-	-	70	-	Beads
" ESB-26	Fed. Rep. of Germany	Cl	3.3	1.3	-	-	70	-	Beads
Permutit S-1	Permutit Co.,	Cl	3.6	1.0	50-60	0.3-1.2	100	0-14	Beads
" NS1	USA	OH	3.5	1.0	50-60	0.3-1.2	60	0-14	Beads, nuclear grade
Resenex HBL	Jos. Crosfield,	-	3.5	1.5	-	-	60	-	Beads
" HBT	UK	-	3.5	-	-	-	60	-	Beads
S-E-TM anex	Výzkumný ústav synthetických pryskyřic a laků, Pardubice, CSSR	Cl	3.45	1.35	-	0.3-0.8	40 (OH)	0-12	
Wolfatit ES	VEB Farbenfabrik	Cl	3.5	0.5	65-75	0.5-2.0	60 (OH)	2-10	
" SBT	Wolfen,	Cl	3.0	0.9	53-63	0.6-2.0	-	0-14	Uranium recovery, beads
" SBW	German Democratic Rep.	Cl	3.5	0.9	58-68	0.3-1.5	60	0-11	Beads
" RO		OH	-	0.9	-	0.3-1.5	60	0-14	Beads, nuclear grade
Zerolit FF-1P	Zerolit Ltd.,	Cl	4.0	1.2	-	0.3-1.2	60	-	Beads, 7-9% DVB
" K-MP	UK	Cl	-	-	-	-	-	-	Beads, macroporous

b. Strong base polystyrene addition polymers Type II [functional group - N(CH₂OH)(CH₃)₂]

Amberlite IRA-410	Rohm & Haas Co., USA	Cl	3.3	1.40	40-45	0.3-0.8	40 (OH)	0-14	Approx. 8% DVB, beads
" IRA-910	distributed by	Cl	-	1.10	55-60	0.3-0.8	40 (OH)	0-14	Beads; macroreticular
" IRA-911	Tokyo Organic Chem. Ind. Ltd., Japan	Cl	2.7	0.9	42-44	0.3-1.2	40 (OH)	0-14	Beads; macroreticular
Diaion SA 20A	Mitsubishi Chemical	Cl	-	1.3	40-45	0.3-1.2	40 (OH)	0-12	Beads
" SA 21A	Ind. Ltd., Japan	Cl	-	0.8	55-65	0.3-1.2	40 (OH)	0-12	Beads, porous

APPENDIX-II (Continued)

Trade name	Manufacturer	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
			(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max.oper. temp.(°C)	pH range	
Dowex 2	Dow Chemical Co., USA	Cl	3.5	1.33	37	0.3 - 0.8	30 (OH)	0 - 14	Beads, ca. 8% DVB; 4% DVB also available
Duolite A-102D	Diamond Alkali Co., USA	Cl	4.2	1.4	45 - 50	0.3 - 1.2	40 (OH)	0 - 14	Beads, porous
Imac S5-52	IMACTI, Netherlands	Cl		1.2	-	0.4 - 0.85	40 (OH)	0 - 14	Beads
Ionac A-550	(Permutit S-2, marketed by Ionac Co., USA)								
Kagel A-300	Montecatini, Italy	Cl	3.2	-	45	0.3 - 1.2	40 (OH)	0 - 16	Beads
Nalcite SAR	(Dowex 2, marketed by Nalco Chemical Co., USA)								
Permutit ES " ES-26	Permutit A.G.,	Cl	3.2	1.2	-	-	40	-	Beads
	Fed. Rep. of Germany	Cl	3.3	1.3	-	-	40	-	Beads
Permutit S-2	Permutit Co., USA	Cl, OH; SO ₃	3.5 (Cl) 3.5 (OH, SO ₃)	1.3	45 - 55	0.3 - 1.2	100 (Cl) 60 (OH, SO ₃)	0 - 14	Beads
S-8-D anex	Výzkumný ústav synthetických pryskyřic a laků, Pardubice, CSSR	Cl	3.45	1.35	-	0.3 - 0.8	40 (OH)	0 - 12	Beads
Wolfatit SBK	VEB Farbenfabrik Wolfen, German Democratic Republic	Cl	3.0	1.0	35 - 45	0.3 - 1.5	40 (OH)	0 - 10.5	Beads, 6 - 8% DVB
Zerolit N-1P " P-1P	Zerolit Ltd.,	Cl	-	1.10	-	0.3 - 1.2	40	0 - 14	Beads; isoporous
	UK	Cl	-	1.14	-	0.3 - 1.2	40	0 - 14	Beads; isoporous

