PEACEFUL USES OF ATOMIC ENERGY

Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy

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Volume 2
Survey of Raw Material Resources

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PREFACE

More than 2,100 papers were submitted by the nations, the specialized agencies, and the International Atomic Energy Agency, which participated in the Second United Nations International Conference on the Peaceful Uses of Atomic Energy. The number of papers was thus about twice that involved in the First Conference. Provision was therefore made to hold five concurrent technical sessions in comparison with the three that were held in 1955. Even so, the percentage of orally presented papers was less in 1958 than in 1955.

In arranging the programme, the Conference Secretariat aimed at achieving a balance, allowing adequate time for presentation of as many good papers as possible and, nevertheless, leaving time for discussion of the data presented. Three afternoons were left free of programme activities so that informal meetings and discussions among smaller groups could be arranged. No records of these informal meetings were made.

A scientific editorial team assembled by the United Nations checked and edited all of the material included in these volumes. This team consisted of: Mr. John H. Martens, Miss L. Ourom, Dr. Walter M. Barss, Dr. Lewis G. Bassett, Mr. K. R. E. Smith, Martha Gerrard, Mr. F. Hudswell, Betty Guttman, Dr. John H. Pomeroy, Mr. W. B. Woollen, Dr. K. S. Singwi, Dr. T. E. F. Carr, Dr. A. L. Kolb, Dr. A. H. S. Matterson and Mr. S. Peter Welgos.

The speedy publication of such a vast bulk of literature obviously presents considerable problems. The efforts of the editors have therefore been primarily directed towards scientific accuracy. Editing for style has of necessity been kept to a minimum, and this should be noted particularly in connection with the English translations of certain papers from French, Russian and Spanish.

The Governments of the Union of Soviet Socialist Republics and of Czechoslovakia provided English translations of the papers submitted by them. Similarly, the Government of Canada provided French-language versions of the Canadian papers selected for the French edition. Such assistance from Governments has helped greatly to speed publication.

The task of printing this very large collection of scientific information has been shared by printers in Canada, France, Switzerland, the United Kingdom and the United States of America.

The complete Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy are published in a 33-volume English-language edition as follows:

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RAW MATERIAL SUPPLIES

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Resources of Nuclear Fuel for Atomic Power

By J. C. Johnson *

At the First International Conference on the Peaceful Uses of Atomic Energy held here in Geneva in 1955, the world was given its first comprehensive view of the resources of nuclear raw materials available for atomic energy purposes. Prior to that Conference much of the information relating to atomic energy, particularly that which had any bearing upon production or production methods, had been protected by the strictest secrecy regulations. For more than ten years—and this was the period during which work on atomic energy programs moved from purely scientific laboratory experiments into vast developmental and production operations—there was limited public discussion on scientific development and practically none on engineering and production.

The development and production of nuclear raw materials also proceeded with a minimum disclosure of essential information. Therefore, a large accumulation of scientific and technical information was available for release for the first time at the 1955 Conference. However, even at that Conference only a limited amount of information was released on uranium reserves and production.

At this Second Conference numerous papers and exhibits will deal with the new developments in the fields of uranium geology, chemistry and metallurgy. Important progress in these fields has been made during the past three years. The public discussions at the last Conference and the free exchange of information that followed have contributed to that progress. In addition to the subjects discussed at the previous Conference, there is now available much detailed information on uranium production rates, production costs, and ore reserves. Since 1955 most of the important uranium-producing nations have removed virtually all security restrictions on information relating to nuclear raw materials.

If all uranium-producing nations were to take similar action, it would be possible at this Conference to compile an inventory of the world's known reserves of nuclear fuels and to undertake a comprehensive assessment of the world's potential resources. The location of these resources is much less important than in the case of fossil fuels since the cost of transporting high-energy nuclear fuel will have little effect on power costs. In a peaceful world with a minimum of trade barriers, atomic power could serve people everywhere, and at much the same cost, irrespective of whether the nuclear fuel came from half-way round the globe or was available close at hand.

It is important then that resources of nuclear fuels be considered from a world point of view. All nations planning or considering atomic power development need access to the maximum information on the availability and cost of the nuclear fuel.

In this paper I shall attempt to summarize the more important data now available.