APPENDIX-II (Continued)

c. Medium and weak base polystyrene addition polymers

Trade name	Manufacturer	Functional group	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
				(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
Amberlite IR-45	Rohm & Haas Co., USA	Weak base	Freebase	5.0	1.9	40-45	0.3-0.84	100 (OH)	0-9	Beads
" IR-68		-N(R) ₂	"	-	1.60	57-63	0.3-1.2	60	0-9	Acrylic resin - beads
" IR-93		"	"	4.8	1.4	46-54	0.3-1.2	100 (OH)	0-9	Beads; macroreticular
AN-18-6	NIIP, USSR	Amino groups	Cl	3.5	-	40-60	0.35-1.2	-	-	Beads
AN-23		"	Cl	5.0	-	30	0.25-1.0	-	-	Beads
AN-25		"	Cl	5.0	-	30	0.25-1.0	-	-	Beads
AV-20		Pyridine base	Cl	3.5	-	60	0.25-1.0	130	-	Beads
AV-23		"	Cl	3.5	-	60	0.25-1.0	130	-	Beads
Dowex 3	Dow Chemical Co., USA	Weak base amino groups	OH	5.5	2.5	35	0.3-0.84	65	-	Beads
Duolite A-14	Diamond Alkali Co., USA	Weak base amino groups	OH	8.0	2.5	-	0.3-1.2	-	-	Beads
Imac A20	IMACTI, Netherlands	Weak base amino groups	OH	-	-	-	0.4-0.85	100	0-8	Beads; prim., sec. & tertiary amines
" A21		"	OH	-	-	-	0.4-0.85	100	0-8	Beads; tertiary amino groups only
Ionac A-315	(Permutit W, marketed by Ionac Co., USA)									
Lewatit MP-60	Farbenfabriken Bayer A.G., Fed. Rep. of Germany	Weak base amino groups	-	6.3	2.2	40-50	0.3-1.5	100	0-14	Beads; macroporous
Nalcite WBR	(Dowex 3, marketed by Nalco Chemical Co., USA)									
Permutit W	Permutit Co., USA	Weak base amino groups	Cl	4.5	1.3	45-55	0.3-2.0	95	-	Beads
Wolfatit Y13	VEB Farbenfabrik Wolfen, German Democratic Rep.	Weak base amino groups	OH	-	1.25	-	0.3-1.2	-	0-14	Beads
Zerolit G	Zerolit Ltd., UK	Amino groups	Cl	3.5	1.6	-	0.3-1.2	100	-	-N(C ₂ H ₅) ₂ groups only; beads
" M		"	Cl	5.5	1.9	-	0.3-1.2	60	-	Beads
" H		Weak & strong base groups	-	3.8	1.28	-	0.3-1.2	70	-	Beads; isoporous

d. Condensation polymers

APPENDIX-II (Continued)