Uranium reserves fall roughly into two broad economic categories: those from which uranium could be recovered and sold profitably at a price of approximately $10.00 per pound of U_3O_8 or even less, and the very low-grade uraniferous shale and phosphate deposits from which exploitation for uranium alone would require a price three to six times that amount. Relatively large tonnages of presently marginal or submarginal ores also are found in some of the uranium mining districts. These ores, which may be considered as forming an intermediate economic class, at present do not constitute a major potential source. However, with continuing exploration and development, and improved methods for preliminary concentration, this intermediate class may become much more important. Very high-grade deposits which might provide uranium at two or three dollars a pound are another possible source. Such deposits are not common and are not likely to be a major source of the world's uranium supply for any extended period.

With respect to reserves of the first category, the type from which uranium can be produced today for approximately $10.00 per pound of U_3O_8, the 1957 estimates by Canada and South Africa indicate that the developed or partially developed reserves in each of these two countries contain approximately 400,000 tons of U_3O_8. Recorded reserves of the United States are now about 220,000 tons. Nearly two years ago, France published reserve figures of 50,000 to 100,000 tons. These estimates, for the four countries, total about 1,100,000 tons of U_3O_8. Taking into consideration the probable conservative nature of these estimates, and including the reserves of Australia, the Belgian Congo, Portugal and other countries, total reserves in areas presently under development in the non-Communist countries may be

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nearer 1,500,000 tons of U_3O_8. Ultimate production from these and adjacent areas may reach or exceed 2,000,000 tons. On the basis of present geologic data, and the discovery experience of the past ten years, an additional 2,000,000 tons of relatively low-cost uranium might be developed in new areas within a reasonable period by an aggressive exploration program.

In a paper presented at the 1955 Geneva Conference, the United States estimated that on the basis of developed reserves and geologic evidence the economic uranium resources of the non-Communist producing countries were 1,000,000 to 2,000,000 tons. However, developed reserves at that time were about 500,000 tons. The increase in developed reserves since then has been mainly in uranium fields discovered before 1956.

A major factor responsible for the lack of discovery of many new areas since 1955 has been the limited market for additional uranium production. From 1948 until 1955 there was a demand by the United States and the United Kingdom for virtually all uranium that could be produced. This greatly stimulated exploration and development, and resulted in rapid expansion of production. As a consequence, the current and near-term requirements of these two countries can now be met from existing sources of production. Other markets have not yet developed since the atomic power programs of most countries still are in the planning stage. However, there is every indication that the market for uranium soon will broaden.

Because estimated reserves in the United States in 1955 were still relatively small, a program designed to encourage private exploration and development was continued. The procurement program, which established firm prices for uranium ores through March 31, 1962, was extended to the end of 1966. However, for the extended period, the price established is \$8.00 per pound of U_3O_8 in a high-grade chemical concentrate. The results of this program demonstrate the effectiveness of private exploration and development under the stimulus of a favorable market. Although few discoveries of entirely new areas have been found since 1955, the development of additional deposits and the increase in reserves in previously discovered uranium-bearing districts have been impressive. At the end of 1954, uranium reserves of the United States were estimated at 10,000,000 tons of ore containing about 30,000 tons of U_3O_8. Today they are estimated at about 80,000,000 tons of ore containing nearly 220,000 tons of U_3O_8.

Theories on favorable areas for uranium exploration have undergone radical changes during the past ten years. When extensive exploration first was initiated, it was thought that vein-type hydrothermal deposits offered the best possibility for large production. The South African gold-bearing deposits were considered unique and it was thought that economic uranium recovery from deposits of that type could only be on a by-product basis. Today approximately 90% of all uranium reserves which have been reported are in sedimentary rocks ranging in age from the Pre-Cambrian conglomerates of South Africa and Canada to late Tertiary sandstones in the United States. It is now generally accepted that many areas not yet explored contain extensive deposits of sedimentary rocks favorable for uranium occurrence and should be carefully examined.

The increase in reserves has been accompanied by a comparable expansion in production. Uranium production has become an important, well-established industry in ten years. Production methods have passed the experimental and development stages. Modern ore-treatment plants using processes introduced since 1950 already have processed in excess of 100,000,000 tons of ore. The uranium plants today have a total combined capacity capable of processing 50,000,000 tons of ore a year. The most rapid increase in production has occurred since 1955. At the end of 1955, total uranium production of non-Communist countries was at an annual rate of 11,500 tons of U_3O_8. Today the rate is about 35,000 tons and in 1959 should approximate 42,000 tons a year. The total annual value of the uranium concentrate production of non-Communist countries is now approximately \$750,000,000.