Trade name	Type of base	Manufacturer	Functional group	Matrix	Ion form	Exchange capacity		Physical characteristics		Operational controls		Remarks
						(meq/g) (dry)	(meq/ml) (wet)	Moisture (wt. %)	Size (mm)	Max. oper. temp. (°C)	pH range	
AN-1	Weak	NIIP, USSR	Amino groups	-	SO ₄	4.2	-	50	0.3 - 2.0	40	-	Fine particles
AN-2FN	Weak	" "	" "	-	Cl	9.0	-	15	0.3 - 2.0	50	-	Fine particles
AN-9	Weak	" "	" "	-	-	4.5	-	-	0.3 - 2.0	-	-	Beads
AV-18G	Strong	" "	" "	-	Cl	9.8 - 10.5	-	60	0.4 - 2.0	60	-	Beads
AN-31	Weak	" "	" "	-	Cl	9.0	-	15	0.3 - 2.0	-	-	Irregular grains
Dowex WGR	Intermed.	Dow Chemical Co., USA	-	Epoxy-amine	Free amine	-	-	50 - 54	0.4 - 0.8	93	0 - 7	Marketed by Nalco Co., USA
Duolite A-2	Weak	Diamond Alkali Co., USA	Sec. amine	Phenolic	SO ₄	8.4	2.3	58 - 64	0.3 - 1.2	40	0 - 4	Granules, porous
" A-6	Weak	" "	Tert. amine	Phenolic	Cl	7.6	2.4	48 - 54	0.3 - 1.2	60	0 - 5	Granules, porous
" A-7	Weak	" "	Sec. amine	Phenolic	SO ₄	9.1	2.4	55 - 62	0.3 - 1.2	40	0 - 4	Granules, porous
" ES-15	Weak	" "	Tert. amine	Aliphatic	Salt	6.2	2.4	38 - 42	0.3 - 1.2	80	0 - 5	Beads
" A-3 OB	Intermed.	" "	Tert. amine	Epoxy-polyamine	OH	8.7	2.6	58 - 62	0.3 - 1.2	80	0 - 9	Beads, high stability
" ES-57	Intermed.	" "	Tert. amine	Epoxy-polyamine	Salt	9.2	2.2	60 - 66	0.3 - 1.2	80	0 - 9	Beads, porous stability
EDE-LOP	Strong & weak	NIIP, USSR	Quat. NH ₃ , sec. & tert. amine	-	Cl, OH	9 - 10 (Cl) 8 (OH)	-	10	0.4 - 1.8 (Cl) 0.5 - 2.0 (OH)	-	-	OH form is of special purity
Imac A-27	Strong & weak	IMACTI, Netherlands	Amino groups	Poly-alkylene	Free-base	-	-	-	0.3 - 2.0	35	0 - 8	Beads, polyfunctional
Ionac A-300	(Pemmuxit A, marketed by Ionac Co., USA)											
Kagel A-100	Intermed.	Montecatini, Italy	Quat. NH ₄ & amino	Epoxy-amine	Cl (partial)	7.5 - 8.0	-	60	0.3 - 1.25	4.5	0 - 5	
L-anex		Chemické závody usti n. labem, CSSR	≡N -N ⁺	-	SO ₄ ⁻	2.6	0.8	-	0.5 - 1.5	50 (OH)	0 - 12	Beads

APPENDIX-II (Continued)

Lewatit MH 59	Weak	Farbenfabriken	Amino	-	-	6.0	2.4	40-50	0.3-1.2	30	0-14	Granular
" MN	Strong	Bayer A.G., Fed. Rep. of Germany	-N (alkyl) ₃ ⁺	-	-	2.3	0.9	46-54	0.3-2.0	30	0-14	Granular
Lewatit MN	Weak	Moskovsk Chem. Technol. Inst., USSR	=NH, ≡N	-	-	4.1	-	-	0.3-2.0	-	-	Fine particles
Mykion G	Weak	MUKY, Hungary	≡N	-	-	4.6	1.25	-	-	-	-	Guanidine, formaldehyde
N	Weak	Moskovsk Chem.	≡NH, ≡N	-	-	4.1	-	-	0.3-2.0	-	-	Fine particles
NO	Weak	Technol. Inst., USSR	=NH, ≡N, -NR ₃	-	-	4.1	-	-	0.3-2.5	-	-	Fine particles
PEK	Strong & weak	Gosud. Institut Prikl. K., USSR	=NH ₂ , ≡N	-	-	6.0	-	-	0.3-1.0	-	-	Fine particles
Permutit E-3	Weak	Permutit A.G., Fed. Rep. of Germany	Amino groups	-	-	6.0	-	-	0.3-1.0	-	-	Granules, -NR ₃ groups only
" E-7P	Weak	"	" "	-	-	6.0	-	-	-	40	-	Granules, highly porous
Permutit A	Intermed.	Permutit Co., USA	NR ₃ , NR ₄	Aliphatic polyamine	Cl-SO ₄	5.5	1.8	1-5	0.3-1.2	40	0-12	Granules
" AB	"	"	NR ₃ , NR ₄	"	Cl-SO ₄	5.5	1.8	1-5	0.3-1.2	40	0-12	Beads
" CCG	"	"	NR ₃	Phenolic	Cl-SO ₄	5.5	1.6	2-7	0.3-1.2	60	0-12	Granules
" Deacidite	Weak	"	NHR ₂ , NR ₃	Aliphatic polyamine	Cl-SO ₄	5.5	1.8	1-5	0.3-1.2	40	0-12	Granules
Resanex	Weak	Jos. Crosfield, UK	Amino groups	-	-	9.0	3.0	-	-	80	0-9	Granules
Wolfatit N	Weak	VEB Farbenfabrik Wolfen, German Democratic Rep.	Amino groups	-	Cl	4.3	-	-	0.3-1.5	30	-	Granules
Zerolit E	Medium	Zerolit Ltd., UK	Amino groups	Phenol formaldehyde	Free- base	-	1.6	-	0.3-1.2	30	0-12	Granules

APPENDIX-II (Continued)

MIXED BED ION-EXCHANGE RESINS

Trade name	Manufacturer	Cation exchange resin	Anion exchange resin	Approx. vol. ratios cation : anion	Remarks
Amberlite MB-1	Rohm & Haas Co., USA	IR-120	IRA 400 or 401	1 : 1.5	
" MB-2		IR-120	IRA 410	1 : 1.5	
" MB-3		IR-120	IRA 410	1 : 1.5	Exhaustion colour indicator
" MB-4		IR-120	IR-45	1 : 1	
" MB-5		IRC-50	IRA 410	1 : 1.5	
" MB-6		IRC-50	IR-45	-	Nuclear grade
" IRN-217		IRN-218 ($^7\text{Li}^+$)	IRN-78	-	Nuclear grade
" IRN-150		IRN-77 (H^+)	IRN-78	-	Nuclear grade
" IRN-154		IRN-163 (Li^+)	IRN-78	-	Nuclear grade
" IRN-170		IRN-169 (NH_4^+)	IRN-78	-	Nuclear grade
Bio-Deminrolit	Zerolit Ltd., UK	Zerolit 225	Zerolit FF-1P	-	Also available with indicator
Nalcite MR-1	Dow Chemical Co., USA distributed by Nalco Chemical Co., USA	HCR-W	SBR	1 : 1	Technical grade; indicator
" MR-2		HCR	SBR	1 : 1	Nuclear grade
" MR-3		HCR-W	SBR	1 : 1	Nuclear grade
" MR-5		HCR-W (K^+)	SBR	1 : 1	Nuclear grade
" MR-6		HCR-W (Li^+)	SBR	1 : 1	Nuclear grade
" MR-7		HCR-W (NH_4^+)	SBR	1 : 1	Nuclear grade
Wolfatit MBW		KPS	SBW	1 : 2	
" ROH		RH	RO	1 : 1	Nuclear grade
" ROL		RK	RO	1 : 1	Nuclear grade (LiOH)
" ROK		RK	RO	1 : 1	Nuclear grade (KOH)
" RON		RN	RO	1 : 1	Nuclear grade (NH_4OH)