The United States, Canada and South Africa are major producing countries. Production in the United States is now about 15,000 tons of U_3O_8 per year and by 1960 will be at an annual rate in excess of 20,000 tons. The production rate of Canada is approximately 13,000 tons a year and in 1959 should reach a level of about 15,500 tons. South African production is more than 6000 tons of U_3O_8 per year. Each of the three countries could expand its output from existing sources of production. Other producing countries also could increase production.

The cost of mining uranium ores in the USA varies widely. Large, open-pit mining operations are increasingly important, and mining costs range from \$4.80 to \$11.50 per ton. Underground mining costs range from \$6.00 to \$10.00 for large mechanized operations to about \$15.00 per ton for small underground mines.

Through most of the uranium industry there is free exchange of technical and operating data on ore processing so that operating procedures, equipment and mill design tend to become standardized. As in all industries, improvements are being made continually and new methods are being introduced. However, recent changes in uranium metallurgy represent normal progress rather than revolutionary changes. The principal objective is to reduce operating costs and improve metallurgical recovery. This suggests that concentrate production costs, exclusive of plant amortization, will only gradually be reduced below present levels.

At the present time 26 plants are operating or under construction in the USA, including three recovering uranium from phosphate rock. Ten of these employ a sulfuric acid leach of the ore followed by ion exchange recovery of uranium from the solution, while 11 mills employ acid leach and solvent extraction. In one phosphate plant, the uranium is chemically precipitated from the phosphoric acid. Seven plants use the carbonate process. Three of the above mills employ both acid and alkaline circuits.

On a tonnage basis, 35% of the ore is processed in a solvent extraction flowsheet, 36% in plants using ion exchange, and 29% by carbonate leach followed by chemical precipitation. Although the solvent extraction process has found wide application due to its simplicity of equipment and ease of operation, costs for this process are equivalent to those of the other processes, and choice of treatment will depend largely upon the metallurgical characteristics of the ore.

The cost of processing sandstone-type ores in the USA ranges from $6.00 to $10.00 per ton for the larger mills, exclusive of amortization and major equipment replacements. The character of the ore, which determines the chemical consumption, has an important bearing on cost and is often the controlling factor in the selection of a mill process. The grade of the ore has a major effect upon the cost per pound of uranium extracted. Although the average recovery in the United States is about five pounds of uranium oxide per ton of ore, the average grade of ore processed by some mills is less than 0.20% U_3O_8 whereas others treat ores containing more than 0.30% U_3O_8.

Canadian and South African processing costs are lower than those in the United States largely because the highly siliceous, lower-grade conglomerate ores consume less reagents. Furthermore, in South Africa crushing and grinding generally are charged to gold production. The United States, however, has the advantage at present of higher-grade ores as compared to the Blind River field of Canada, where average recovery is approximately two pounds of uranium oxide per ton, and South Africa's recovery of one-half pound per ton. South African uranium is considered a by-product of the gold operations, and gold bears most, or all, of the mining costs, as well as crushing and grinding. However, for many operations uranium now is about as important as gold.

Although no general statement can be made regarding the cost of producing uranium, it is important for those considering atomic power to be able to make reasonably accurate estimates of the price of uranium. On the basis of current production costs, a price of from $8.00 to $10.00 per pound of U_3O_8 in a mill concentrate should support substantial production—a production rate in excess of 40,000 tons of U_3O_8 per year. The United States anticipates that the domestic price of $8.00, which has been established for the period March 31, 1962 through 1966, will provide most of its producers with a profitable market. Many of the mills in the USA will have been fully amortized by 1962, and this will influence the profit margin considerably.

Because of the wide variation in production costs, some operations will be highly profitable while others will be marginal. The price established by supply and demand will be that which will provide the amount of material required. For the next ten to fifteen years it appears that a price in the range of $8.00 to $10.00 a pound should supply the requirements now anticipated. If there is a major expansion in total requirements, to something substantially in excess of 40,000 tons of U_3O_8 per year, the price for uranium may increase because of the need to encourage exploration and development and the construction of new plants.

Fortunately for the initial development of atomic power, nuclear fuel for some time will be available at reasonably low prices. Improvements in the efficiency of power reactors as experience is gained probably will offset, or more than compensate, the higher uranium prices that might come with an expanded market.

At present the uranium producers are concerned about the market for their future production. They are optimistic about the long-range outlook but are uncertain as to when power requirements alone will equal or exceed the present uranium production rate. Most estimates indicate a rapidly expanding market for uranium beginning about 1965. However, some of the large power programs currently being considered could provide an increased market within the next few years. The papers and discussions at this Conference may give an indication as to the growth of atomic power and requirements for nuclear fuel.

In the past those planning power development have been concerned about the availability of uranium. Although the outlook is now favorable, it must not be forgotten that the mineral industry can meet a growing requirement only if it has the basis and incentive for long-range planning and exploration. If the requirements can be estimated well in advance, the growth of atomic power will not be impeded by lack of uranium.

With the increase in reserves and potential supplies of relatively low-cost uranium, the prospect of having to turn to high-cost sources, such as the low-grade shale and phosphate deposits, now seems much farther in the future than it did a few years ago. It is reasonable to expect that higher-grade resources of the type now being mined will supply the world's requirements for many years. However, the low-grade shale and phosphate deposits constitute a vast uranium reserve which assures adequate supplies of nuclear fuel for many generations.

Low-grade bituminous shale and phosphate deposits contain from $^1/_{10}$ to $^1/_5$ of a pound of uranium per ton and, considering only the larger of the world's known deposits, represent a uranium reserve of more than 20,000,000 tons. The most uraniferous part of the Chattanooga shale in the United States contains five or six million tons of uranium and the phosphate deposits in the USA more than 600,000 tons. Portions of the extensive deposits of bituminous shale in Sweden and the Russian Baltic area have a considerably higher uranium content than the Chattanooga shale.

A limited research program for the US Atomic Energy Commission indicated a uranium cost of $40.00 to $50.00 a pound if the Chattanooga shale were to be mined and processed for uranium alone. Undoubtedly costs would be reduced by process improvements and operating experience. However, major cost reduction depends upon the economic recovery of various by-products such as bituminous materials, alumina and iron. Although no assessment can be made of the chances for success, recovery of by-products offers a possibility of moderate cost uranium from at least some shale deposits.

Recovery of by-product uranium from certain commercial phosphate operations already has proved successful. Two phosphate plants in the United States have achieved costs in the range of $7.00 to $12.00 a pound of U_3O_8. Although production is small, the phosphate chemical and fertilizer industry is assured of continuing growth and eventually by-product uranium from this industry could be several thousand tons a year.

Thorium has had a limited market with the result that there has been no great incentive for exploration. Although utilization of thorium for atomic energy purposes undoubtedly will gradually increase, as yet no major projects involving the use of thorium have been announced. United States requirements for thorium for atomic energy uses have been amply met through the purchase of thorium produced as a by-product of the processing of monazite sands for the extraction of rare earths.

Known economic reserves of thorium within non-Communist countries may be about 500,000 tons. The major portion of these reserves is in the beach placer sands of India and in the Blind River and Bancroft uranium districts of Canada. The remainder is in placer and vein deposits in Australia, Brazil, Madagascar, South Africa, southeast Asia and the United States.

The recent major development which has greatly increased thorium reserves and thorium availability has been the discovery of the Blind River and Bancroft uranium deposits in Canada. These deposits average about one part of ThO_2 for two parts of U_3O_8. Furthermore, approximately 85% of ThO_2 is dissolved during the uranium treatment process and is available for recovery from the solutions after extraction of uranium by ion exchange. By-product thorium from the uranium operations probably will be one of the lowest cost sources of supply, if not the lowest.

The uranium ore reserves of the Blind River and Bancroft areas probably contain about 200,000 tons of thorium. Assuming a production rate of 10,000 tons of U_3O_8, between 4000 and 5000 tons of thorium oxide may be available for by-product recovery annually. The Canadian estimate of a potential of 3500 tons a year may allow for production from only the more favorable sources. World production has never been more than a fraction of 3500 tons of ThO_2 per year. Therefore, a new large source of nuclear fuel is now readily available.