APPENDIX-II (Continued)

ION-EXCHANGE MEMBRANES

a. Cation exchangers

Trade name	Manufacturer	Matrix	Functional groups	Exchange capacity (meq/g) dry membrane	Transport number (solution used)	Moisture content (wt. %)	Thickness (mm)	Electric resistance (ohm-cm ²) (ion form)	Remarks
AMF ion C-60 (Series 60)	American Machine & Foundry, USA	Polyethylene-styrene copolymers	-SO ₃ ⁻	1.5 ± 0.3	0.92 ± 0.03 (0.2N/0.1N KCl)	35	0.28 - 0.33	5 ± 2 (K)	91.5 and 112 cm wide roll
AMF ion C-100 (Series 100)	" "	"	-SO ₃ ⁻	1.3 ± 0.3	0.98 ± 0.1 (0.2N/0.1N KCl)	15	0.20	7 ± 2 (K)	Roll
AMF ion C-310	" "	Polymeric fluorocarbon	-SO ₃ ⁻	0.6 ± 0.2	0.86 ± 0.5 (0.5N/1.0N KCl)	-	0.28	4.5 ± 2	Roll
AMF ion C-313 (Series 300)	" "	"	-SO ₃ ⁻	0.6 ± 0.2	0.90 ± 0.003 (0.2N/0.1N KCl)	12	0.17	4.5 ± 2 (K)	112 cm wide roll
CK-1	Asahi Chem. Industry Co. Ltd., Japan	Polystyrene	-SO ₃ ⁻	2.6	0.99 (0.5N NaCl)	36	0.23	4.2	
MC-3142	Permutit Co., USA, distributed by	-	-	1.06	0.941 (0.5N/1N NaCl)	-	0.15	3.4 (1.0N NaCl)	Heterogeneous
MC-3235	Ionic Chemical Co., USA	-	-	1.26	0.953 (0.5N/1N NaCl)	-	0.30	11 (1.0N NaCl)	Heterogeneous
MC-3470 XL	"	-	-	1.05	0.962 (0.5N/1N NaCl)	-	0.30	4.8 (1.0N NaCl)	Heterogeneous
MK-40N	NIIP, USSR	Polystyrene (KU-2)	-SO ₃ ⁻	2.3	0.93 (0.01N/0.2N NaCl)	41	0.7 - 0.8	Spec. resist. 250 ohm-cm	Heterogeneous, 500 x 500 mm sheets
Nal film 1	Nalco Chem. Co., USA	-	-SO ₃ ⁻	-	0.91	20	0.09	10 - 15 (K) (0.15N KCl)	96.5 cm wide
Napcon CR-61	Ionics Inc., USA	Polystyrene	-SO ₃ ⁻	2.8	0.9 - 0.95	45 - 50	0.58	5.3 (Na) (0.5N NaCl)	Porous: Dynel reinforced
Serion C-100	Japan Organo Co. Ltd., Japan	-	-SO ₃ ⁻	-	0.9 (0.5N/2.5N NaCl)	-	0.20 - 0.23	4 - 5 (0.5N NaCl)	90 cm wide roll
Selemon CMG-10	Asahi Glass Co. Ltd., Japan	-	-SO ₃ ⁻	1.06	0.91	-	0.20 - 0.25	5.5 - 8.5 (Na) (0.5N NaCl)	98 x 98 cm
" CMG-20	" "	-	-SO ₃ ⁻	-	0.60 (0.5N/1.0N NaCl)	-	0.23 - 0.25	1.5 (Na) (0.5N NaCl)	98 x 98 cm, porous

APPENDIX-II (Continued)