The discovery and development of nuclear source materials during the past ten years, and the development of efficient methods for their production, have made possible the undertaking of large atomic power projects and the planning of even larger programs. The knowledge and experience gained from extensive geological investigations and explorations indicate that there need be no concern about the availability of adequate supplies of nuclear fuels for current and future atomic power requirements.

Geologic Distribution of Nuclear Raw Materials

By R. D. Nininger *

Of the many metals needed for the industrial utilization of atomic energy the ores of four—uranium, thorium, beryllium and zirconium—have special significance as nuclear raw materials. They are listed in order of importance and in inverse order of availability and geologic knowledge of their occurrence at the beginning of the atomic age.

Exploration for uranium has been more intensive than for the other nuclear raw materials because of its greater importance and initial short supply. Rapid development of new supplies and a great advance in knowledge of uranium geology have resulted. The demand for thorium for atomic energy purposes has so far been almost entirely restricted to quantities needed for research and development. Consequently, exploration and advance in thorium geology have been limited. Beryllium and zirconium ores had substantial commercial uses prior to the advent of atomic energy and existing sources of supply have proven adequate for atomic energy requirements as well. Unlike uranium, utilization of these materials for atomic energy has been primarily a metallurgical problem rather than a problem of raw material supply, and intensive exploration programs have not been required.

URANIUM

As the intensive and widespread uranium geologic and exploration program of the past decade has proceeded, changes have taken place in the relative importance of the various types of uranium deposits. Geologic theories of uranium distribution and exploration concepts have been modified. These changes have an important bearing on exploration for new reserves.

A decade ago uranium deposits in sandstones and other sedimentary formations were considered, at best, a minor supplementary source; the great potential of the metaconglomerate or conglomerite deposits was not yet recognized; the significance of the oxidized outcrops of many vein-type uranium deposits was not understood.

Typical hydrothermal vein deposits in Pre-Cambrian metamorphic rocks, in which uranium is associated with cobalt, nickel, silver and copper, comprised the major portion of uranium reserves and production and were therefore thought to represent the most favorable exploration objectives. In spite of the realization about 1950 of the significance of uranium recovery from South African gold ores, exploration concepts did not appreciably change until 1953 with the discovery of major uranium reserves in sedimentary rocks in the United States and in conglomerite deposits not dependent upon gold production for economic uranium recovery at Blind River, Canada. Such deposits then became the major exploration objectives.

Reserves in disseminated deposits in sedimentary rocks and in conglomerites have continued to expand. On the other hand, the proportion of reserves in veins and related deposits in igneous and metamorphic rocks ceased declining about 1955 and has since then retained its relative importance (Fig. 1).

In 1955, deposits in conglomerites in South Africa and Canada represented approximately 75% of the uranium reserves of the non-Communist countries. Approximately 15% of the reserves in 1955 were in disseminated deposits in sedimentary rocks of Mesozoic age almost entirely in the United States. Reserves in vein or vein-type deposits in igneous and metamorphic rocks, largely in Australia, Belgian Congo, Canada, France, Portugal and the United States, had declined to about 10% of the total, although such deposits originally represented almost the entire known reserves of uranium.

The order of importance of geologic types of uranium deposits remains the same today as in 1955, but a significant trend is evident. Although the known reserves in conglomerite deposits have increased markedly since 1955, this type of deposit now represents only 65% of the total. In contrast, the proportion of reserves in sedimentary rocks has increased to 25%, and this category now includes large deposits in Tertiary rocks. The proportion of reserves in vein and vein-type deposits has remained at about 10% in spite of the large overall reserve increase. This has been due both to the development of additional reserves in known districts and to important new discoveries.

Although the largest individual exploration targets are the uraniferous conglomerites, the trend indicates that the other types may now collectively offer the greatest opportunity for reserve expansion. No new

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areas of uraniferous conglomerite known to be capable of economic production have been discovered for a period of five years.