CMV-10	-	-	-SO ₃ ⁻	-	0.91 (0.5N/1.0N NaCl)	-	0.22 - 0.25	6.0 - 8.0 (0.5N NaCl)	98 x 98 cm
CSG	-	-	-SO ₃ ⁻	-	0.92 (0.5N/1.0N NaCl)	-	-	10 - 14 (Na) (0.5N NaCl)	98 x 98 cm
Zerolit C-30	Zerolit Ltd., UK	-	-SO ₃ ⁻	3.0	0.94 (1.0N NaCl)	30 - 40	0.75	10.3 (K) (0.1N KCl)	152 x 152 mm to 760 x 304 mm

b. Anion exchangers

AMF ion A-60	American Machine & Foundry Co., USA	Polyethylene & styrene graft-copolymer	-NR ₃	1.6 ± 0.3	0.93 ± 0.03 (0.2N/0.1N KCl)	22 ± 5	0.31	6 ± 2 (Cl) (0.6N KCl)	91.5 x 112 cm wide roll
" A-104B			-NR ₃	1.5 ± 0.3	0.98 ± 0.01 (0.2N/0.1N KCl)	15 ± 3	0.15	9 ± 3 (Cl) (0.6N KCl)	51 x 112 cm wide roll, high selectivity
MA-3148	Permutit Co., USA	-	-	0.96	0.899 (0.5N/1.0N NaCl)	-	0.30	1.7 (1.0N NaCl)	Density 196 g/m ³
MA-3236	Ionac Chemical Co., USA	-	-	0.765	0.933 (0.5N/1.0N NaCl)	-	0.30	20 (1.0N NaCl)	heterogeneous Density 356 g/m ³
MA-3475XL		-	-	0.743	0.941	-	0.30	5.3	heterogeneous Density 358 g/m ³
MA-40N	NIIP, USSR	Heterogeneous-ED ⁺ OP resin	Amino groups	3.0	0.84 (0.01N/10.2N NaCl)	38	0.7 - 0.8	Spec. resist.	1500 x 500 mm sheets
Nal film 3	Naico Chemical Co., USA	Polystyrene	-NR ₃	-	0.96 (0.2N/0.1N KCl)	30	0.10	20 - 25 (Cl) (0.15N KCl)	
Nepton AR-111-A	Ionics Inc., USA	Polystyrene	-NR ₃	2.0	0.90 - 0.95 (0.6N NaCl)	40 - 45	0.58	5.9 (Cl) (0.5N NaCl)	Dynei backing, porous
	Permutit Co. Ltd., UK	Polystyrene	-NR ₃	2.0	0.93 (1N NaCl)	30 - 40	0.75	8.1 (Cl) (0.1N KCl)	
Sarion A-100	Japan Organo Co. Ltd., Japan	-	-NR ₃	-	* 0.9 (0.5N/2.5N NaCl)	-	0.10 - 0.12	4 - 6 (Cl) (0.5N NaCl)	90 cm wide
Selemon AMT-10	Asahi Glass Co., Ltd., Japan	-	-	1.25	0.92 (0.5N/1.0N NaCl)	21	0.18 - 0.2	2.0 - 4.0 (Cl) (0.5N NaCl)	98 x 98 cm
" AMT-20	"	-	-NR ₃	-	0.78 (0.5N/1.0N NaCl)	58	0.34 - 0.36	2.4 (Cl) (0.5N NaCl)	98 x 98 cm
" AST	"	-	-	-	0.95 (0.5N/1.0N NaCl)	20	0.21 - 0.23	6.0 - 9.0 (Cl) (0.5N NaCl)	98 x 98 cm
" DMT	"	-	weakly basic	-	0.93 (0.5N/1.0N NaCl)	-	0.10 - 0.12	1.5 (Cl) (0.5N NaCl)	88 x 88 cm
Zerolit A-20	Zerolit Ltd., UK	-	-NR ₃	2.0	0.93 (1N NaCl)	30 - 40	0.75	8.1 (Cl) (0.1N KCl)	152 x 152 mm to 760 x 304 mm