URANIUM DEPOSITS IN CONGLOMERITES

Uraniferous Pre-Cambrian conglomerites lithologically similar to those in Canada and South Africa are known in many parts of the world. However, experience since the Blind River discovery indicates that conglomerite deposits from which uranium can be produced at present prices are the exception. Some are capable of small gold production, or may be potential sources of thorium, but have insignificant uranium. Others may have slightly greater uranium content but insufficient gold. Most have only trace amounts of these three elements. New productive areas may be found eventually, but it is suggested that in view of the rapid expansion of reserves in sedimentary rocks, the proportion of reserves in conglomerites will not increase and is more likely to decline. Nevertheless, because of the substantial additions to our long-range supplies which new discoveries would represent, exploration for additional conglomerite deposits should continue. Exploration should be carried out with due regard to the experience at Blind River which has shown that significant gold values are not required for economic uranium production and that due to leaching the uranium content of outcrops is not necessarily diagnostic of tenor at depth.

URANIUM DEPOSITS IN SEDIMENTARY ROCKS

Because of the widespread occurrence of deposits of uranium in sedimentary rocks and the large areas of favorable sedimentary terrane yet to be explored, this type of deposit will probably continue to increase in relative importance. Reserves in such deposits represent more than 95% of recorded reserves in the United States which now total about 220,000 tons U_3O_8. The remaining reserves are in vein and vein-type deposits; no conglomerite deposits are known. No large reserves in sedimentary rocks have yet been reported from other non-Communist countries although developments in Argentina, Italy and French Africa may rapidly change this situation.

Continued expansion of geographic and stratigraphic distribution of United States reserves has resulted in a five-fold increase since 1955 and the establishment of new major productive areas. The states of New Mexico, Oregon, South Dakota, Texas, Washington and Wyoming have been added to the three original producing states of Colorado, Utah and Arizona. Individual areas in New Mexico and Wyoming, largely developed since the first Geneva Conference, now have the largest reserves in the United States—114,000 and 25,000 tons U_3O_8 respectively.

Important production of sandstone ores now comes from two stratigraphic units each in rocks of Triassic, Jurassic, Cretaceous and Tertiary age.[1] Four important producing stratigraphic intervals have been added since 1955. Small but significant production has been achieved from Jurassic limestone in New Mexico and from Mississippian limestone in Montana and northern Wyoming.[2]

Prior to 1953, only two known deposits in the United States contained more than 1500 tons of uranium. Some 15 or 20 deposits of 300 to 500 tons had been discovered. In late 1952 and in 1953, new mineralized areas of Triassic, Jurassic, and Paleocene sandstones were discovered, and by 1956 were proven to contain many deposits ranging from 2000 to 20,000 tons.

As discoveries continued there became apparent at least an empirical relation between many uranium deposits and certain oil- and gas-type structures, particularly anticlines and domes, and occurrences of natural gas, petroleum, and petroliferous materials.[3] The three areas of largest reserves—Grants, New Mexico, Big Indian Wash, Utah, and Gas Hills, Wyoming—as well as several other areas such as Palangana Dome, Texas, show these relationships. Deposits, or clusters of deposits, associated with such structures in uranium provinces in the United States commonly contain 2000 tons or more uranium. Reserves with these associations in the United States now represent about 60% of the total.

Channel deposits in conglomerates and sandstones such as those in White Canyon, Utah, and the Black Hills, South Dakota, have not exceeded 1500 tons of uranium and in most cases are less than 500 tons. Deposits in limestone discovered to date are small; the largest contain about 250 tons, but most contain 50 tons or less.

The rapid discovery and development of deposits in sedimentary rocks give promise of the continuing discovery of large reserves of this type in the United States as well as in areas of similar lithology and structure elsewhere in the world. Success in the future will depend much more than in the past on well-planned geologic and geophysical studies and subsurface exploration. Exploration for the large unoxidized deposits in sedimentary rocks will require many of the techniques of petroleum exploration —deciphering the geologic and tectonic history of an area, location of buried favorable host lithology and structure and final proving by drilling.

It would be of very great interest to have information developed at this conference on the development of deposits in sedimentary rocks in the USSR. The description of occurrences in Kazakh S.S.R. in the early literature indicated similarities to the carnotite deposits of the Colorado Plateau and to some of the limestone deposits in New Mexico and Montana. Such information would help to complete the knowledge of world distribution of uranium.

URANIUM IN VEIN AND RELATED HYDROTHERMAL DEPOSITS

Vein-type uranium deposits will probably remain in third place in importance. Nevertheless, it is significant that the proportion of reserves in this